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FINAL REPORT

The Use of Element Level Data & Bridge Management Software in the Network Analysis of Big Bridges

Transportation Pooled Fund Study

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Paul D. Thompson

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16. Abstract

The project goals are to investigate the inspection practices, management strategies, and analysis systems currently employed for Big Bridges and to suggest modifications, improvements, and recommendations for enhancement. Currently, Big Bridges are treated the same as smaller or less-complex bridges within existing bridge management programs and software packages. This simplistic approach is sub-optimal for Big Bridges that are composed of various structure types that function more as a network of adjacent structures with complex interactions between various components. Several products, recommendations, documents and guidelines were developed as part of this study, including: recommended additions and changes to the list of currently recognized AASHTO National Bridge Elements and Bridge Management Elements contained in the AASHTO Manual for Bridge Element Inspection; guidelines for the breakdown of Big Bridges into smaller units; a methodology for the inspection and collection of element level data; a framework for modifications to the AASHTOWare BrM™ software; recommended approaches for asset management, including adapting and supplementing existing tools as a part of network level decision making; a recommended migration path to location aware recording of damage instances while maintaining long-term cost analysis; and recommendations for future research.

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* Former advisory panel member

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EXECUTIVE SUMMARY

The project goals are to investigate the inspection practices, management strategies, and analysis systems currently employed for Big Bridges and to suggest modifications, improvements, and recommendations for enhancement.

Currently, Big Bridges are treated the same as smaller or less-complex bridges within existing bridge management programs and software packages. This implies:

- The bridge is considered as one structure composed of and analyzed using the bridge elements provided in the AASHTO Manual for Bridge Element Inspection (MBEI),
- Deterioration rates and consequences of member deterioration or failure are similar to typical bridges that repair/preservation/replacement costs of the various components per unit are similar to other bridges, and
- Rehabilitation needs are driven by individual component condition threshold percentages.

This simplistic approach is sub-optimal for Big Bridges that are composed of various structure types that function more as a network of adjacent structures with complex interactions between various components. Characteristics important to Big Bridges are/contain:

- Various structure types may be constructed of different materials and different structural systems that have different anticipated failure modes,
- Series of inter-connected structures rather than one single entity,
- AASHTO MBEI elements are insufficient to accurately represent and analyze important components, therefore, additional elements need to be defined to identify and assign condition ratings,
- A system for accurately locating defects along affected members is required to support detailed analysis and condition tracking of defects.

Due to the sheer volume of element quantities, and the importance of location specific defect information, inspection efforts are greater than smaller bridges. Developing technology in the form of portal recording/reporting devices, unmanned aerial vehicles and semi-automated NDE techniques may be important. Some modifications or improvements to bridge management software packages such as AASHTOWare Bridge Management will be required to support these characteristics.

Herein several products, recommendations, documents and guidelines were developed and are presented, including:

- Recommended additions and changes to the list of currently recognized AASHTO National Bridge Elements and Bridge Management Elements contained in the *AASHTO Manual for Bridge Element Inspection*, see Chapter 4 Section 4.2 and Appendix A
- Guidelines for the breakdown of big bridges into smaller units, see Chapter 4 Section 4.3
- Methodology for the inspection and collection of element level data, see Chapter 4 Section 4.4
- Framework for modifications to the AASHTOWare BrM™ software, see chapter 6 section 6.2
- Recommended approaches for asset management, including adapting and supplementing existing tools as a part of network level decision making
- Recommended a migration path to location aware recording of damage instances while maintaining long-term cost analysis
- Recommendations for future research

The guidelines are aimed at assisting in the planning and performance of Big Bridge inspections with specific direction concerning the accurate collection and use of element level data. However, as Big Bridges are often complex structures with unique details and configurations, this report cannot prescribe specific solutions for all bridges. The fundamental principles behind the current inspection standards and element level analysis are conveyed which support responsible inspection and condition reporting.

The definition of a Big Bridge is complex with many factors that can influence the categorization. Factors include overall length, mains span length, deck area, number of spans, traffic volume, structure type, border status, essentiality, dedicated maintenance and/or management staff, revenue sources, and increased maintenance needs. It would be appropriate to consider a combination of these factors when deciding if a bridge should be viewed as a Big Bridge.

The project was organized into six tasks which have been organized into five chapters. This final report collects all the findings, data, and products developed under these tasks and presents them as individual chapters. The organization follows the order in which the tasks were performed. A summary of the main findings for each task is presented next.

Chapter 1 - Recent Research Review

Chapter 1 consisted of a literature review of recent, current and ongoing research pertaining to the element level data and bridge management software (BMS) for network analysis. The team identified key areas of research. Chapter 1 provides a brief history of the development and overview of bridge elements, element level data collection, and how collected inspection data are compiled and used to analyze bridges on both the individual and network level. Also presented is an overview of the commonly used AASHTOWare Bridge Management software, and outlines some variations developed and implemented by different agencies. Some recent and current research projects regarding the operation, management and maintenance of big bridges are also outlined. Chapter 1 concludes with a review of advanced inspection techniques for complex bridges, including Non-Destructive Evaluation (NDE) methods and some recent domestic efforts to make the bridge inspection process more efficient and economical. Findings indicate that Big Bridges are currently subjected to the same inspection and reporting criteria as non-complex bridges. Current research in the U.S. regarding consideration of Big Bridges as a series of interactive networks is limited. European and Asian efforts can provide lessons learned and guidance, particularly towards SHM in long-span cable structures and location aware recording of specific damage instances as part of the inspection process. Ongoing research topics, such as 3DBRIDGE and UAVs for asset management, present opportunities that may be applicable.

Chapter 2 - Review of Big Bridge Inspection and Management Reports / Owner Survey

Chapter 2 presents findings from the review of inspection and management reports for big and complex bridges. Relevant objectives that were explored include:

- Refining the “Big Bridge” definition,
- Determining the typical methods for division of Big Bridges into smaller sub-units,

- Evaluating the National Bridge Elements (NBEs), Bridge Management Elements (BMEs), and Agency Developed Elements (ADEs) that are currently used for Big Bridges, and
- Analyzing methods for the efficient inspection and collection of element level data.

A nationwide survey was conducted pertaining to the element level analysis of Big Bridges. It was distributed to all state DOTs and numerous Big Bridge authorities/owners. Responses were received from 22 state DOTs and 4 organizations which manage Big Bridges. Summary of the responses are presented in Section 2.10. Additional bridge inspection and management reports were also gathered from several agencies. Findings indicate that AASHTO's MBEI is an indispensable tool in the risk-based assessment; however, it is currently difficult to express all the unique and complicated defects using the current elements and defect types. Using the current element quantity calculation definitions in AASHTO's MBEI, the typical details used to describe defects are often not sufficient to immediately convert to defect quantities. Furthermore, the current grouping of elements does not lend itself to the detailed inspections required. Greater effort is needed in the planning and preparation phases for inspections, requiring the establishment of defect quantities. There must be thorough understanding of the complexities of the structure and required element level details by both the owners and inspectors to ensure consistency between individual inspector findings and subsequent inspection cycles.

Chapter 3 – Review of Big Bridge Management Methodology

Chapter 3 presents a review of the state-of-the-art in Big Bridge management methodology including evaluation of analytical tools and processes. This review is based on the literature, survey results, and management reports data gathered in Chapters 1 and 2, as well as a series of interviews with appropriate bridge management personnel. The scope includes:

- needs assessment for capital preservation and functional improvements,
- planning and scoping of bridge projects, including work zone traffic planning,
- priority setting and resource allocation,
- programming of investments over a ten-year timeframe, and
- establishment and tracking of performance targets.

The in-depth review of various management reports, interviews and bridge management systems yielded a wealth of information on the current state of the practice in Big Bridge management. Limitations of various BMS were revealed. The following typical actions are highlighted:

- Develop some agency-defined elements to facilitate inspection,
- Divide bridges into separate structure units to organize inspection records and help define projects,
- Create business plans focused on long-range capital needs estimates, public service goals, physical operations, revenue and customer satisfaction, and finally
- Develop separate capital programs to address future requirements.

Actions typically not performed by Big Bridge owners include:

- Modify BMS models to reflect special characteristics of Big Bridges with respect to life-cycle costs, deterioration, action effectiveness, etc.,
- Develop detailed Transportation Asset Management (TAM) plans that address condition tracking, life-cycle cost analysis and risk management, and
- Take full advantage of BMS systems for estimating long-range preservation needs.

Most current bridge management systems are capable of:

- Adding new elements,
- Modelling deterioration, costs, action effectiveness, life cycle costs,
- Dividing of bridges by span or unit,
- Managing detailed biennial/annual inspection information,
- Performing life-cycle costs, deterioration and effectiveness for “standard” bridge types, and
- Modelling likelihood and consequence of hazards/risks that affect these risks.

Bridge management systems typically lack:

- Ability to develop project scopes for limited portions of bridges or automatically segment bridges for separate projects,
- Database flexibility to store varying characteristics (structure types, roadway types, etc.),

- Means to document more frequent, focused inspections (safety checks, NDE, etc.), and
- Recording of defects as separate objects with location, severity and extent over time

Chapter 4 – Big Bridge Inspection Methodology Using Element Level Inspection Data

This task developed a methodology in the form of guidelines for the inspection of Big Bridges in order to optimize the collection and use of element level data. Specifically, suggestions are made for modifications to the AASHTO's MBEI including: new National Bridge Elements, new Bridge Management Elements, new defect types, clarifications to element definitions/descriptions and modifications to quantity calculations. Methods for planning and performing the element level inspection are discussed, including recommendations for recording, formatting, and presenting element level data. The concept of the division of Big Bridges into appropriate sub-units is also discussed with suggestions for different subdivisions based on span type, geometry, material type, jurisdictional boundaries, etc. Further organization of element inspection data to improve inspection efficiency is also discussed.

The importance of location-specific defect data is discussed and two methods are presented as the "subdivided units" and "enumerated damages" methods. Briefly, the "subdivided units" method relies on a permanent breakdown of bridges into smaller units, such as spans or panels, to a level where defect locations can be approximated and more accurately modeled based on the associated element sub-unit. The "enumerated damages" method assigns a specific location to each instance of damage, allowing it to be accurately modelled and tracked over time. Damage locations and sizes change from one inspection to the next as some are corrected and new ones arise.

Various advancing non-destructive evaluation methods and their potential benefits for the inspection of various bridge types are presented. A discussion of new inspection technologies, including 3D bridge modelling, used to improve inspecting and reporting efforts is also presented.

Chapter 5 – Recommend Analytical Tools and Processes for Big Bridge Management

Chapter 5 addresses the existing and emerging analytical tools and processes for analysis and management of Big Bridges. Chapter 5 discusses how such tools could improve decision making about the allocation of resources to best achieve agency performance objectives. Management software with enhanced prioritization and robust risk analysis capabilities could potentially avoid future costly emergencies. The needs for analytical tools follow from an analysis of the business use cases where decision making could benefit from those tools. Network and Project level analysis tools are also presented. Findings indicate that the analysis is conducted for supporting management in making decisions about policy, resource allocation, and project development. Analytical tools help to identify needed work, to estimate the schedule, and to forecast the likely outcomes of current decisions.

The development, maintenance, and frequent use of the best available predictive modelling tools to aid management decision making especially with respect to deterioration, traffic volume and risk is also recommended. Among these models, probabilistic deterioration models would likely be created, and corroborated with as-inspected conditions. The use of the subdivided units approach for element and defect recording is recommended. This may require some additional modification of bridge management systems to support practical recording and usage of the more detailed data. Finally, because the population of Big Bridge owners is small, it is recommended that they share their inspection data in cooperative research to help improve deterioration models.

In conclusion, Big Bridges are sufficiently different from typical bridges because their analytical needs and level of detail required. This drives the need to consider separate bridge management models. Such models could be implemented spreadsheets that address the program periods, subdivided units, deterioration and risk behavior, action criteria, unit costs, work zone plans, and other attributes specific to one bridge. It would inform work candidates and projects into the agency's enterprise bridge management system and would serve as the documentation of the bridge's preservation plan.

CHAPTER 1 - RECENT RESEARCH REVIEW

1.1 Introduction

In the United States, there are currently national and state level guidelines for bridge inspection. In the past 25 years, bridge inspections have been modernized to become a process of collecting element level data and reporting it to the overseeing entity, most often state departments of transportation, along with local agencies. However, these procedures and subsequent standards have primarily been developed for "standard" bridges, with different metrics used for different types of bridges (e.g. concrete bridges, steel bridges, etc.). To date, there are not specific standards for the inspection and management of big bridges. The objective of this research is to develop and recommend such procedures and standards with the goal of eventual implementation.

This chapter contains the findings from a literature review of recent and current research pertaining to the use of element level data and Bridge Management Systems (BMS) for network analysis of big bridges.

1.1.1 Big Bridge Definition

Due to the size, complexity and uniqueness of big bridges, a concise definition is difficult to establish. Big bridges were first defined for this project as bridges that, because of their size, complexity or importance, have dedicated maintenance and management staff or programs. Another possible definition is that which the National Bridge Inspection Standards (NBIS) have established for complex bridges, defined as "movable, suspension, cable-stayed, and other bridges with unusual characteristics" (Hearn, 2007). While bridges with moving components typically require their own operation and management procedures, movable bridges are excluded from the scope of this study. The inspection and evaluation of these types of bridges is thoroughly defined in the AASHTO Movable Bridge Inspection, Evaluation, and Maintenance Manual (AASHTO, 2016). Floating bridges are excluded as well.

Another important aspect to defining big bridges is that they can be viewed as a series of interactive networks, rather than just as a single structure. The relatively recent utilization of element level data makes this a practical way to view bridges of excessive size or complexity because there are many individual structural systems on these bridges that both work together and can fail independently. Therefore, it is prudent to develop inspection and management techniques that identify these systems, evaluate each thoroughly, and recognize their interactive nature.

For the scope of this study, big bridges include those with complex bridge types such as suspension bridge, cable-stayed bridges, cantilever or continuous truss bridges, arch bridges and open girder or box girder bridges with long spans or a high number of spans. Movable and floating bridges will be excluded from the study.

1.2 Element Level Data Collection and Inspection

1.2.1 History and Development

In the early 1990s, element level data was introduced as a system for bridge inspection and management. The goal of the AASHTO elements is "to completely capture the condition of bridges in a simple way that can be standardized across the nation while providing the flexibility to be adapted to both large and small agency settings" (AASHTO, 2011). As a result, a series of Commonly Recognized (CoRe) Elements for Bridge Inspection were developed. The CoRe elements initially consisted of approximately 160 structural components, but were later reduced to approximately 108 elements. A total unit quantity (length, area, each, etc.) of a bridge component represented by a CoRe element was calculated, and during an inspection each unit was evaluated by inspectors and assigned a standardized score (or rating). These results were then compiled into a scoresheet and submitted to the state or local jurisdiction. The CoRe element method was successful in advancing bridge management in part because element level data represents bridges as a series of interactive networks with specialized individual elements. Prior to the development of the CoRe element method of data collection, National Bridge Inventory (NBI) data was collected. It had a much more limited classification structure for elements, grouping all elements into more generalized categories such as deck, superstructure, substructure and joints.

Due to the increased volume of detailed data being collected for the nation's bridges, a new software package, Pontis, was developed to aid bridge owners and managers in the collection and processing of this data (Cambridge Systematics, Inc., 2005). This software is now the AASHTOWare Bridge Management (BrM) software tool.

In 2011, the first edition of the AASHTO Guide Manual for Bridge Element Inspection introduced the National Bridge Elements (NBE) and Bridge Management Elements (BME) (AASHTO, 2011). The NBEs consist of the primary structural components of the bridge and represent members critical to the overall structural integrity of the bridge. The BMEs generally consist of secondary members or components whose deterioration or failure would not directly affect the capacity of the bridge but may affect serviceability and longevity. The NBEs improved on the element level condition assessment methods of the AASHTO CoRe elements by eliminating obsolete elements, separating protective coatings and wearing surfaces as individual elements and simplifying and standardizing the rating system while still providing a complete set of elements to capture all of the necessary condition information to manage all aspects of the bridge inventory. The Guide Manual also provided standard guidelines for the development of Agency Developed Elements (ADE) to help ensure consistency between elements. These ADEs provided bridge owners flexibility to collect and monitor additional conditions. In the new element level system, specific defects based on the element material type have been created to help inspectors evaluate and rate each element. In this system, all elements and deficiencies are assigned a condition state rating between 1 and 4 (good to poor). In comparison, each element in the CoRe system had a variable rating scale, ranging from 1 to 3, 4, or 5, and the NBI system only rated four main bridge components on a scale of 9 to 0 (excellent to critical). The NBEs are intended to provide consistency from state to state to help provide an image of element condition at a national level while improving the bridge inspection process to be more complete and effective.

Although the AASHTO elements improved on the NBI rating system, 36 states identified and collected data for additional agency-defined elements in 2011. This indicated a need for further improvement to the AASHTO elements (Thompson et al. 2012; FHWA, 2010). The collected element level data are currently being utilized to effectively assist transportation agencies in their decision-making. BrM uses this element level data to forecast deterioration of bridge elements based on their current condition states (Figure 1.1).

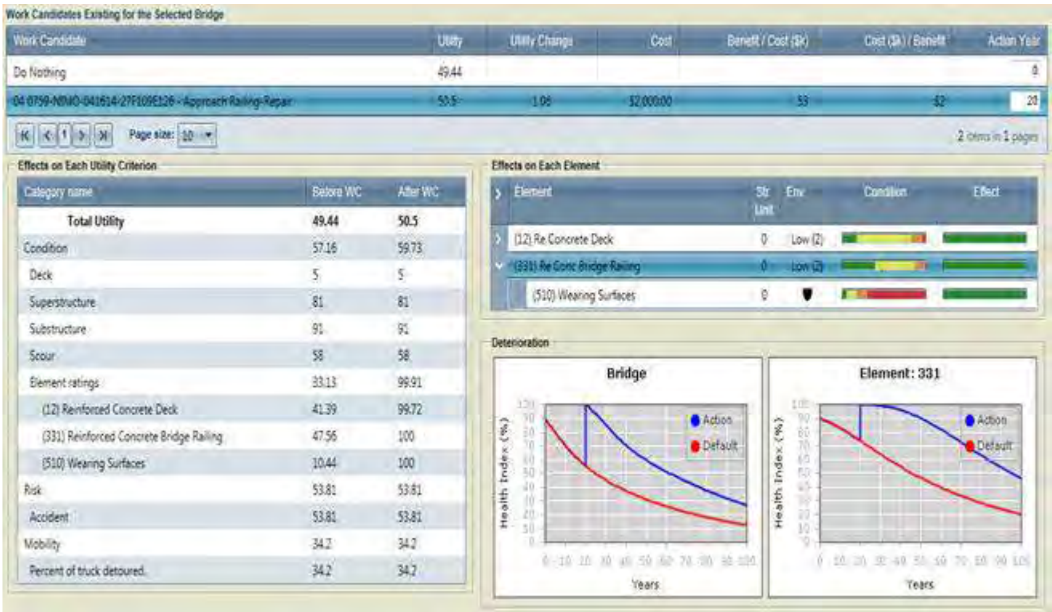


Figure 1.1. - Screenshot of BrM software showing deterioration modelling. (http://aashtowarebridge.com/?page_id=32)

During the summer of 2012, the MAP-21 transportation bill (The Moving Ahead for Progress in the 21st Century Act) was signed into law. MAP-21 required that NBE data be collected for bridges carrying National Highway System (NHS) routes and brought a fresh focus on Risk-Based Inspection (RBI) practices for highway bridges (U.S. DOT, 2015). The RBI approach helps to determine where, when, and how often to focus inspection efforts with the overall purpose of improved safety. National Cooperative Highway Research Program (NCHRP) Report 782, "Proposed Guideline for Reliability-Based Bridge Inspection Practices," is a valuable resource for managers seeking guidance in updating their inspection practices based upon risk-based assessments (Washer et al., 2014).

The number and variety of NBEs for complex bridges is very limited. For example, while there are many NBEs that apply to both common and complex bridges, there are only two specific NBEs used for the assessment of suspension and cable-stayed bridges: Elements 147 (Steel Main Cables) and 148 (Secondary Steel Cables) (U.S. DOT, 2012; AASHTO, 2011). A number of key components critical to the overall condition assessment of a cable system such as anchorage metalwork, saddles, and cable sockets are not represented. The creation of additional elements may help improve bridge management processes for such structures; the Bridge Inspectors Reference Manual (BIRM) references several common elements of cable supported bridges (such as anchorages, connections, cable planes, and vibrations) that could be subdivided into many more individual AASHTO elements.

1.2.2 Management Systems

One goal of the detailed collection of bridge inspection conditions on an element level is to apply this data to management and preservation decisions through the use of deterioration modeling, cost/benefit analysis, and bridge life cycle tracking. The BrM software package used in conjunction with the CoRe element system incorporated these features by applying a Markovian Decision Process to model bridge deterioration and recommend bridge preservation strategies.

Over the course of a bridge's life, its individual components undergo traffic, weather, floods, earthquakes, collisions, movement, and fatigue, and eventually the entire bridge is likely to need replacement. Each individual element in a bridge has its own life expectancy, and replacement intervals. Certain bridge elements are designed to take higher and more frequent loading than others, and are intended to be replaced more frequently. Often these elements protect larger, more expensive components that are more difficult to replace, thereby making the protective elements the most cost-effective to fix. Examples of these types of elements include expansion joints, coating systems, deck wearing surfaces, cathodic protection systems, bearings, drainage systems, pile jackets, fenders, and slope protection, and are generally categorized as BMEs. BrM has a built-in process to generate Markovian transition probabilities from the collected element level data for both protective elements and the more important, expensive elements they protect. Researchers can take the Markovian transition probability models generated by BrM and create life expectancy estimates for each individual element.

1.2.3 Markov Models/Variations

In "Estimating Life Expectancies of Highway Assets," also referred to as NCHRP Report 713, researchers discussed estimating life expectancy models for bridges (and other infrastructures) from Markovian transition probability matrices that are derived from element level condition ratings (Thompson et al., 2012). States have been collecting element level data for over 12 years now, and these data are sufficient to create reliable life expectancy estimates. Based on design considerations, market conditions, and site characteristics, bridges are typically designed to last somewhere between 50 to 100 years while trying to minimize maintenance costs. A bridge's life expectancy "is shaped more by land use, economic conditions, climate change, and service standards than by material deterioration" (Thompson et al., 2012). These factors are often unpredictable, which is important to consider when utilizing element level data to predict future deterioration. To determine when elements should be replaced, the AASHTO Guide Manual for Bridge Element Inspection defines the end-of-life for each individual AASHTO element instead of the whole bridge. Determining the end-of-life for a whole bridge is more complex. One definition for the end-of-life of a bridge is when 50% of elements are in the worst defined condition states. The NCHRP Report 713 (2012) defines the end-of-life as the age when replacement has a lower lifecycle cost than any other preservation strategy.

A Markov model is used to predict the condition states of an element in the future based on a constant probability of jumping from any one condition state to any other state. Markov models require an input for the initial condition state for an element, and then predict the transition probabilities for that element at one-year intervals for years to come based on a constant rate of deterioration. For example, for a particular element there is a percent chance (which is constant) that its condition state will transition to another in one year. There is also a percent chance that its condition state will not change in one year. This method does not factor in repairs; therefore, the models assume that a condition state for an individual element cannot improve. Due to unforeseen circumstances such as earthquakes, landslides, flooding, and atypical usage that will inevitably occur in some combination over the life of the bridge, the error margin for the Markov model increases as the time period for the condition estimate gets longer (Thompson et al., 2012).

NCHRP Report 713 (2012) mentions several other variations of the Markov model that utilize element level data in predicting future deterioration of bridges. One is the “quick and dirty” Markov life expectancy model. This model is one of the quickest ways to estimate a bridge's life expectancy as it categorizes elements in either a “failed” state or a “non-failed” state. For example, even if an element is considered poor (but not severe), that element would be in a failed state. Furthermore, if an element is considered “fair,” it is simply classified as “non-failed.” This binary system produces a simplified model for any particular bridge, then looks at the amount of elements that are in the failed state to determine the optimal course of action. Another variation of the Markov model is the Weibull Survival Probability, which adds in an age dependency (the older an element is, the faster it will deteriorate; see Figure 1.2) (Thompson et al., 2012). The Markov model does not take age into account, as it has constant rates of deterioration for all elements. The Weibull Survival Probability model produces more accurate results in estimating the onset of deterioration for newer bridges. A final approach to the Markov model is the Cox Survival Probability model, which adds in a multiplier to the survival probability to account for explanatory variables (Thompson et al., 2012). Element level data can be utilized in numerous ways, and has proven to be very useful in predicting future deterioration of bridge elements.

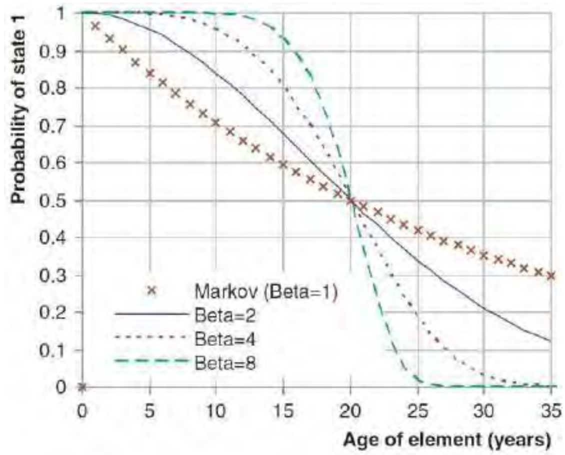


Figure 1.2 - Comparison of estimated deterioration using the Markov and Weibull models. From Thompson et al. (2012).

1.3 BRIDGE MANAGEMENT SOFTWARE REVIEW

The goal of BMS software tools is to assist State DOTs in analyzing how to most efficiently and effectively allocate their limited resources based on past bridge inspection data. Although there are great similarities in BMS used by each DOT, many states have taken different approaches to best suit their needs (Sobanjo and Thompson, 2004). BrM has been the most common BMS that was used to capture and store bridge inspection/condition information and to forecast deterioration of bridge elements. However, in response to a Bridge Management Questionnaire conducted in 2010, many states said they used their own proprietary or other software in addition to BrM (FHWA, 2010).

1.3.1 History, Development and Usage of Pontis / BrM

Pontis was developed by AASHTOWare in 1989 for the Federal Highway Administration (FHWA) and by 2005 was licensed through AASHTO to over 45 State DOTs and other agencies (Cambridge Systematics Inc., 2005). Since 1989, Pontis was developed and advanced to provide a comprehensive BMS which could “assist agencies in allocating scarce resources to protect existing infrastructure investments, ensure safety and maintain mobility” (Cambridge Systematics Inc., 2015). Pontis was designed to take element level inspection data and predict projects that would allocate the DOT’s resources most efficiently on a network level. Pontis used the most updated bridge inspection element condition data for its deterioration forecasts, and was instrumental software in the decision-making process for most DOTs. It led to many other variations of BMS since it was so widely used (Sobanjo and Thompson, 2004; Patidar et al., 2007). Additionally, Pontis allowed for agencies to assess current and future preservation needs through its deterioration and cost models, while also aiding in project planning, priority-setting, and resource allocation (Cambridge Systematics Inc., 2005).

In 2012, AASHTO re-branded Pontis BMS as AASHTOWare BrM software. AASHTO changed the name to align the software to follow the naming and branding convention that is more consistent with other AASHTOWare software products. BrM continues to have the software features of Pontis and still allows agencies to use the BMS for storing inspection data, while also outputting recommendations of how an agency allocates its scarce resources. It is used by over 44 State, Federal, local and international agencies (AASHTO, 2014). Through BrM, inspectors can schedule inspections, record the inspection data, and produce all of the necessary inspection reports from the information within the database. In addition to allowing for agencies to collect and display all of the correct inspection data, BrM also has decision support capability. This includes forecasting deterioration, determining the life-cycle benefit/cost analysis of possible strategies, identifying budget needs for managing the bridges or individual components, and recommending programs and policies to manage the conditions of all bridges (aashtowarebridge.com A).

The initial release of BrM was in May, 2012 as version 5.1.2. The software featured additional support for new AASHTO elements and also added support for importing and exporting XML file types. The new software also added a new risk framework which enabled inspectors to define various risks for each bridge such as scour, or seismic vulnerability (AASHTO BrM Manual). Since its initial release in 2012, AASHTOWare has continued to update and improve the features of BrM. The current version is 5.3, which was recently released in September of 2017. Recent updates include new Tunnel and Load Rating modules, an overhaul of the Inspection Condition Grid, enhanced deterioration modeling capabilities, and other improved modules that allow agencies to define and view Funding Allocation, Program Planning, Network Policies, Utility Weight Profiles, and Performance Measures (aashtowarebridge.com B).

In addition to BrM (which has a generalized approach, thereby working for most bridges), there are other BMS systems that have been developed to focus on unique issues. One such BMS system analyzes advanced deterioration of primary elements to improve the respective cost-benefit analysis for replacement (Sobanjo et al., 2013). The Minnesota DOT (MnDOT) utilizes a cost-benefit analysis aimed at long-term benefits over short-term costs (MnDOT, 2013). MnDOT analyzes the benefits and costs of one planned project, and compares these with those of alternative projects to formulate their long-term goals for their transportation needs.

Early developments of Pontis assisted in analysis of primarily a network-level view of bridge management decision support, rather than providing insight on the level of individual bridges. Florida's Department of Transportation (FDOT) took an active role in addressing this gap by utilizing state-developed software to improve on the functionality of Pontis to better fit their DOT's needs. FDOT created the Florida Project Level Analysis Tool, which provided additional bridge management system analysis (Sobanjo and Thompson, 2004). The goal of this particular system was to add project-level analysis to the network-level analysis provided by Pontis in its unmodified condition. This type of development improved the decision-making capabilities of FDOT. In addition to collecting and analyzing data for the CoRe elements, FDOT identified its own set of elements such that a broader spectrum of bridge components could be accurately analyzed. FDOT also developed an improved NBI translator that was incorporated into their Project Level Analysis Tool. Additionally, FDOT improved upon the deterioration, cost, and action effectiveness models for Pontis and their Project Level Analysis Tool (Figure 1.3) (Sobanjo and Thompson, 2011). Based off of their improvements, a new simplified procedure was developed for estimating Markovian models that was able to rely on a smaller sample size while still creating usable results.

Figure 1.3 - Screenshot of the project-level analysis tool used by Florida DOT (https://www.fhwa.dot.gov/infrastructure/asstmgmt/bmcs705.cfm)

1.3.2 Other BMS Tools

One of the Bridge Management Software tools that was created as an extension of Pontis was the Multi-Objective Optimization System (MOOS), published in the NCHRP Report 590 (Patidar et al., 2007). This study revealed that bridge investment decisions made solely on the basis of lowest cost will return unsatisfactory results. Instead, bridge investment decisions should factor in other criteria such as bridge condition, safety, traffic flow disruption, and vulnerability. The MOOS study developed network-level and bridge-level methodologies that involve multiple performance criteria, which is optimized by a user assigning a value to certain preferred options. Improved decision making capabilities in BrM enable user customizations to produce different, optimized project plans.

The MOOS study set up performance criteria on which bridge actions could be evaluated based on preservation of bridge condition, traffic safety enhancement, protection from extreme events, agency cost minimization, and user cost minimization. For decision-making problems that involve several performance criteria, the user sets a preference order based on utility theory. Utility theory allows the user's preference structure to be represented by a single utility function. The utility function is comprised of three major steps: weighing, scaling, and amalgamation, and is based on either the certainty of the alternatives, or on risk as the alternatives are unknown. After the utility function was created, optimization was applied from a set of bridges where the utility function with the maximum value was determined.

The findings published in NCHRP Report 590 can be applied at the network level and bridge level such as to narrow down projects and elements of selected bridges. This methodology is also recursive in that it remains consistent with input data available from existing bridge management systems (or in this case, BrM). The bridge model evaluates each bridge in to three categories: do nothing; management, repair, rehabilitation, and improvement (MRR&I); or total replacement. The MRR&I approach evaluates element level data, just like Pontis, but factors in life-cycle costs over individual element repair costs. This BMS allows for efficient decision-making in allocating resources by utilizing Pontis, while also allowing for DOTs to customize their preference on certain criteria the DOTs would like to improve. MOOS was originally developed as an extension for Pontis, but has now been directly incorporated into BrM. The MOOS study inspires the possibility of creating similar extensions for BrM, including an extension specifically designed for complex bridges.

"Determination of Bridge Deterioration Matrices with State National Bridge Inventory Data" researched the effectiveness of Louisiana's NBI in creating Markov matrices of the deterioration of bridge elements to use in Pontis (Zhang et al., 2003). At the time of the study, element level data collection was fairly new, and Louisiana did not have enough element level data for predicting their future bridge preservation needs. Louisiana had also recently adopted using Pontis to help allocate resources in the most efficient way. Pontis/BrM requires element level data to make predictions on bridges deteriorations, and although Louisiana did not have sufficient element level data at the time, they did have extensive NBI data that had been collected over the past several years.

Zhang et al. (2003) considered bridges in a three-element preservation model, analyzing each bridge on its deck, superstructure and substructure. The team then converted the NBI ratings to element level data that could be used in Pontis/BrM by categorizing the NBI ratings into element level data condition ratings. The results of this research illustrated the Markov matrices, based on element level data from converted NBI ratings, can be used to "reasonably estimate" future deterioration of bridge elements, which could help agencies analyze future preservation needs for bridges on a statewide network level. When using NBI data to generate Markov matrices for bridge elements, the resulting probabilities will be affected by the average bridge age in the database and the time intervals depending on the NBI data being analyzed. This is important because this study also revealed that NBI ratings had no correlation to the bridges age, but the Markov prediction matrices are determined by multiplying a set probability matrix determined by the bridge age and NBI data. Although the team concluded that reasonable estimates could be created from Markov models derived from NBI data, element level data has now been collected for over 12 years, and there is currently enough data to utilize the collected element level data directly to create the Markov models as opposed to using NBI data. However, this study does help in that it supports the effectiveness of Markov models in predicting future deterioration.

1.4 RECENT RESEARCH TOWARDS MANAGEMENT AND OPERATIONS TECHNIQUES FOR BIG BRIDGES

1.4.1 Introduction

While inspection, management, and operations techniques using element level data have been very effective in the bridge industry for the past 25 years, at present the methods are not particularly adaptable for big bridges. The reason for this is that the condition of big bridges usually cannot be effectively assessed with the same element level data procedures used for smaller bridges. For instance, giving one rating for the “deck” on an extremely big bridge is not very precise, as big bridges can have decks exceeding a mile in length that could, and arguably should, be assessed in smaller sub-units rather than just being given a single metric as a score. Therefore, there is a demand for development of management and operations procedures for big bridges. Both within the United States and internationally, a small number of projects have been undertaken with the goal of developing these aforementioned procedures.

1.4.2 US – Operations

In the United States the collapses of the Tacoma Narrows Bridge (Tacoma, WA) in 1940 and Point Pleasant Bridge (connecting Point Pleasant, WV and Gallipolis, OH via US-35) in 1967 demonstrated the need for inspections and modifications of suspension bridges, and organized bridge inspections, respectively (Doebling et al. 1996; Xu and Xia 2011). The 2007 collapse of the I-35 W bridge in Minneapolis, MN (Figure 1.4) is a continued reminder of the necessity of a focus on bridge health and action. The bridge was listed as “structurally deficient” since 1990 due to corroded bearings, and Minnesota DOT had advised the implementation of strain gages and structural health monitoring, though the study had concluded there should be no problems with fatigue cracking in the near future (MnDOT 2001). To avoid catastrophes such as these, structural health monitoring systems (SHM) have been developed to provide bridge managers with better data regarding the integrity of bridges.

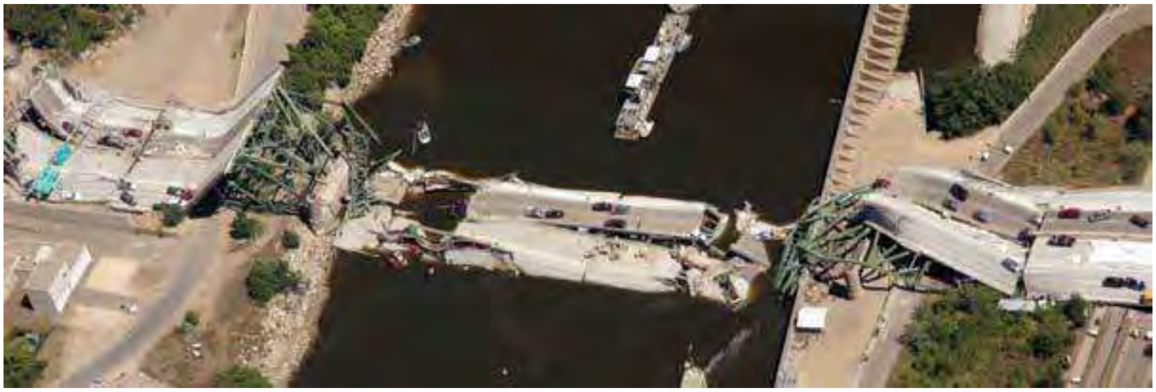


Figure 1.4 - Aerial photograph of the collapsed bridge deck truss sections of the I-35 W bridge after the collapse. (MnDOT 2008).

At its core, SHM technology has been described as "an autonomous system for the continuous monitoring, inspection, and damage detection of a structure with minimum labor involvement" (Chang 1999). One of the largest breakthroughs has been the rise of computational power, which has greatly increased the ability for complex SHM networks to be implemented and utilized. For a detailed timeline of progressions starting in the late 1800's in the field of structural monitoring readers are referred to Patel and Vesmawala (2015). Visualizations by Dr. Ken Chong of the National Science Foundation inspired many bridge owners and operators to embrace the idea of a smart bridge, equipped with real-time SHM equipment (Pines and Aktan 2002). More recently, many bridges around the world have been outfitted with long-term and real-time monitoring systems, including in the US; examples are listed in Table 1.1; Figure 1.5.

Table 1.1 - Examples of Major Bridges in the United States Equipped with Real-Time Health Monitoring Systems

Bridge Name	Location	Type	Length of Main Span (m)	Total Length (m)	Sensors Installed
Golden Gate Bridge	San Francisco, CA	Suspension	1280	2,700	1,2,3
Mackinac Bridge	Mackinaw City, MI	Suspension	1,158	8,038	4,7
Fred Hartman Bridge	Houston, TX	Cable-stayed	381	4,185	1,2,4,5,6
Sunshine Skyway Bridge	St. Petersburg, FL	Cable-stayed	366	1,800	2,4,6,7,8
Bayview Bridge	Quincy, IL	Cable-stayed	274	1,374	8,9
Tacony-Palmyra Bridge	Palmyra, NJ	Steel Arch	170	1,115	4,2,11,13,14
Commodore Barry Bridge*	Chester, PA	Truss	548	4,240	1,2,4,5,6,10,11, 12,13,14
Ironton-Russel Bridge**	Ironton, OH	Truss	241	731	2,5
New Benicia Martinez Bridge	Benicia, CA	Box	201	2,720	2,4,5,8,11,15
Saint Anthony Falls I35-W Bridge	Minneapolis, MN	Box	154	371	2,4,5,8,16,17

Table 1.1 - Examples of Major Bridges in the United States Equipped with Real-Time Health Monitoring Systems (Cont.)

Bridge Name	Location	Type	Length of Main Span (m)	Total Length (m)	Sensors Installed
North Halawa Valley Bridge	Halawa, HI	Box	110	2,000	2,4,6,11
Cut River Bridges	Mackinac County, MI	Cantilever	91	195	4,8,10,13,14,18

*1 = Anemometers, 2 = Temperature Sensors, 3 = Seismometers, 4 = Strain gages, 5 = Accelerometers, 6 = displacement transducers, 7 = GPS, 8 = Corrosion sensors, 9 = Cable tension force sensors, 10 = weigh-in motion sensors, 11 = tiltmeters, 12 = Joint meters, 13 = Meteorological Station, 14 = Video cameras, 15 = dynamometers, 16 = Optic fiber sensors, 17 = potentiometers, 18 = Traffic Sensor. *Figure 5. ** Closed with new cable-stayed bridge opened Nov 2016.*

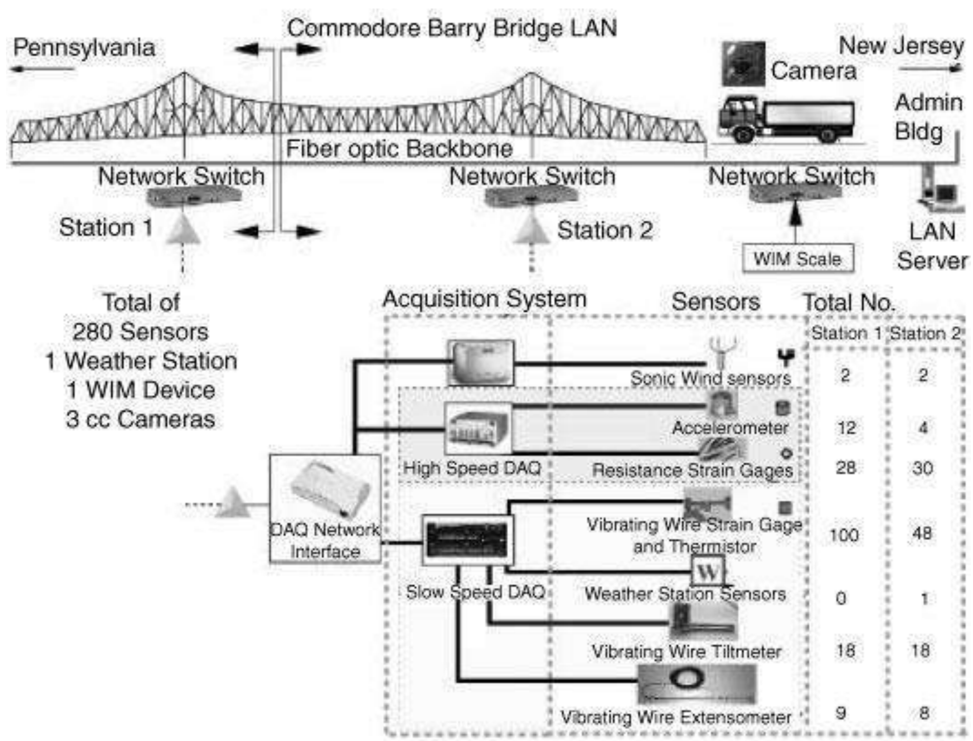


Figure 1.5 - Example overview for a real-time structural health monitoring system on the Commodore Barry Bridge. From Pines and Aktan (2002).

An early obstacle for implementing early large scale SHM networks were prohibitive costs associated with wired technology (Shaladi et al. 2015), though practical deployment of wireless networks early on was also inhibited due performance and reliability in addition to cost (Farhey 2006). Understanding applications of SHM techniques is additionally hindered as most studies in the literature applied different monitoring methods and on dissimilar structures, making comparisons between studies challenging (Johnson et al. 2004). This non-uniformity challenge of

SHM systems is also compounded for long-bridges, which vary in design and fall outside of standardized AASHTO specifications (AASHTO 1998).

As of 2002 of the 1100 major long–span bridges in the US that fall beyond the AASHTO Standard Specifications, many are greater than 50 years old and more than 800 are listed as fracture critical in the NBI (Pines and Aktan 2002). This fact indicates that development of SHM technologies and implementation of NDT methods in the United States should be highly prioritized and utilized to efficiently monitor bridge conditions.

Conventional sensors such as resistance strain gages, three-axis accelerometers, weigh-in-motion systems, and tiltmeters have worked well in past but need to become more accurate, more affordable, stronger against environmental stresses, and capture the most relevant data (Pines and Aktan 2002; Farhey 2006). One advancement in this area has been micro-electro-mechanical-systems (MEMS) technology, which has reduced the size and cost of sensors and greatly increased the scalability of wireless sensor networks (Pakzad et al. 2008). Researchers from the FHWA collaborated with fiber optic manufacturers to develop fiber optic sensor technologies for bridge applications. The advancements in fiber optic technology for NDT have developed rapidly, as the potential for this technology was only first researched in the late 1980's and early 1990's (Bligh et al. 1993), with leading research in the United States (Nanni et al. 1991; Ansari 1992). Currently fiber optic sensors have numerous applications to SHM (Figure 1.6), and are described in detail by Lopez-Higuera et al. (2011).

Figure 1.6 - Micron Optics strain gauge (Top, Model No. os3100) and temperature sensor (Bottom, Model No. os4100), which utilize fiber Bragg grating (FBG) technology. From Darwish et al. (2015).

Modern developments have increased the feasibility of wireless systems, leading to the implementation of wireless smart sensor networks, which are seen as an improvement to wired systems in cost, maintenance, installation and accuracy (Shaladi et al. 2015). Wireless systems have the potential to be utilized more practically on large scale projects as the complexity, cost of installation and maintenance required of large wired systems would be impractical (Farrar et al. 2000; Pakzad et al. 2008)

Early designs for field deployment of wireless SHM networks were described by Maser et al. (1996), called the Wireless Global Bridge Evaluation and Monitoring System (WBGEMS). This design utilized two stages of wireless communication; one designed for the collection of measurement data from the traditional sensors to on site data repositories, and the other to send compiled bridge response data to off-site officials. An early vibration-based wireless system was developed at Stanford University by Eric Straser (Straser 1998) and tested at the Alamosa Canyon Bridge (Farrar et al. 2000). Later, Lynch et al. (2003) conducted a parallel field test of forced vibrations on the Alamosa Canyon Bridge (Figure 1.7) using a wireless network of MEMS accelerometers and a cable based system using piezoelectric accelerometers. The study concluded that the wireless network was less expensive and less laborious to install and that in most cases recorded response data were very similar. A follow-up study by Lynch et al. (2006) in South Korea on the Geumdang Bridge demonstrated further improvements of the wireless systems from the Alamosa Canyon study and used a scaled up network as well (Figure 1.7). Additional testing around the same time period corroborated the finding that wireless systems were soon able to match the accuracy of traditional wired systems (Farhey 2006). With improved accuracy and reliability, along with lower costs, there are fewer barriers for widespread implementation of wireless SHM networks. While there are numerous types of monitoring systems, each with strengths and drawbacks, much of the advancements in SHM have been in the monitoring of superstructure bridge elements, though the importance of monitoring substructures is very important as well (Collins et al. 2014).

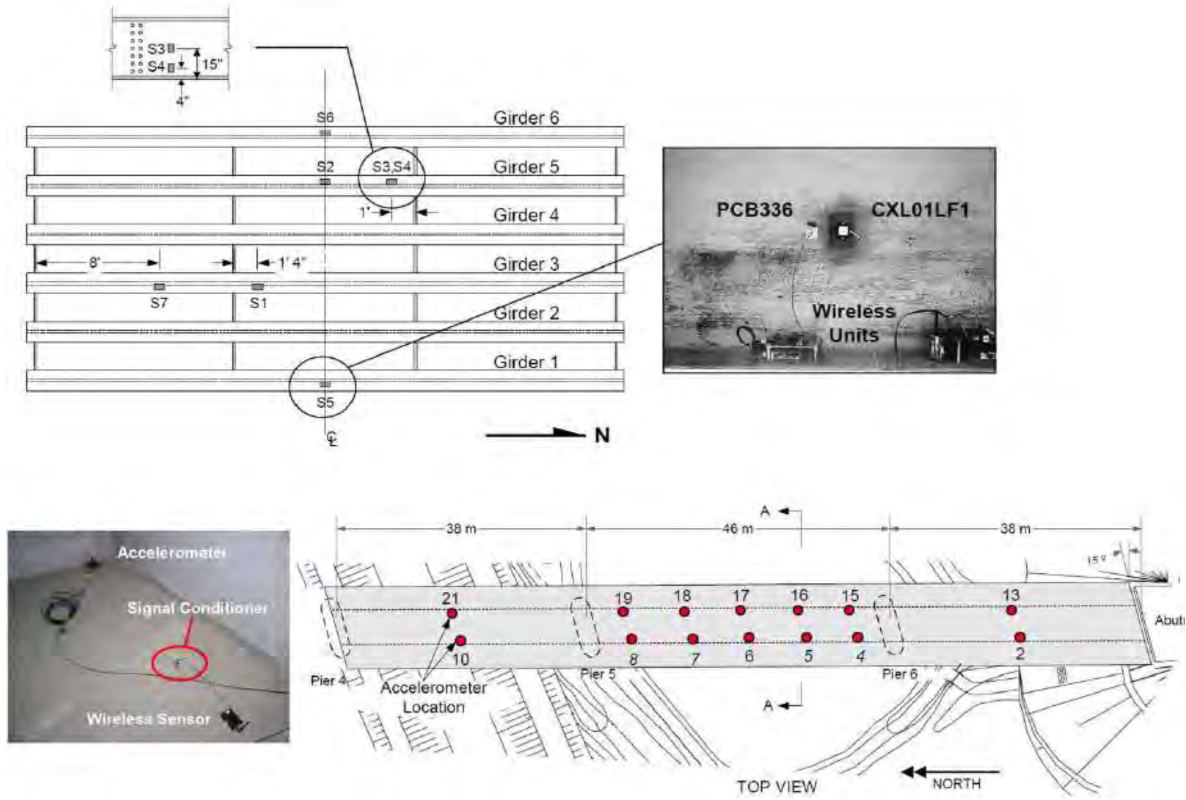


Figure 1.7 - Wireless network setup on Los Alamosa Canyon Bridge, New Mexico from Lynch et al. (2003) (above), and scaled up wireless network system used on Geumdang Bridge in South Korea from Lynch et al. (2006) (below).

A particular concern for cable bridge managers is the detection of internal corrosion of cables which is not easily detected upon visual inspection. Bligh et al. (1993) reviewed several early avenues (magnetic field disturbances, radiography, ultrasonography, and acoustic emissions) of NDE techniques for this specific problem. Since then several new technologies have been developed using some of the techniques from these avenues for this specific purpose such as the SoundPrint acoustic monitoring system developed by Pure Technologies in Alberta Canada which has been used on the Fred Hartman Bridge (Houston, TX) by TxDOT (Wood et al. 2008) and the Waldo-Hancock Bridge (Verona Island, ME) by Maine DOT (Dong et al. 2010; Figure 1.8), and also CableScan, a NDE magnetostrictive sensing method (Figure 1.8) developed by Southwest Research Institute, (headquartered in San Antonio, TX) which has been used on the George Washington Bridge (connecting Fort Lee NJ and Manhattan NY), The Bridge of the Americas, (Balboa, Panama), and the Walt Whitman Bridge (connecting Philadelphia, PA and Camden NJ), among others (Pure Technologies LTD). These technologies have been used as feasible tools for bridge managers of suspension, cable-stayed or post-tensioned bridges.

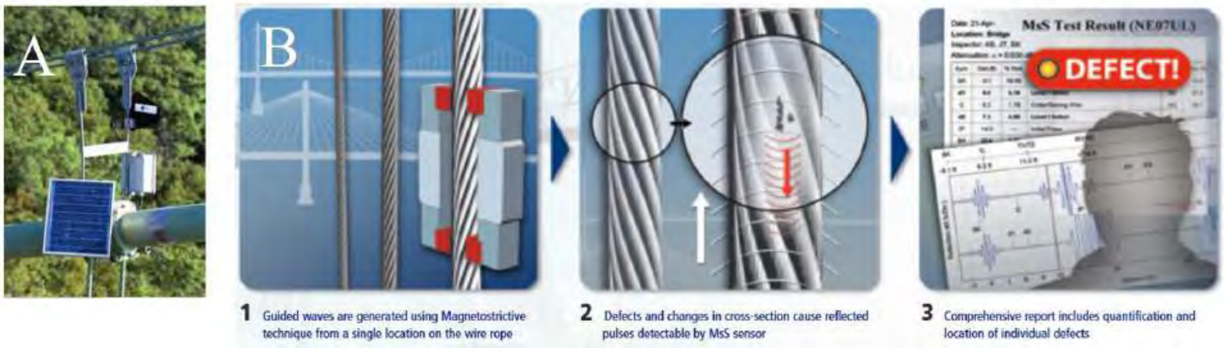


Figure 1.8 - A. SoundPrint acoustic monitoring system installed on the Waldo-Hancock Bridge. From Dong et al. (2010). B. Outline of CableScan process (Pure Technologies Ltd).

Notable U.S. Examples

A few examples of bridges in the United States that adopted or tested early SHM systems include: The I-40 bridges over the Rio Grande in Albuquerque New Mexico which evaluated modal response algorithms from vibration data collected from accelerometers (Doebling et. al 1996) and led to many workshops focused on improving SHM using modal response data (Pines and Aktan 2002); The Commodore Barry Bridge, connecting Chester Pennsylvannia and Bridgeport New Jersey, tested a real-time SCADA (supervisory control and data acquisition) system using a range of suite of sensors such as: of vibrating-wire accelerometers, strain sensors, weigh-in motion sensors, strain gages and tiltmeters (Aktan et al. 2000); The Jamboree Road I-5 Highway Bridge, Irvine California, and several other California Highway Bridges (Feng et al. 2001), and the Benicia-Martinez Bridge all using vibration monitoring systems (Murugesh 2001).

One of the United States' most iconic bridges, The Golden Gate Bridge, provides examples of both early and modern large-scale SHM studies. Abdel-Ghaffar and Scanlan (1985a,b) used the bridge for analyses of spectral densities and vibration data caused by traffic and wind from 28 points, building upon a previous study at the Vincent-Thomas Suspension Bridge at the Los Angeles Harbor (Abdel-Ghaffar and Housner 1978). In 2006 the bridge was chosen for large-scale installation and testing of a scalable wireless sensor network (Pakzad et al. 2008). The network consisted of 64 sensor nodes containing two sets of MEMS accelerometers (a high level and low level for cost-quality comparison) and a temperature sensor. A multi-hop network was utilized to minimize power requirements that otherwise be required for a single-hop network over a long distance. The outcome of the study confirmed the scalability of the WSN, but suggested that for faster reactions in a real-time network that the operating system support multiple threads and that hardware should be equipped with a separate microcontroller (Pakzad et al. 2008).

The Bill Emerson Memorial Bridge is a relatively new cable-stayed bridge, opened December 2003, with a main span of 1,148 ft and total length of 3,953 ft that crosses the Mississippi River at Cape Girardeau, MO. The bridge is located near the New Madrid Seismic Zone, has caissons of which the tops can be submerged, and is in an area of frequent intense thunderstorms and lightning; and therefore serves as an example of a unique challenge of bridge design, management, and SHM instrumentation. To account for the challenges regarding the bridge, several institutions: FHWA, MoDOT, MCEER, and USGS, began preliminary designs for seismic instrumentation of the bridge in 1996, before the construction contract was granted (Çelebi 2006). The finalized plan included a wireless network consisting of; 84 channels of accelerometers upon the foundations, deck, piers, towers and the nearby vicinity; low power digitizers; and data concentrators with data transmitted off site (Figure 1.9). The design allowed for both the detection of the global structural response and individual sites, yet rocking of the piers could not be monitored (Çelebi 2006). Upon installation the wireless network was designed as a state-of-the-art seismic monitoring system, capable of both recording and real-time streaming of seismic data (Figure 1.10), yet it was demonstrated that the equipment was also sensitive to low amplitude motions, such as wind, traffic, and tower-cable-deck interactions (Çelebi 2006).

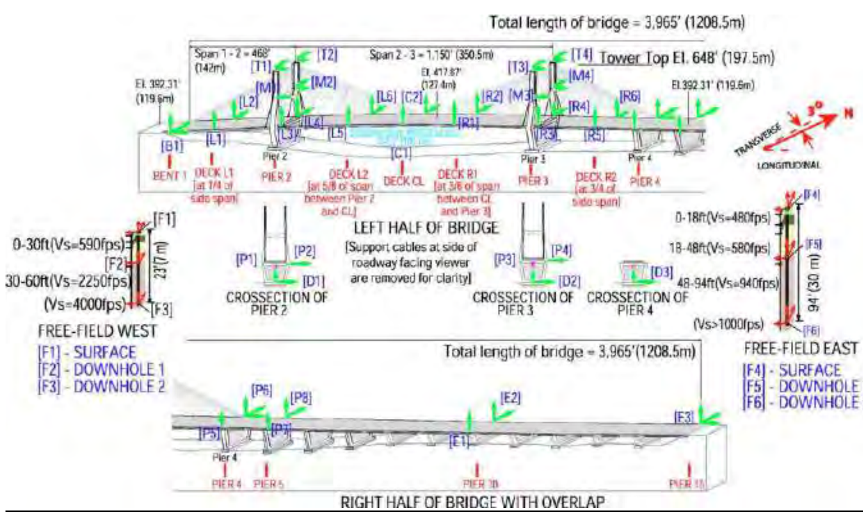


Figure 1.9 - Diagram of instrumentation at Bill Emerson Bridge in Cape Girardeau, MO. Locations and orientation of accelerometers on bridge, towers, and piers are shown. Arrows indicate an accelerometer channel and its orientation. From Çelebi (2006).

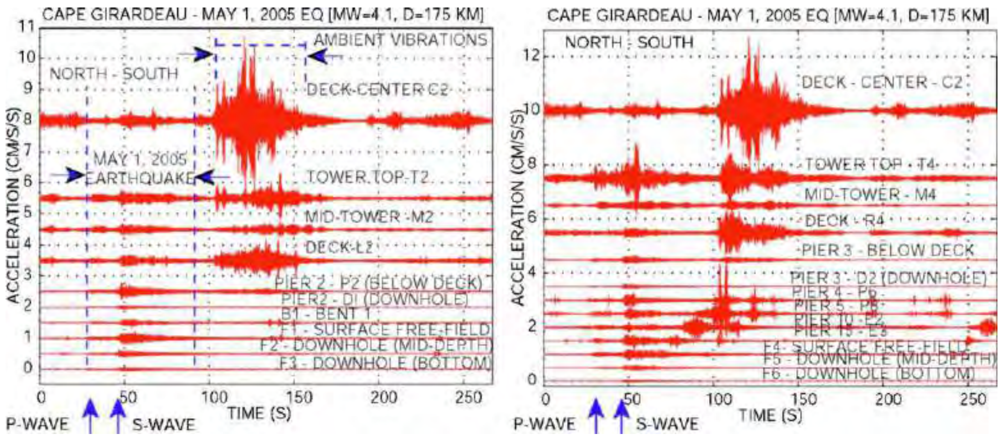


Figure 1.10 - Example output data from SHM system installed on Bill Emerson Bridge during an earthquake on May 1, 2005. From Çelebi (2006).

Temperature Based Systems

One of the more widely adopted methods for SHM of long-span bridges has been the ambient vibration based approach, yet this method may not be the best suited to serve a core tenet of SHM; the characterization of a baseline-response of which long-term changes are beyond the ordinary day to day variation (Yarnold and Moon 2015). One emerging alternative to vibrational techniques is temperature and temperature induced responses (Yarnold et al. 2012; Laory et al. 2013). Early studies suggest that temperature based systems maybe be more sensitive to realistic damage scenarios, however the drawbacks of the temperature based systems include implementation time and the large temperature swings required to establish a baseline and to diagnose damage scenarios (Yarnold and Moon 2015).

Influence Lines

Influence lines are one possible method to determine bending moments and shears, though much forethought and consideration is required for full comprehension (MDOT Interim Update 2009). Published in 1959, Moments, Shears and Reactions for Continuous Highway Bridges, is a valuable reference for analysis and interpretation of influence lines.

On Clarks Summit Bridge, a two–girder riveted steel bridge near Scranton, Pennsylvania with length of 1627’ recently retrofitted, replacing each pin and hanger system with a full-girder splice, and strain gages were utilized to collect data after the retrofit. Comparing analytically created influence lines with experimentally derived influence lines demonstrated that the pin and hanger model accurately represents bridge conditions both before and after the retrofit (Conner et al. 2004) (Figure 1.11).

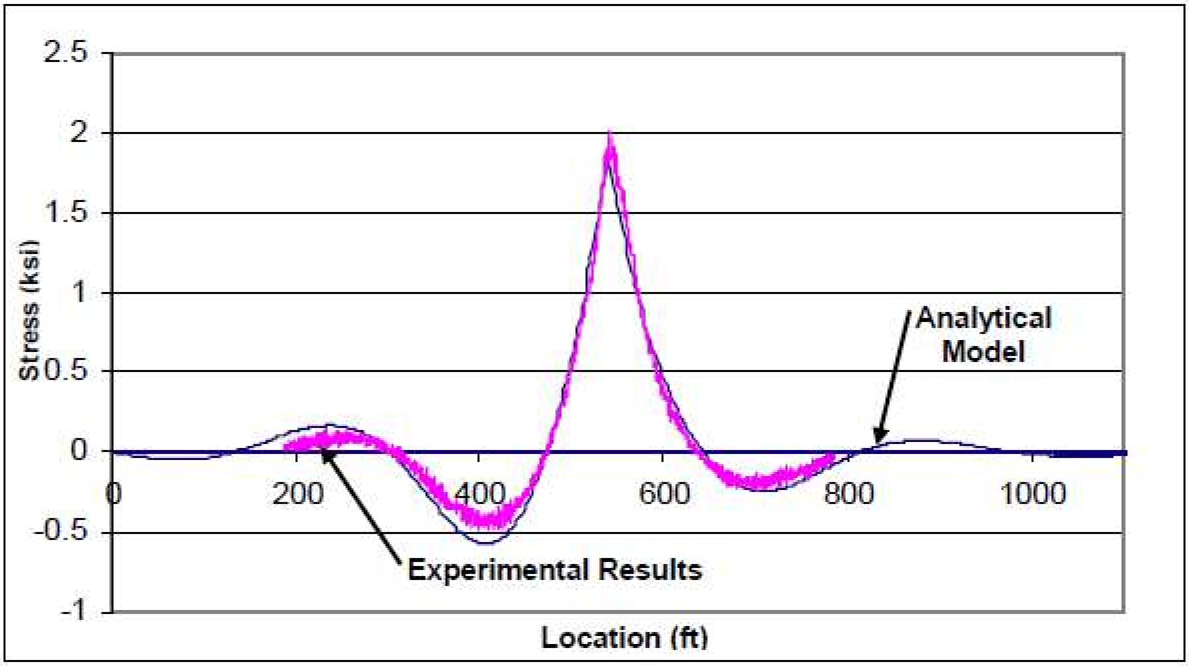


Figure 1.11 - Comparison of measured and calculated influence lines.
From (Conner et al. 2004).

Guidelines to Improve the Quality of Element-Level Bridge Data

"Guidelines to Improve the Quality of Element Level Bridge-Inspection Data" (NCHRP 12-104) is a current initiative to improve bridge inspection procedures with regards to element level data across the country, as well as to provide consistency across different states (Washer, Active). The project will conduct a literature review of inspection practices across several states to determine how element level data is used for asset management, surveying bridge owners and other stakeholders to identify discrepancies among states' inspection procedures. After these investigative measures, the team will recommend a unified methodology for element level data inspection and management procedures with the goal of having consistent, high-quality bridge assessment across the country. NCHRP 12-104 will not directly develop procedures for inspection and management of big bridges, but it will improve the quality of element level data collection practices that will be a critical component of inspection and management of any bridge, including big bridges. The project is scheduled for completion in November 2017.

Robotics Assisted Bridge Inspection Tool (RABIT)

There has also been an advance in the collection of element level data through the development and introduction of the RABIT bridge inspection tool in 2014 (FWHA 2014) (Figure 1.12). This tool was developed by the FHWA through the Long-Term Bridge Performance Program (LTBPP). The RABIT is a robot that travels on a bridge deck and deploys a number of non-destructive testing technologies at once (Figure 1.12). It has a panoramic camera to collect 360 degree images of the bridge deck, a high-definition camera to produce detailed images of the deck, electric resistivity probes to check for corrosion, impact echo and ultrasonic surface waves to check for delaminations in the concrete, ground penetrating radar to find and evaluate rebar (and other metallic objects) below the deck's surface, and a global positioning system (GPS) that marks the location of data taken with the other five technologies. This comprehensive bridge inspection machine collects data that bridge inspectors would otherwise have to record by hand, and gives a geotagged location for data collected.

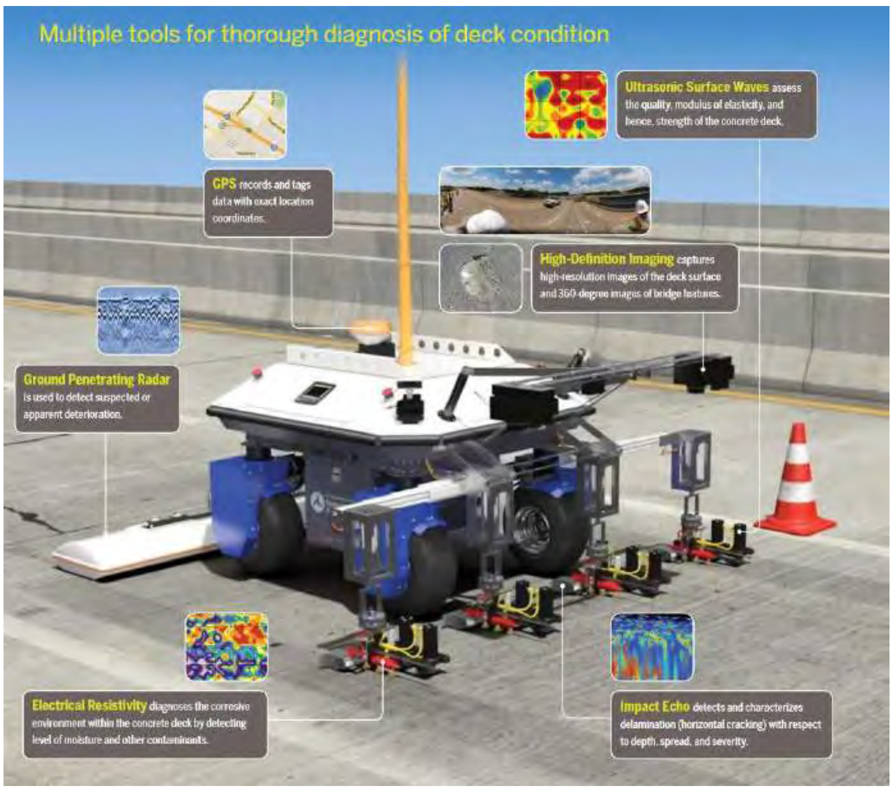


Figure 1.12 - Picture of the RABIT along with explanations of sensors and example visualized data outputs. From CAIT (2013).

The RABIT has yet to be implemented into state inspection manuals, as it has been in the development stage for the past three years. However, it is viewed as having a lot of potential to make bridge deck inspections both more efficient and more complete (FWHA 2014). Plans are underway for more widespread deployment around the country via the LTBPP. If the RABIT was used to inspect big bridges, the time savings over current inspection methods would be much greater than for standard bridges. One drawback to implementation of the RABIT is that the robot would require lane closures for use.

Proposed AASHTO Guidelines for Complex Bridge Inspection

AASHTO Task 337 realized the need for further inspection guidance for complex bridges, defined as a bridge with unusual characteristics, such as a movable bridge, a suspension bridge, or a cable-stayed bridge (Leshko, 2015). The resulting report, "Proposed AASHTO Guidelines for Complex Bridge Inspection," explains that according to the National Bridge Inspection Standards (NBIS), states are responsible for defining complex structures and developing inspection procedures. Therefore, complex bridge inspection procedures are typically found in states' individual bridge inspection manuals, if at all. Because of this, there were significant discrepancies in complex bridge assessment procedures amongst different states. Thus, a demand was realized for standardized complex bridge assessment techniques. An objective of the research project was to fill that demand, with many of the resulting standard recommendations developed for complex bridges being incorporated into the standards for inspection, management and operations for big bridges.

The study suggests checks to be done during inspections for several components of suspension bridges, cable-stayed bridges, movable bridges, segmental bridges, pin and hanger connections in bridges, orthotropic decks and other complex bridges or complex bridge components. For example, the report recommended that the suspender cables for suspension bridges be checked for corrosion or deterioration, broken wires, kinks, slack, abrasion or wear at sockets, clamps or spreaders, and that the cables be checked for vibration. The suspender cables were just one element with inspection recommendations for suspension bridges, which was just one type of complex bridge studied. The report also contains full, detailed examples of inspections for suspension bridges and cable-stayed bridges as performed with the recommended procedures. The goal of this project was to produce guidelines for bridge owners to develop inspection procedures for complex components of bridges. Material in the report also could be incorporated into the national inspection manuals.

1.4.3 US - Management

Combining Individual Scour Components to Determine Total Scour

A major premise for this study is that there is no current standardized procedure for combining element level data for different components of a big bridge, at several different spots along a big bridge, into a total bridge assessment. A component of any bridge inspection and evaluation is the evaluation of the substructure (e.g. piers and abutments), of which portions of some components are often submerged in water. When a bridge contains structural elements that are completely or partially submerged in water, they must each be evaluated for several different types of scour. The NCHRP is currently funding Georgia Tech to perform an investigation for combining individual scour components to determine total scour (NCHRP 24-37, Sturm, Active). Current guidance by the FHWA specifies that total scour at a bridge be computed simply as a summation of the scour of the different components. Individual scour components can include local scour at abutments and piers, pressure scour, and contraction scour. These scour components can also contribute to long-term scour, which is added in the evaluation as another part of the summation. However, engineers have criticized this whole practice as being extremely conservative. The objective of NCHRP 24-37 is to determine the interaction between scour components and how they each contribute to total scour for all bridges, including big bridges. This particular scour research project uses principles expected to be used in the pooled fund big bridge research project. For big bridges, scour components and any other element level data (e.g. deck, piers, etc.) can be analyzed individually and eventually compiled into a full system assessment.

Michigan Bridges

The Mackinac Bridge is the longest suspension bridge in the western hemisphere and is a highly revered structure in the state of Michigan. The nearly 5 mile long bridge has a main span of 3,799 feet, was opened in 1957, and connects Michigan's upper and lower peninsulas. The bridge is the site of an annual event known as the Bridge Walk where 40,000-65,000 walkers traverse the bridge, adding a level of strain atypical of normal conditions. In 2007, in preparation for the event MDOT installed four vibrating wire strain gauge sensors to transmit data wirelessly to compare data from before, during, and after the event with the allowable stress loads on the bridge's original design. Building upon the success of the test, eight permanent strain gages were later installed near the bridge's south tower. The data network is also connected to a SHM system at the Cut River Bridge and sends data to MDOT in Lansing (MDOT 2011).

In 2005, General Positioning LLC, Leica Geosystems, MDOT, and the Mackinac Bridge Authority set out to capture the natural movements of the bridge while it is relatively young and in good health. Using six high sensitivity GPS receivers, two atop the two towers, two on the mid-span, and two on the ground at the ends of the bridge, and in combination with meteorological data, they built a solid representation of the bridge's natural movements. Data from the GPS receivers were collected every second for eight days. The testing found that under wind speeds of 13 mph the bridge deck moved over 3 feet and also documented noticeable sagging with warmer temperatures. In addition to providing useful information for bridge monitoring, the testing also demonstrated the utility of high precision GPS for structural health monitoring (Olson 2007).

In order to prevent catastrophes such as the 2007 I-35W bridge collapse in Minnesota, MDOT is using the fracture critical Cut River Bridge to pilot test a SHM system that could be used for the Mackinac Bridges as well as other Michigan bridges in the future (Figure 1.13). The pilot project will also aid in the goals of the MDOT's Connected Vehicle Program. The Cut River Bridge is a 640 feet steel deck cantilever bridge opened in 1947, located 25 miles northwest of St. Ignace, MI.

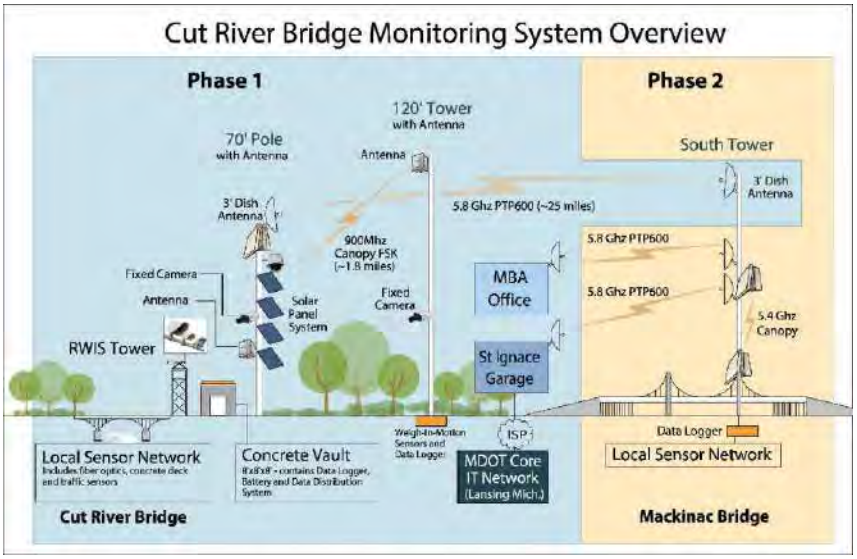


Figure 1.13 - Overview of combined Cut River and Mackinac Bridges SHM wireless network. From Darwish et al. (2015).

A wireless network of 16 fiber optic strain gages and four temperature sensors provide critical SHM data about the Cut River Bridge. Also located at the bridge are four traffic sensors, a camera, a meteorological station, and two road sensors capable of collecting surface and subsurface temperatures, salt concentration, water-film height, and road condition data. Additionally, two miles east of the bridge is a weigh-in-motion station and traffic camera that are connected to the grid. Five solar panels charge the batteries that the SHM systems runs on and all data is sent wirelessly from towers to the Mackinac Bridge Authority and also to MDOT (Darwish et al. 2015).

Several lessons were learned from Cut River Bridge study resulting in suggestions for improvements, namely: adding redundancy in power generation equipment and source, sensor arrangements, and communication equipment; coupling each strain gage with a temperature sensor to correct for thermal effects; streamlining of data processing and improving hardware and software compatibility by reducing number of manufacturers; moving weigh-in-motion sensors closer to the bridge site; and the addition of accelerometers for better capturing bridge response.

The full range of recommendations can be found in section 7.1 of Darwish et al. (2015). The last step of the test project is to establish a functional automated SHM by incorporating the research with MDOT's Data Use Analysis Processing (DUAP) project.

Accelerated bridge construction (ABC) uses prefabricated bridge elements and systems that are able to quickly and effectively replace bridges and therefore lessen the burden of construction zones and traffic delays (Culmo et al. 2013). The Parkview Bridge, located in Kalamazoo, MI, is the first fully prefabricated bridge built using ABC techniques with a SHM network. The design of the wired SHM network had a high level of sensor redundancy, consisting of 184 strain gauges with built-in thermocouples, and also compatibility, using one vendor for all the sensor and data collection devices (Abudayyeh 2010). Analyses of the load test data and three years of sensor data demonstrated that the primary stress factor is from thermal loads and that stress from live loads is relatively insignificant. It was concluded that using a calibrated finite element model can predict degradation of deck panel joints (Abudayyeh et al. 2012).

Iowa Bridges

In 2003, stemming from concern of the state's fracture-critical structures, the Iowa Department of Transportation (IADOT) began investing in research to develop a SHM system with the ability to identify damages and to report on general bridge conditions; with the goal of capturing degraded elements in between scheduled biennial inspections (Phares et al. 2013). One part of this investment resulted in a three-part report describing the results of several SHM approaches on the US-30 bridge of the South Skunk River, which received sacrificial damage during the experimentation. The overarching goal of the project was to create a SHM system for mass deployment in three phases; by finalizing SHM hardware and software design, validating vibration based damage detection algorithms, and utilizing energy harvesting techniques for wireless sensor networks (Phares et al. 2013).

In order to meet an objective of the Innovative Bridge Research and Construction program the East 12th Street Bridge over I-235 in Des Moines, Iowa was equipped with a continuous SHM system. The system utilizes Fiber Bragg Grating technology with 40 optical fiber sensors at several critical points along the bridge to measure real-time strain data and also video cameras. The data are sent wirelessly to a nearby secure computer and automatically uploaded for researchers at Iowa State University, allowing for viewing real-time bridge traffic with corresponding strain data (Hemphill 2004). The system is considered quite useful and efficient (Collins et al. 2014).

As of late 2016, IADOT and Benesch Engineering, were seeking qualifications for the installation of a permanent and dedicated SHM system for the planned I-74 bridge over the Mississippi River, scheduled for construction 2017-2020. When completed the twin bridges will be 3,400 ft long with a main span of 800 ft. The proposed SHM is expansive and multifaceted, consisting of: 128 vibrating wire strain gages, 218 strain transducers, 10 embedded corrosion sensors, 40 leaf wetness sensors, 8 temperature and humidity probes, 10 accelerometers, 4 thermocouples, 42 multiplexers, and 42 data loggers (Benesch 2016).

Minnesota Bridges

In attempts to mitigate the high costs associated with traditional bridge inspections MnDOT is investigating the use of Unmanned Aerial Vehicles (UAVs). Four bridges of various size and type across Minnesota were imaged using UAVs equipped with high resolution cameras and infrared sensors to test the practicality of such use, yielding several conclusions (Figure 1.14). Based off observations it was determined that the use of UAVs are practical by: minimizing risks to the general public and MnDOT employees, being applicable to all sizes of bridge, low costs, ability to give pre-inspection information, and additional information given by other sensors, such as the presence of delaminations via infrared thermal sensors. The few drawbacks include complications with federal guidelines and a lack of replicating physical measurements (Zink and Lovelace 2015).

Figure 1.14 - Example of high resolution photography in difficult to access locations obtained with UAV. From Zink and Lovelace (2015).

Immediately following the 2007 I-35 bridge collapse MnDOT began searching for contractors to build a new bridge with SHM instrumentation to create a new “smart-bridge” system to collect structural behavior data. In all, the replacement bridge was equipped with over 500 sensors including: 198 vibrating wire strain gages, 24 resistive strain gages, and 12 fiber optic strain gages to measure structural deformations; 246 thermistors to measure bridge temperatures; 26 accelerometers to measure vibrations; 12 linear potentiometers to measure expansion and contraction; and 4 sensors measuring electrochemical activity and concrete resistivity as a proxy measurement for corrosion potential. Since the bridge’s completion in 2008, finite element models were constructed, concrete samples tested, static and dynamic truck load tests completed, and continuous sensor and environmental data collected, resulting in the validation of the finite element models. After three years of monitoring and rigorous testing, MnDOT concluded that the new bridge is performing as anticipated (French et al. 2012). Though installation and performance of the SHM system were successful, several recommendations, such as sensor type, location, and usability, for future SHM installations were also summarized.

Minnesota contains 1,710 bridges with timber superstructures and numerous more using timber as decking or in substructure elements (USDOT 2012). Routine inspections of these bridges traditionally includes limited visual inspections, sounding with a hammer, and coring; all techniques that are capable of detecting late-stage damage, but insufficient for identifying early damage (Branshaw et al. 2015). Due to the susceptibility of deterioration of wood structures MnDOT investigated NDE timber bridge inspection technologies and protocols to address concerns of bridge engineers. Several methods were found to be capable of detecting early onset damage and, following a study by MnDOT, were incorporated into bridge inspection protocols. Moisture meters, stress wave timing, and resistance micro-drilling were among the technologies found to be most useful. In addition to amending these techniques into standardized inspections and forms, MnDOT also engaged over 150 people through outreach programs to train for the use of these technologies (Branshaw et al. 2015).

New Jersey Bridges

Electrochemical fatigue sensors (EFS) are a nondestructive method that, in conjunction with analysis software, allows for the detection of fatigue cracking, and also determining if cracks are actively growing or not. In 2006, The New Jersey Department of Transportation (NJDOT) used this technology on the Manahawkin Bay Bridge, a 2,400 ft cantilevered steel bridge that has been subject to cracking as a result of out-of-plane distortion. The bridge connects Long Beach Island with the US mainland in Ocean County. Using EFS at 17 locations along the bridge NJDOT was able to determine that of the 17 test locations, 5 exhibited no crack growth while 12 cracks were reported as actively growing. The following year NJDOT conducted visual inspections of the test locations to determine reliability of the technology. Upon inspection, it was found that two locations had actively growing cracks not reported by EFS, while one crack that was reported as growing had not (FHWA 2009).

The use of long-gauge fiber optic sensors has been recently researched by NJDOT to develop effective standardized methods for SHM evaluations. The Center of Advanced Infrastructure and Transportation at Rutgers investigated strain monitoring using long-gauge fiber-optic sensors in the field using the US-202/NJ-23 overpass and lab testing to give usage recommendations. In particular, the research focused on two general factors of multi-beam structures, the neutral axis and deformed shape. After testing, several suggestions were offered, including placement of sensors, number of sensors, and methodology for achieving higher accuracy (Glisic 2014).

The Burlington County Bridge Commission (BCBC) operates and manages eight bridges in the largest county of New Jersey, including the notable Tacony-Palmyra Bridge (TPB) and the Burlington-Bristol Bridge. The BCBC uses unique financing initiatives to keep the county's bridges safe, accessible and updated. In addition to performing routine inspections, the commission has been taking initiatives to equip bridges with "smart" technology, to provide data on the safety and integrity of bridges in the county; starting with the Bristol-Burlington Bridge. Other initiatives outline by the BCBC include: equipping a new grid deck on the TPB with "smart" gauges; and the installation of a traveler system on the Burlington-Bristol Bridge to allow staff to easily inspect the underside of the bridge, with similar plans underway for the TPB as well (BCBC 2012).

With the objective of "indefinitely preserving" the 88-year-old Tacony-Palmyra Bridge by utilizing the most recent technology, a SHM system was developed following the structural identification process (Aktan et al. 1997; Catbas et al. 2008) and implemented. The TPB is a 3,658 ft steel arch bridge with a bascule opening and multiple spans that crosses the Delaware River, connecting New Jersey and Pennsylvania. The SHM included both high-speed and electrical resistance strain gages, tilt sensors, temperature sensors, digital cameras, and a weather system; synchronized through a supervisory control and data acquisition (SCADA) platform (Yarnold et al. 2012). The TPB is also under monitoring efforts using the newer methodology of temperature-based structural identification (TBSI) which uses changes in temperature at critical joints to actively sense the structural conditions of the bridge (Aktan et al.

2013). These methods allow engineers to monitor real-time data for the multiple sensors concomitantly with live video of the bridge traffic.

New York Bridges

Columbia University recently created a 20” diameter, 20’ long replica cable and enclosed it within an accelerated corrosion chamber to test the durability and utility of a range of sensors. The research was pushed due to insufficiency of routine inspections to fully detect deterioration in all regions of a cable. New York City contains numerous older cable suspension bridges, resulting in an urgency for accurate and reliable corrosion detection in cables. This research looked in-depth into both indirect and direct sensing technologies and concluded that applicable technologies included: Acoustic emission (AE), Magnetostrictive (MS), Fiber Optics, Electromagnetic, Linear polarization resistance (LPR), and Electrochemical impedance spectroscopy. Based on the results of the experimental corrosion tests the sensors chosen for the installation phase were the temperature and relative humidity sensors, the LPR sensors, coupled multi-electrode corrosion sensors, and bi-metallic sensors. In agreement with the New York City Department of Transportation (NYCDOT), one of the cables on the Manhattan Bridge was chosen to be outfit with sensors (Figure 1.15). The entire monitoring system installed upon the cable included: AE sensors, accelerometers, a weather station, temperature and humidity sensors, fiber-optic strain gauges, and a wireless sensor interface; a total of 38 sensors (Betti et al. 2014).

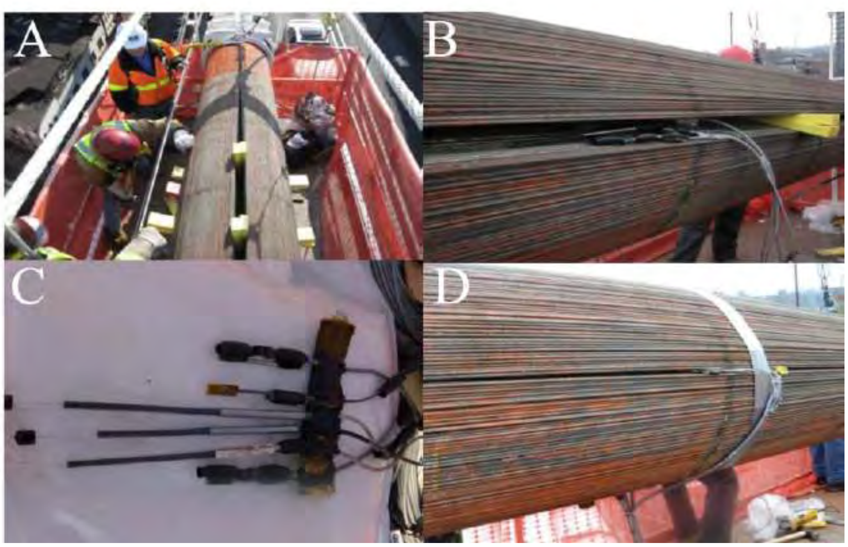


Figure 1.15 - Process of installing sensors in a cable on the Manhattan Bridge. A. Unwrapping and wedging the cable, B. Placement of sensors, C. Sensors used in the study and D. The sealed cable with exit wires. From Betti et al. (2014).

The University Transportation Research Center at the City College of New York has recently been testing the use of mobile robots to use in conjunction with NDT/NDE technologies to investigate bridge conditions, with a focus on automation and addressing hard to access locations. Two test robots have been developed to date: one equipped with an impact-echo device that roams bridge decks; and another wall-climbing robot equipped with GPR capable of scaling vertical structures. Though still in development both innovations have been tested, yielding some promising future applications (Xiao and Agrawal 2015).

The New York State Bridge Authority (NYSBA) and New York State Department of Transportation (NYSDOT) have funded efforts evaluating the conditions of cables on the Mid-Hudson Bridge and forecasting cable longevity. The evaluations were completed by Bridge Technology Consulting (BTC) utilizing their proprietary method. The method eliminates bias by using random sampling and employs probabilistic modeling to evaluate cable integrity and projected lifespan based on the results of mechanical testing (Mahmoud 2011).

The historic Brooklyn Bridge, a 5,989 ft hybrid cable-stayed suspension bridge, opened in 1883, connecting Manhattan and Brooklyn over the East River. It had a test SHM system installed in 2009 as part of a PhD research project. This system focused on the two largest masonry approach arches, with the goals of insuring bridge safety and understanding the cause and activity of masonry cracks. The SHM project used 40 fiber optic sensors, including 16 crack sensors, 5 displacement sensors, 5 accelerometers, 8 tiltmeters, and 6 temperatures sensors. The real-time monitoring system helped calculate acceptable crack openings and can aid in predicting the effects on overall bridge structure (Fischer 2011). More recently, with the goal of bringing the bridge into a state of good repair, the NYCDOT has invested more than $17,000,000 into bridge rehabilitation (NYCDOT 2015).

The new Tappan Zee Bridge, a set of twin cable-stayed bridges replacing the 1952 cantilever steel bridge, are scheduled to fully open in 2018. The existing bridge was decided to be replaced, with NYSDOT citing numerous structural, operational, security and mobility deficiencies (FHWA 2012). The new bridge has been highly anticipated for its decorative LED system, but is also slated to be instrumented with an advanced SHM "closed loop" system; processing real-time data to be graphically displayed in the bridge's control room. In the approach span piers and deck elements tiltmeters, sonic displacement sensors, and bridge bearing sensors were planned to be installed in 2015. Upon the main-span superstructure sensors include accelerometers and fiber optics sensors in the stay cables, accelerometers and GPS on the towers and bridge deck, and corrosion sensors and weather stations (Geocomp). The design and specifications of the SHM system were independently reviewed to ensure functionality.

Pennsylvania Bridges

The first implementation of a smart bridge in Pennsylvania was in 2005 at the Hawk Falls Bridge, a 738 ft long three-span deck truss bridge on I-476 in Carbon County, PA. The Pennsylvania Turnpike Commission (PTC) choose to install a three-part remote health monitoring system, likely an early word usage of SHM, consisting of dual-channel strain sensors, a hardwired data acquisition control box with wireless data transmission, and an isolated operations center for data storage and usage for PTC management. The data provided was integrated with a finite element model, providing accurate bridge performance data (Hartle and Balan 2006). Consequently, the bridge is slated for replacement with an estimated completion date of June 2020.

Though integral abutment bridges (IABs) have become standardized and a frequently chosen design for many bridge replacements, there is a deficiency of long-term field data regarding predicted and observed structural behavior of these types of bridges. A seven-year bridge monitoring study selected four IABs in central Pennsylvania, along with a centralized weather station, to provide actual field data to improve upon IAB design and analyses. The four bridges vary in length, from 62' – 420', but are all constructed with prestressed concrete girders with cast-in-place deck. In total, 240 sensors were installed on the bridges, including: backfill pressure cells, abutment displacement extensometers, girder axial force and moment strain gages, girder tiltmeters, abutment tiltmeters, pile moment and axial force strain gauges, approach slab sister-bar strain gauges and thermocouples. After seven years of data collections and monitoring, the project yielded several findings applicable to construction design and IAB behavior. The generalities of these findings relate to the allotment of more plasticity in IAB bridge design and construction as several elements tend to move over time as a result of thermal loading, differential girder and abutment rotation, and passive earth pressure (Kim and Laman 2012).

More recently, the Pennsylvania Department of Transportation (PennDOT) sponsored a study investigating the causes that lead to, or limit, early-age concrete bridge deck cracking; the role these cracks have on continuing stability of bridge decks; and to identify best methods to limit early-age bridge deck cracking. Drawing from exhaustive literature review, survey data of PennDOT personnel experiences, and field inspections of over 200 bridge decks ranging in age, the study established best course of action protocols for deck preservation and remediation. Also developed was a spreadsheet to assist asset managers in selecting the ideal management strategies to optimize the balance of bridge life span and cost using a life-cycle cost analysis (LCCA). The report has suggestions ranging from timing of construction, consideration of construction weather conditions, chemical usage, choice of materials, timing of repairs and bridge design (Hopper et al. 2015).

Currently, PennDOT is committed to a study developing a lasting feasible fatigue crack monitoring method using a wireless elastomeric skin sensor network. This study also has partnership with the DOTs of KN, MN, NC, OK, and TX. The purpose of the study comes rises from the error, cost and time limitations of human inspections, and the absence of standardization of NDE techniques leading to an inability to collect accurate timelines of crack progression. This novel research proposes the development of skin sensors 40 µm thick, implementing these sensors into a wireless network with autonomous operation, and eventual validation of the system on an existing 30 ft long bridge (TPFP 2017). The project is estimated to be completed August 2019.

Wisconsin Bridges

The National Center for Freight and Infrastructure Research and Education (CFIRE), located at the University of Wisconsin-Madison has performed numerous investigations focused on bridge health monitoring, construction techniques, and performance. One study from CFIRE created an Analytical Hierarchy Process (AHP) based on the synthesis of several states current practice for rapid bridge replacement to aid decision-makers to best prioritize bridges needing replacement, and also in selecting bridge design and construction system (Sriraj and Li 2012) (Figure 1.16).

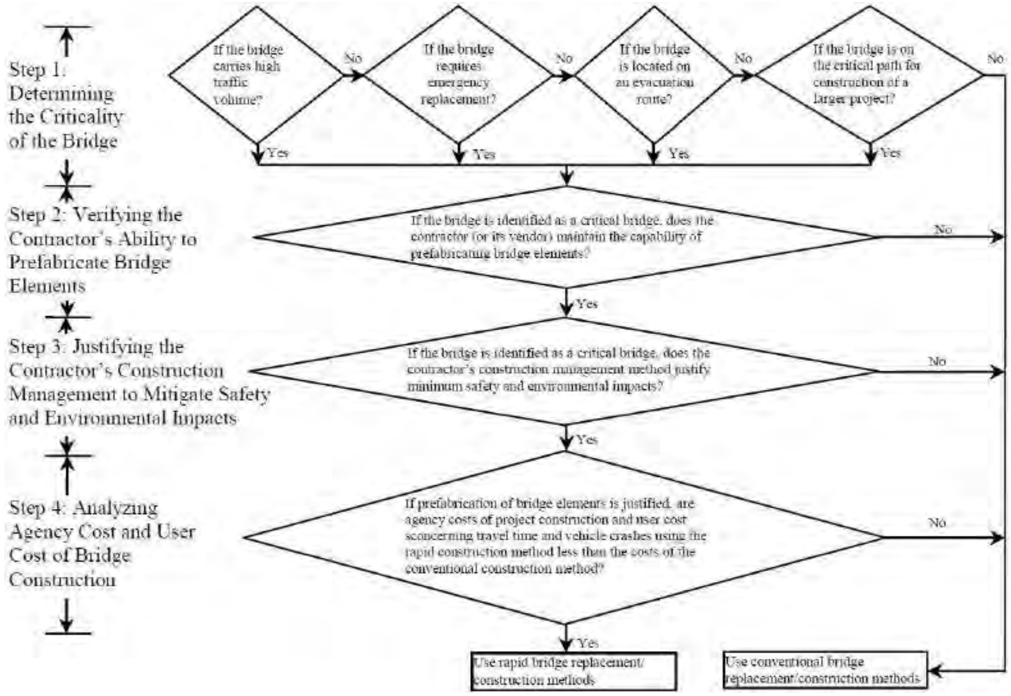


Figure 1.16 - Framework of the proposed decision tree by Srijaj and Li (2012) used in the Analytical Hierarchy Process. From Srijaj and Li (2012).

Another CFIRE study specifically investigated the short and long-term impacts that special purpose freight vehicles have upon complex bridges in Wisconsin. These vehicles are uniquely oversize/overweight, often carrying such items as wind turbines, transformers, or military equipment and can weigh up to seven times the legal limit. The study generally concluded that most complex bridges can handle the weight of these vehicles but identified several key elements of different types of bridges that are recommended to be observed during bridge crossings (Yanez-Rojas et al. 2016). Currently CFIRE is also engaged in a study evaluating a range of NDT techniques to assess and prevent damage to transportation infrastructure, including bridge elements. In regards to transportation infrastructure the study aims to: identify best uses of NDT, control impacts of heavy vehicles, use performance data to better schedule maintenance, increase economic efficiency, and work towards environmental sustainability (CFIRE 2017).

The Wisconsin Department of Transportation (WisDOT) was engaged in identifying the practicality of NDE to assist in biennial inspections early on. Starting 1999 WisDOT funded a study to describe the strengths and weaknesses of several NDE techniques on assessing different types of bridge defects (Ghorbanpoor and Benish 2003). Research funded by WisDOT created a database that allows for easy identification and review of SHM technologies in 2005. The comprehensive study collected information on SHM technologies from several state's DOT with a focus on those having "smart" capability (Phares et al. 2005).

More recently WisDOT is sponsoring a project, performed by Michael Baker International, to facilitate the application of a new generation of BMS to be implemented by WisDOT (Aldayuz 2016). The WisDOT also funded a study to report upon the structural condition of eleven “innovative” bridges, considered different from conventional bridge design or construction, using customized inspections for each of the bridges (Dahlberg and Phares 2016).

The Hurley Bridge on US-2, which connects Michigan and Wisconsin over the Montreal River, has been the subject of concern due to overweight logging trucks passing from Michigan to Wisconsin. Wisconsin bridges, such as the Hurley Bridge, were not intended to carry the loads, leading to concern that premature damage may occur (Kosnik and Simon 2010). The Infrastructure Technology Institute at Northwestern University, in partnership with WisDOT, used this situation as an opportunity to install a SHM system on the bridge to address these concerns. The full real-time SHM system consists of strain-gages, thermocouples, accelerometers, displacement tranducers, and also a weigh-in-motion system. The SHM system has been able to identify both short and long term changes to the bridge, and thus far indicate that the Hurley Bridge has no signs of overloading or damage (Chen et al. 2013).

Florida Bridges

FDOT, through the University of Florida, is currently conducting research for improving the monitoring and management procedures for the Sunshine Skyway Bridge in the Tampa Bay area. This iconic bridge is 5,808 ft long and connects the two sides of Tampa Bay in Florida. The first objective of this research is to investigate and assess the current condition of the monitoring hardware on the bridge. The second objective is to define the intent of the current and soon to be installed monitors. Finally, the project aims to analyze the current system for how it collects and compiles bridge data, and to determine how the Sunshine Skyway Bridge should be monitored and managed in the future to optimize efficiency. The final product of the research will be recommendations for upgrading the monitoring system to optimize efficiency in maintenance procedures. Florida is striving towards efficiency and accuracy for monitoring and managing the Sunshine Skyway in the same way that this research project is striving to develop efficiency and accuracy-based standards for management and operations of big bridges (Davis, Active).

1.4.4 Internationally

There has been a more prominent drive towards research and development of management techniques for big bridges internationally than there has been within the United States. Within the past ten years, European and Asian countries have funded valuable research projects in the area of big bridges (Radic et al., 2006; Ou et al., 2014). Much of this research has been incorporated into the procedures for big bridge management in these countries.

Developments from Research in Europe

In 2007, a team of American researchers from AASHTO, the FHWA and the NCHRP conducted a study tour in Europe to investigate bridge operations and management techniques used by European countries that could potentially be beneficial, and therefore be implemented, in the US (Everett et al., 2008). The researchers visited Denmark, Finland, France, Germany, Norway, and Sweden. Over the course of their comprehensive research, the team identified several European practices specifically pertaining to big bridges that could prove valuable if incorporated into BMS used in the US.

In both Denmark and Germany, the research team found that the designers included features to make routine bridge inspections easier and more accurate for certain bridges. For instance, in Germany concrete steps were included in the wing wall design of some bridges to provide access to the abutments and wing walls for inspection. Although the idea is not exclusive to big bridges, the benefit for such structures would be much greater and the additional cost is relatively small compared to the cost of the entire project.

In Denmark, the research team found an example of inspection and operations-driven design features on a very big bridge. During design of the Great Link Bridge, a 22,277 ft suspension bridge connecting the eastern and western parts of the country, engineers included elevators at the towers and a permanent traveler beneath the deck. The purpose of the elevators was to take inspectors up and down the side of the towers efficiently to perform a comprehensive assessment of the tower condition. The permanent traveler is a movable, enclosed platform installed on the underside of the superstructure that can move along the length of the bridge. This traveler can be accessed from the bridge deck, and can be used for both inspection and maintenance purposes. This concept proved to be extremely relevant to the improvement of operations and management for big bridges because the relative amount of inspection time saved for such a feature on a big bridge vastly exceeds the time saved for a smaller structure.

Another useful management technique the team found in Europe was detailed an interview with the Finnish bridge management team. Finland has two types of bridge inspections they perform: a general inspection and a basic inspection. A general inspection is the standard inspection performed on every bridge every five years, and must be done by a certified inspector. However, big bridges (or long-span bridges) require a supplemental evaluation known as a basic inspection. This means that in addition to all the actions required for a general inspection, additional supplemental tests must be performed and samples of structural material from the bridge must be collected and delivered to the Research Centre of Finland (VTT) for testing.

Recent Research in China

Life-Cycle Performance Monitoring and Evaluation of Long-Span Bridges

In China, there has been recent research into how SHM systems are currently used and how they can be improved to optimize efficiency and accuracy of bridge inspection and management (Ou et al., 2014). This research focuses mainly on the SHM systems for the longest bridges, ranging from 453 to 5,413 ft, as the utilization of SHM systems for big bridges in China is a fairly standard practice. After the investigation, it was found that the SHM systems for such long bridges include sensors for environmental conditions, loading conditions and global and individual component monitoring. Sensors for environmental conditions include those to measure temperature, wind and ground motion, such as accelerometers. Weigh-in-place sensors and digital cameras on these bridges are used to record loading conditions. The condition of local components of bridges is determined via strain gauges, cable tension meters (for cable-stayed bridges), corrosion sensors, monitors on supports and scour monitoring systems. Global conditions are evaluated through data from accelerometers, GPS, displacement transducers, inclination sensors and interconnecting pipes, which are combined to give representative data for displacement and acceleration of the full system. One purpose of various sensors installed in SHM systems on long bridges is to measure fatigue. Out of all the conditions monitored by an SHM, monitoring of fatigue distress is the most relevant to improving inspection and management techniques for big bridges.

One type of SHM sensor that has a particularly high potential contributing to fatigue monitoring on long bridges is self-sensing smart cables on suspension and cable-stayed bridges. The sensors on these cables, used in sync with the load sensing technology, can measure the tension in a particular cable under certain vehicle loads. Over time, the stress caused by vehicle loadings in the cables can change, potentially indicating fatigue. Fatigue damage can be accurately calculated by applying stay cable stress history data to fatigue models. Ou et al. (2014) used the rain flow method and the Miner fatigue model. Once this fatigue is properly identified and analyzed, appropriate bridge maintenance activities can be undertaken.

When the research project was presented at the International Association for Bridge Maintenance and Safety (IABMAS) Conference, the Design Code of SHM Systems for Long-Span

Bridges was being written. This code, released for use in September 2014 (Moreu, 2014), specifies that bridges of different types with spans longer than a minimum distance must be equipped with appropriate SHM systems (Ou et al., 2014). These SHM systems must monitor environmental conditions, loading conditions, global performance (i.e. sensors to monitor displacement of the entire bridge and members) and local performance (i.e. sensors to measure and record metrics for strain, cracking, fatigue and scour), similar to the SHM systems mentioned earlier.

Damage Detection for Local Components of Long Suspension Bridges using Influence Lines

At the IABMAS conference in 2012, a team of structural engineers from China presented "Damage detection for local components of long suspension bridges using influence lines" (Chen et al., 2012). The premise of this research is that most long-span, cable-supported bridges have insufficient SHM systems for evaluating minor, localized damage. Most of the existing SHM systems use vibration-based damage detection techniques, which do a good job for analyzing full structure performance. However, failure in big bridges is often a result of minor, localized damage. Therefore, it is prudent to design an SHM system which can detect such issues. The team conducted a feasibility study for local component damage detection using stress influence lines, and evaluated the detection method through a case study of the Tsing Ma Suspension Bridge in China.

The Tsing Ma Bridge is a long-span (4,518 ft main span) suspension bridge in Hong Kong that carries both vehicle and rail traffic. The top deck has six lanes of highway traffic (three in each direction), and a lower deck carries two railway tracks and two carriageways. A finite element model of the Tsing Ma Bridge was developed (Figure 1.17) and the corresponding loads it was frequently subjected to were applied. Rail traffic was found to be the controlling load case.

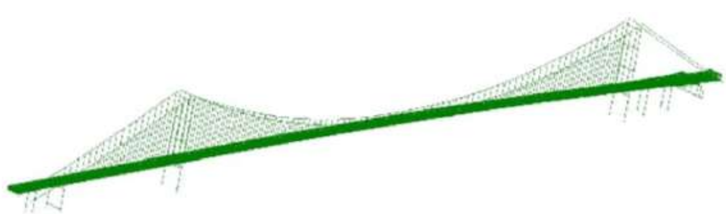


Figure 1.17 - 3D Finite element model of the Tsing Ma Bridge. From Chen et al. (2012).

Once the model was created, a simulation was run to produce stress influence lines for train loadings at different locations of the bridge. These stress influence lines were then compared to stress influence lines from the actual SHM system on the bridge, using strain time history and train information at these locations. It was found that the results from the simulation and the results from the actual loading and strain data were very comparable. Therefore, the method was valid for basic loading.

The second portion of this research project involved local damage detection for dynamic loading cases. The computer model of the bridge was modified by reducing the area of certain bridge elements (e.g. a truss member), which represented localized damage. The simulation was then run to produce the stress influence line at the location of damage for both the model with the simulated element damage and the model without the damaged element. It was found that the influence lines had similar shapes, but significant deviation in peak stress values. The team hence proposed implementing a damage index, which would be determined by finding the relative difference in peak stress values for the damaged and undamaged states.

This research found that the stress influence line method was feasible for minor, localized damage detection for large bridges. The damage index for several different elements could be recorded and analyzed to determine where maintenance was most needed. This method has potential for big bridge inspection and management at the bridge element level.

Safety Assessment and Life-Cycle Management of Steel Suspension Bridges

The influence line stress analysis technique was used in fatigue analysis for a research paper presented at the IABMAS Conference in 2014 by a team of researchers from China (Zeng et al., 2014). A finite element model of the Jiangyin bridge (another long-span suspension bridge in China) was created with the intent of analyzing the fatigue reliability of the hangers, deterioration of the main cables, and microcracks propagating in the steel box girders. The results from simulated loading identified potential areas of damage such that inspection and maintenance procedures could be assigned.

Stress influence lines were input into the model, and simulated loads were applied over a simulated period of 25 years. The fatigue damage of each modeled hanger was analyzed such that inspection and maintenance efforts could be appropriately assigned to particular hangers at the right times. For instance, a hanger that shows the potential for a lot of fatigue damage should have more in-depth inspections performed regularly than a hanger shown to not be susceptible to fatigue, which could be assigned only routine inspections.

During the analysis of the main cables, several types of cracking and corrosion of the strands were considered, as was time-dependent reliability of the main cable. As the main cables cannot be replaced during the service life of a suspension bridge (in contrast to the hangers), and failure in the main cables could result in a full system collapse, maintenance and inspection strategies are even more critical. The probabilities of the different types of cracking and corrosion over time were used as a basis for time intervals at which particular maintenance activities should take place. For example, the team found that surface cleaning and paint inspection should be undertaken every year, while checking for corrosion and cracking of wires and strands need only be performed once every three years. These intervals ensure that the bridge is assessed for safety regularly enough that any fatigue that could potentially cause failure of the main cables is identified early.

The last suspension bridge element evaluated for operations and maintenance procedures was the steel box girders on the Jiangyin Bridge. After assessment, it was found that repetitive loads from heavy trucks caused microcracking in the steel, especially in joint areas such as welds. After formation, these microcracks can propagate under the continuing cyclic loading caused by the aforementioned heavy trucks, and the condition of the bridge steel deteriorates at an accelerated rate. Therefore, the team concluded that it is crucial that stress and deformation of the box girders be monitored when heavy trucks use the bridge such that damage can be identified and repaired in a timely fashion.

The overall product resulting from this research was a series of recommendations for how to manage large suspension bridges to ensure safety. Hangers can be analyzed on an individual basis using stress influence lines, with different inspection criteria developed for each hanger based on its projected fatigue damage. This procedure is applicable for all suspension bridges, not just the Jiangyin Bridge (the subject of the case study). Main cables and steel box girders should be inspected and maintained on a regular basis, with particular attention being paid to cracking and corrosion of the strands in the main cables, and microcracking at welds on the box girders. These procedures, especially the hanger analysis system, have the potential to streamline suspension bridge management processes in the US.

Long-Term Monitoring of PSC Box Girder Bridges

In China, research was conducted in 2014 with the goal of developing a state of the art structural health monitoring (SHM) system specifically for long, prestressed concrete bridges (Chen et al., 2014). The research team first conducted a review of the current state of SHM systems in China. The team found that long-span steel bridges in China were typically equipped with comprehensive SHM systems to determine when, where and how individual bridges were susceptible to failure and should be repaired. These long span steel bridges typically had suspension cables, and the primary structural health issue was vibration. Thus, the SHM system consisted of such sensors as accelerometers, anemometers and strain gauges. However, as large prestressed concrete bridges typically have shorter spans they are less susceptible to vibration, but such failure states as shrinkage and creep of concrete and steel relaxation of the prestressing tendons must be accounted for. Therefore, a different SHM system must be introduced for large prestressed concrete bridges.

A case study of structural health monitoring for the Jinghan Canal Bridge in China was conducted. The Jinghan Canal Bridge is a three-span prestressed concrete box girder bridge with a 492 ft long main span and two 279 ft side spans. The case study used SHM sensors to determine the actual stresses and displacements during construction and service loads for the bridge, and compared them to stresses and displacements measured under the design loads. The study found that the sensors were accurate in measuring these deflections and stresses, and that the measured values were lower than the deflections and stresses the bridge components were designed for. However, it was shown that the long-term midspan deflection indicated by various sensors exceeded the allowable design deflection. The team appropriately concluded that long-term deflection is crucial in design, maintenance and management of prestressed concrete bridges. Therefore, it is justified that sensors used to determine long-term deflections on long prestressed concrete bridges must either have an appropriately long service life or be replaced accordingly. This entire study exemplifies the international efforts to develop a system for inspection and management of large bridges. Many of the conclusions discerned for large prestressed concrete bridges in China are applicable not just for large prestressed bridges in the United States, but for domestic large bridges in general.

Maintenance Management of Big Bridges

A state-of-the-practice for big bridge management was compiled by consultants from Chinese highway engineering companies (Zhang et al., 2014). An overview of highway bridges in China in the general sense was followed by the bridge management practices, particularly for large bridges. Current procedures and flaws in the bridge inspection process were identified and recommendations for improved big bridge inspection and management techniques in China were reported.

The first major problem identified in big bridges in China was that bridges with high traffic volume had fatigue cracking. Meanwhile, there were insufficient funds to meet this demand for bridge repair. Therefore, the team recommended that inspections be done by reputable professional institutions selected via competitive bid, helping provide high quality data at the lowest possible cost.

The other substantial problem in big bridge management in China came from a lack of consistency in bridge inspections among different companies doing inspections of the same bridges. The engineers claim that regular inspection is the most important component of long-term bridge safety, but several companies doing regular bridge inspections provide insufficient technical data for an accurate representation of the condition of a bridge. Especially lacking is long-term data on deformations and cracking.

Lessons learned and recommendations for big bridge operations and maintenance in China are relevant in the United States. At the time of the publication of “Bridge Inspection Processes” by the NCHRP in 2007, 9 out of the 28 responding DOTs had specific teams for evaluating large and complex bridges (Hearn 2007). Another approach is having consultants perform inspections of large or complex bridges in certain states.

1.5 Review of Inspection Techniques for Complex Bridges

1.5.1 Commonly Used Inspection Techniques

In 2013, the National Bridge Inspection Program (NBIP) Metrics were created by the FHWA. The NBIP requires complex bridges to have specialized inspection procedures which clearly identify the complex features, specify the frequency of inspection of those features, describe any specific risk factors unique to the bridge, and clearly detail inspection methods and equipment to be used during the inspection (U.S. DOT, 2013). The NBIP also identifies common features found in complex bridges including but not limited to suspension cables, stay cables, anchorages of cables and post-tensioning, electrical systems, mechanical systems, operational systems and controls, floating bridge components, materials with known problems or special seismic features. Other unique features should be noted, and complex bridge inspections should follow the NBIP’s levels of assessments.

The NBIP specifically details three different levels of assessment for complex bridges: minimum, intermediate, and in-depth. The minimum level of assessment requires inspectors to monitor the Plan of Corrective Action (a description of the process and schedule that will be implemented to resolve the deficiencies of a bridge) if it is in effect while also assessing the complex bridges based on past reviews and inspections. The intermediate assessment level of complex bridges requires verifying the specialized procedures are followed for a specific complex bridge. The in-depth assessment of complex bridges requires observing complex bridge inspections to ensure specialized procedures are being followed. The in-depth assessment also requires the inspector reviewing NBI bridge data to check if any bridges that have not been identified as complex, should be. Additionally, the inspector should look for any evidence of risk factors, unique circumstances or conditions at each complex bridge. Inspectors should also evaluate whether the inspection procedures and reports developed for the complex bridge adequately comply with NBIP requirements for complex bridge inspections.

Nevada Department of Transportation (NDOT) addresses complex bridges in their Nevada bridge inspection program by referencing the NBIS definition of complex bridges (movable, suspension, cable-stayed, and other bridges with unusual characteristics) (NDOT, 2008). NDOT assigns a senior staff person to the inspection of complex bridges who is given additional training and follows specialized inspection procedures for complex bridges. NDOT often requires assistance from the Non-Destructive Testing Squad as complex bridges usually take more time to inspect, and are often much more difficult to inspect.

Texas Department of Transportation (TxDOT) enforces strict qualifications for project managers inspecting complex bridges. These criteria include being registered as a professional engineer, having seven years of bridge inspection experience (including one year of inspection of bridges considered as complex) and having successfully completed an FHWA approved comprehensive bridge inspection training course (TxDOT, 2013).

Ohio Department of Transportation (ODOT) requires complex bridge inspections to be in accordance with the BIRM (ODOT, 2014). Additionally, every complex bridge is required to have its own Operating and Maintenance Manual and Field Inspection Plan. Guidelines for a good inspection plan for complex bridges are detailed by ODOT as well. Although DOT's place different emphasis on complex bridges across the country, most states defer to the BIRM for guidelines on inspecting complex bridges.

Several state DOTs reference the BIRM as a guideline to inspect complex bridges. The BIRM defines complex bridges as "movable, suspension, cable-stayed, and other bridges with unusual characteristics" (Federal Register, 2004; U.S. DOT, 2013). This definition was left relatively vague to allow bridge inspection program managers to determine the specific bridge types that require special attention in their state. The BIRM contains fine details regarding inspection techniques of common elements associated with cable bridges, movable bridges and floating bridges (U.S. DOT, 2012).

Complex bridges share common materials and structures with non-complex bridges. For instance, cable-stayed and suspension bridges contain steel and concrete members. These common material types for complex bridges would be inspected for the same deficiencies of the same material as in non-complex bridges. Similarly, if a complex bridge has the same structures as a non-complex bridge (such as concrete girders or concrete abutments) the manual states that normal inspection techniques of these elements may be used.

While complex bridges should use the same techniques that are used for similar materials and structures in non-complex bridges, complex bridges often have unique features of which the condition cannot be assessed as easily. No complex bridge is identical to another and many of them contain features not shared with other bridges. Therefore, the BIRM states that inspections of complex bridges should be led by an inspector who is very familiar with the bridge. Complex bridges will often have an inspection manual or owner's manual that contains specific details pertaining to the bridge, which should be utilized throughout the inspection if available.

Although non-complex bridges require only standard inspection forms, a complex bridge requires an inspection file in addition to any required inspection forms. Inspection files should include a list of elements that comprise the bridge, sketches of elements showing typical and deteriorated conditions, and a standard notation system for indicating the condition of the elements. The inspection file on the complex bridge should also include a log or index for photographs, and brief descriptions of element conditions. The inspector should utilize the customized pre-printed inspection forms, if available, to record their findings in a rigorous and systematic manner.

1.5.2 Cable Supported Bridges

The BIRM identifies common elements and inspection procedures for cable supported bridges. Common deficiencies for inspectors include corrosion, fatigue cracking, overloads, collision damage, heat damage, and paint failure. Again, for these cable-supported bridges, inspectors should look for deficiencies similar to non-complex bridge inspections based on the material or structure. The BIRM outlines common elements and inspection methods for both cable-stayed and suspension bridges.

Suspension Cable Bridges

Common elements that usually compose suspension cable systems are the main cable anchorage elements, main suspension cables, saddles, suspender cables and connections, sockets and cable bands.

The main cable anchorage elements are composed of a number of their own elements, which include the splay saddle, bridge wires, strand shoes or sockets, anchor bars, and the chain gallery. The splay saddle should be inspected for missing or loose bolts as well as for cracking in the casting. Inspectors should also look for splay movement up the cable, which can be indicated either by unpainted strands below the splay or by bunched up wrapping above the splay. The bridge wires of the main cable anchorage should be inspected for abrasion, damage, corrosion, and movement, and inspectors can take a screwdriver and apply pressure on the wires that will help reveal broken wires. The shoe strands of the main cable anchorage elements should be inspected for signs of displaced shims, movement, corrosion, misalignment, and cracks while the anchor bars or rods should be inspected for corrosion (section loss), deficiencies, or movement at the face of their concrete embedment. Inspectors should also note if there is any protection against water entering or collecting where it may cause corrosion, and if there is proper ventilation on the interior of the anchorage. All deficiencies in any of these elements should be diligently recorded.

When reviewing the main suspension cables of suspension bridges, inspectors should check for indications of corroded wires. Inspectors should also evaluate the condition of the protective covering or coating of the wires. Areas of great concern are the low points of the cables, areas adjacent to the cable bands, saddles over towers, and at anchorages. Additionally, the wrapping wire needs to be checked for cracks, staining, dark spots, and if the wrapping wire is loose. If there are cracks in the caulking where water can enter, this can cause corrosion of the main cable and inspectors should also search for evidence of water seepage at the cable bands, saddles, and splay castings. Loose connections at the stanchion (hand rope supports), cable bands, anchorages, or towers must be inspected for any deterioration. Hand ropes are prone to corrosion, deterioration, bent or twisted stanchions, and excessive slack. Cable wrapping, and vibrations throughout the cables should be noted.

Cable-Stayed Bridges

Cable-stayed bridges have slightly different common elements than suspension bridges, and different inspection techniques should be used to properly inspect this type of complex bridge.

Common elements of cable-stayed bridges include cable wrapping, cable sheathing, dampers, anchorages, anchor pipe clearances, flange joints, and polyethylene expansion joints. The forces in the cables and all excessive vibrations should be recorded. The amplitude and type of vibration along with wind speed and direction should be recorded as well. Inspectors should also evaluate cable and tower lighting systems and note all discrepancies.

Common wrapping variations for corrosion protection of cables include spirally wound soft galvanized wire, neoprene, or plastic wrap type tape. Inspectors should evaluate the wrappings for corrosion, cracking, staining, dark spots, and loose wrapping wires or tape. Corrosion or broken wires may be indicated by the bulging or deforming of wrapping material. Inspectors should also check for evidence of water seepage at the cable bands, saddles, and castings.

The two most common types of cable sheathing assemblies for cable-stayed bridges are steel sheathing and polyethylene sheathing. If steel sheathing is used, inspectors must evaluate it for corrosion, the condition of the protective coating, and weld fusion. Water infiltration and corrosive action may cause splitting. If polyethylene sheathing is used, inspectors need to look for nicks, cuts, and abrasions. Temperature fluctuations sometimes cause splitting. In both cable sheathing assemblies, fatigue may cause cracking and bulging may indicate broken wires.

There are a variety of dampers that may be installed on the cable-stayed bridge. If the shock absorber type dampers are used, inspectors need to check the system for corrosion, oil leakage in the shock absorbers, and deformations in the bushings. If the damper is tie type, inspectors must evaluate the damper for corrosion, and deformations in the bushings. If the damper is a tune mass damper, development of corrosion and deformations in the bushings must be checked. For all types of dampers, the tightness in the connection to the cable pipe, and torque in the bolts must be evaluated.

A cable-stayed bridge may also have numerous types of anchorage. For end anchorages, inspectors have to check the transition area between the steel anchor pipe and cable for water tightness of neoprene boots at the upper ends of the steel guide pipes. The drainage between the guide pipe and transition pipe should also be inspected. Inspectors must also look for deteriorations, such as splits and tears in the neoprene boots. There must be sufficient clearance between the anchor pipe and cable while any rub marks or kinks should be noted. If the bridge has a tower anchorage, corrosion can occur at the cable anchorages. They should also inspect for cracks and nut rotation at the socket and bearing plate, and seepage of grease from the protective hood.

The BIRM recommends inspectors prepare a set of customized, preprinted forms for documenting all deficiencies encountered in the cable system for any cable supported bridge. Separate forms should be used for each main suspension cable. Any vibrations must be recorded, whether local or global, while performing inspections of cable supported structures. Although the BIRM describes inspection methods for common elements from suspension and cable-stayed bridges, no cable-supported bridge is the same, and so these inspection methods are guidelines for inspecting cable-supported bridges. Suspension and cable-stayed bridges are just two types of complex bridges, and there are variations from state to state in how they handle complex bridges.

1.5.3 Non-Destructive Evaluation Techniques for Bridge Inspection

NDE is becoming more available and a preferred choice among bridge inspection teams. As the name implies, NDE refers to a group of analysis techniques used to evaluate the properties of certain materials or systems without causing damage to the component(s) being investigated (MnDOT 2014). This is particularly important when it comes to monitoring the safety of bridges, as methods such as taking core samples can be detrimental to the health and longevity of critical elements. Visual inspection is the simplest form of NDE. The chosen methods depend on the materials. For instance, some NDE inspection methods for steel structures include Ultrasonic Thickness (UT), Liquid Penetrant (PT), and Magnetic Particle (MT) testing. Each of these assists inspectors in investigating bridge materials without causing damage to the structure. Some NDE methods particularly applicable to concrete structures include Ground Penetrating Radar (GPR) and Infrared Thermography. Each of these evaluation types hold their own merit, however multiple factors will influence the effectiveness and applicability of their use for big bridge inspection.

In UT testing, an ultrasonic thickness gauge is used to measure the thickness of steel plates at specific locations (Figure 1.18). The gauges function by emitting high-frequency ultrasonic waves towards bridge components and measuring the time it takes for generated pulses to reflect back to the emitting unit. Variations in echo delay indicate how much material is present, and this data can be used to determine plate thickness. Typical applications of UT testing are obtaining plate thickness measurements along seams of built up members (e.g. truss gusset plates) and determining the thickness of members that have been subjected to rust or corrosion. This method is advantageous because one good data can be obtained even in extremely confined or hard-to-access areas. UT testing can also determine the thickness of particularly large plates, which often cannot be measured accurately with standard calipers. The primary disadvantage is that any surface subjected to UT testing must be cleaned down to bare metal to get accurate results. This method is applicable to big bridge inspection, and especially in the evaluation of older bridges that may be subject to internal degeneration.

Figure 1.18 - An anchor bolt being inspected with a straight-beam ultrasonic transducer. (https://fhwaapps.fhwa.dot.gov/ndep/DisplayTechnology.aspx?tech_id=6)

The PT method relies on discontinuities on a surface that allow liquids to enter. It may be applied to any surface given that it is non-porous and would not be negatively affected by the penetrant. After application of the PT, a developing material is applied that forms a high contrast visibility indication on the tested surface. This method is used to test for the existence and extent of visible cracks. PT testing is less costly than most other NDE methods, and is highly portable as well. PT testing does not require power or special tools, which makes its use highly effective and efficient, particularly in hard-to-reach areas. One disadvantage to PT testing is that any paint on the subject surface needs to be removed. The testing is also ineffective under extreme temperature, and can take much longer to complete than other NDE methods. This type of testing is useful for spot checking, but in itself does not provide comprehensive data about a bridge's condition. PT is generally best used to further investigate potential findings from other inspection types.

Locating surface and near-surface discontinuities in ferrous steel elements can be accomplished using the magnetic particle testing method, which is done using magnetization with an electromagnetic yoke. Emitted magnetic field flux leakages are determined using ferrous particles, which are attracted to the leak and therefore show areas of distress. Unlike previous methods, magnetic particle testing does not require paint removal or elaborate pre-cleaning. It is also a relatively fast method of inspection. The primary disadvantage of magnetic particle testing is that the method requires some advanced equipment, and therefore requires both a power source and an adequate understanding of the equipment. Because many big bridges are principally composed of ferrous steel, this type of testing would be quite useful for big bridges.

GPR is used to create an image of the subsurface of bridge elements using high-frequency radio waves that penetrate the surface (Figure 1.19). Reflected signals are measured to determine locations and depths of delaminations, along with the presence of rebar, cables, and conduits. GPR can be automated into a high-speed real time system and offers a high degree of accuracy. The record produced with the GPR method is a continuous, cross-sectional profile of subsurface conditions. Stored data can be compared to new results to help track deterioration. Like MT testing, this method requires costly specialized equipment and training. Using GPR for big bridge inspection would be favorable because this method can be accomplished quickly and accurately without the need for extended traffic control measures or lane closures.

Figure 1.19 - Air coupled vehicle mounted GPR being collected data to examine a bridge deck. (https://fhwaapps.fhwa.dot.gov/ndep/DisplayTechnology.aspx?tech_id=9)

Infrared thermography, also referred to as thermal IR (and TIR), helps to characterize the properties of measured materials by monitoring their response to thermal loading. Thermal IR can be completed both at highway speeds through automated systems and with a handheld device for spot-checking. Temperature differences will appear on the imagery and can be overlaid on

CAD drawings or GIS layers to locate areas of concern. This type of testing is environmentally sensitive. Factors such temperature and wind must be factored in during the evaluation and Thermal IR testing cannot be performed under wet conditions. Similar to GPR and MT, those using Thermal IR testing methods need specialized training, and can be costly. While very useful for inspection, the cost and usability concerns of Thermal IR for big bridges should be considered on a case-by-case basis.

Through the National Highway Institute (NHI) the FHWA offers several courses incorporating NDE training (U.S. DOT, 2012). Nearly all types of NDE require particular equipment and knowledge. This is true not only in use of the equipment, but also for interpreting the results. Specialized computer software may need to be used in the process. In addition to those methods mentioned above there are many other NDE methods used for bridge condition assessment. For measuring the parameters of stay cables, bridge inspectors may use a laser vibrometer. Acoustic methods similar to UT may also be used in evaluating wooden structures. Evaluation of all bridge types can benefit from using NDE for collecting condition data. Some methods lend themselves to big bridge applications more than others based upon their speed and the type of results achieved. Big bridges tend to be busy bridges, therefore inspection that minimally impacts traffic is favorable.

State DOT Use of NDE Methods

As part of this research review, several state DOT bridge manuals were reviewed. There is a wide range of NDE presence throughout them. The Minnesota and Oregon manuals provide in-depth detail about the utilization of various types of NDE methods used for bridge condition assessment. In Canada, the Ontario Structure Inspection Manual from the Ontario Ministry of Transportation (OMT) provides another example of thorough incorporation of NDE. The Ontario Structure Inspection Manual even includes tables detailing and comparing the different methods applicable to specific inspection topics (OSIM 2008).

The Michigan Department of Transportation (MDOT) has recently reviewed three NDEs (UT, MT, and Electrochemical half-cell potential assessment) specifically for obtaining detailed data for steel corrosion and concrete deterioration in bridges (MDOT, 2016). Concrete bridge beams are constructed with steel-reinforcements and are susceptible to corrosion when exposed to air, water, and dicing chemicals. This corrosion from the steel reinforcement can lead to the deterioration of the surrounding concrete and can cause cracking, delamination and spalling. As stated before, visual inspection can be used to evaluate bridges for deterioration, but this method does not give inspectors a good way to quantify the degree of corrosion and deterioration, and deterioration would only be detected after obvious damage had occurred. Destructive methods can weaken them further.

UT was able to detect debonding of the steel reinforcement, internal voids, cracking and delamination, but was unable to determine the length of debonding around strands unless cracking and delamination had reached an advanced stage. UT was also able to accurately estimate the thickness of beams and quantify the depths of defects and the area of delamination. MDOT concluded that additional methods would be needed to more specifically quantify the loss of reinforcement material and the extent of corrosion.

Electrochemical Assessment is a NDE in which electrodes and a voltmeter are used to detect electrochemical indicators of corrosion. Electrochemical testing was able to isolate the areas in beams with a high chance of corrosion. This tool was proven useful in assessing areas prone to corrosion. Magnetic flux leakage assessment was able to detect changes in the cross-section of steel reinforcement. The correlation is strongest when the loss is spread out over a longer area than when it is concentrated. All three methods proved to be at least somewhat effective in predicting deterioration of concrete before it became visually obvious. These methods could be applied to a big bridge in areas of concern, as they help predict deterioration before it becomes significant damage to give a more accurate assessment of the bridge condition.

Although there are a variety NDE's that may be effective, using all of them may not be cost-effective and would be very time consuming. Relatively little attention has been given to remote sensing technologies in evaluating bridge conditions. Remote sensing technologies are a subset of non-destructive evaluation that eliminates the need for traffic disruption or total lane closure, as remote sensors do not come in direct contact with the structure. In 2010, Michigan Tech evaluated twelve commercially available remote sensing technologies that could be potentially valuable in assessing bridge condition (GPR, spectra, 3-D optics, electro-optical satellite and airborne imagery, optical interferometry, LiDAR, thermal infrared, acoustics, digital image correlation, radar, interferometric synthetic aperture radar, and Bridge Viewer Remote Camera System, BVRCS, a high resolution "StreetView-style" digital photography) (Ahlborn, 2010). Using a rating methodology developed specifically for assessing the applicability of these remote sensing technologies, each technique was rated for accuracy, commercial availability, cost of measurement, pre-collection preparation, complexity of analysis and interpretation, ease of data collection, stand-off distance, and traffic disruption.

Key findings from the evaluation are that 3-D optics and "StreetView-style" photography have the greatest potential for assessing surface condition of the deck and structural elements, while radar technologies including GPR and higher frequency radar, as well as infrared thermography demonstrate promise for subsurface challenges. Global behavior can likely be best monitored through electro-optical satellite and airborne imagery, optical interferometry, and LiDAR. Remote sensing technologies are very useful in analyzing bridge condition, and could possibly be utilized to analyze big bridges by helping provide more efficient methods to collect data that save time and resources without requiring lane closures. Remote sensing technologies can be utilized to analyze very large structures very quickly. These technologies could provide a more efficient, effective, and safe to analyze large or complex bridges.

1.5.4 Innovative Technologies for Mapping Location and Condition of Distress

3DOBS (the 3D Optical Bridge-evaluation System) is an easily deployable integrated 3D photogrammetric-based system used for rapidly assessing surface condition indicators such as the area, volume, and location of deck spalls and scaling (Dobson et al. 2013; Ahlborn and Brooks, 2015). This work was originally funded by the USDOT Commercial Remote Sensing and Spatial Information Program (CRS&SI) and developed into a faster, dual optical-imaging combination system through Michigan DOT funding (Vaghefi et al., 2013; Ahlborn and Brooks, 2015). The original version of the 3DOBS consisted of a vehicle-mounted digital SLR camera, such as a Nikon 5000, that takes frequent, regularly-spaced pictures with GPS tagging information as the vehicle drives across the bridge (Figure 1.20). A newer version has been developed to use advanced cameras with higher frame rates so that bridge condition data can be collected at near highway speeds (at least 45 mph) while also connected to a thermal imaging system. Overlapping digital imagery enabled creation of very high-resolution 3D models of the bridge deck surface. To assess one standard 12-foot (3.7m) lane width per collected pass, the cameras have been set at a height of 9 feet (2.7m) above the bridge deck to collect overlapping, 36-megapixel images. Photographs collected in the field are processed with close-range photogrammetry software into a high-resolution 3-D model of a lane; multiple lanes are combined into a 3-D model of the bridge deck surface.

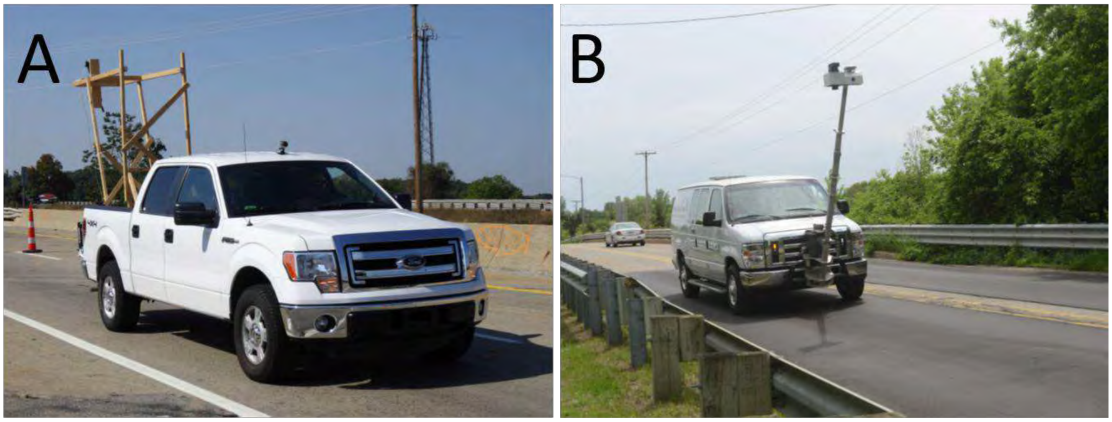


Figure 1.20 - Field testing of the 3DOBS while A. Rigged with custom apparatus, and B. Mounted to the BridgeGuard vehicle mount.

A Digital Elevation Model (DEM) is then created after adding reference points and setting up a coordinate system. An automated spall detection algorithm then locates and details all the spalling on a bridge using the DEM. 3DOBS, as an automated spall detection system, has the capability to be a tool for finding location-specific bridge defects that can be applied to both small and big bridges. This tool has the potential to rapidly analyze large and long bridge decks for complex bridges to create a visualization of all of the defects on the surface.

1.5.5 MDOT's 3DB^{RIDG}E Project

The 3D Wireless Bridge Inspection System (3DB^{RIDG}E) is a mobile application designed to facilitate bridge inspection processes by enabling inspectors to enter element level bridge inspection data using 3G/4G network-enabled tablet devices (Brooks and Ahlborn, 2016) (Figure 1.20). The system collects information from MDOT's bridge management database, and then renders a dynamic, interactive 3D model representative of the desired bridge. The bridge inspector is able to record the locations and attributes of new defects in an element-level form by touch interaction and manipulation of the 3D model. The interactive model, marked up with existing defects, allows for bridge inspectors to better visualize past inspection data. The inspector can also take pictures of the defects and record comments while navigating along the bridge model just as they would during a normal inspection. The application gives users further insight into the progression of defects over time.

The 3DB^{RIDG}E tool is currently funded by MDOT and is under development to improve its functionality (Figure 1.21). This tool was designed to handle inspection of non-complex bridges. However, this tool could be further developed to include inspection of complex bridges. Its main functionality is to assist bridge inspectors by allowing better visualization past inspection data on a 3D model rather than interpreting defect information from forms or text. The visualization of previous defect data could be even more useful for complex bridges as often times what makes a complex bridge complex is its size. Element level data is less effective in assessing a large bridge's condition, as giving a single rating for one abnormally long or big element may not be the best indicator of the condition at some parts of that element. For example, during an inspection of a very long deck, one area of the deck might be in very poor condition, while the rest is in fair condition. A single rating for the deck would be insufficient in cases like this. With the 3DB^{RIDG}E application, an inspector would easily be able to navigate along the bridge while seeing all of the marked up defects instead of either having to inspect the areas themselves (which could be very time consuming) or interpreting past inspection comments. This application could also allow for multiple inspectors to inspect different areas of the bridge at the same time, allowing for a more coordinated inspection.

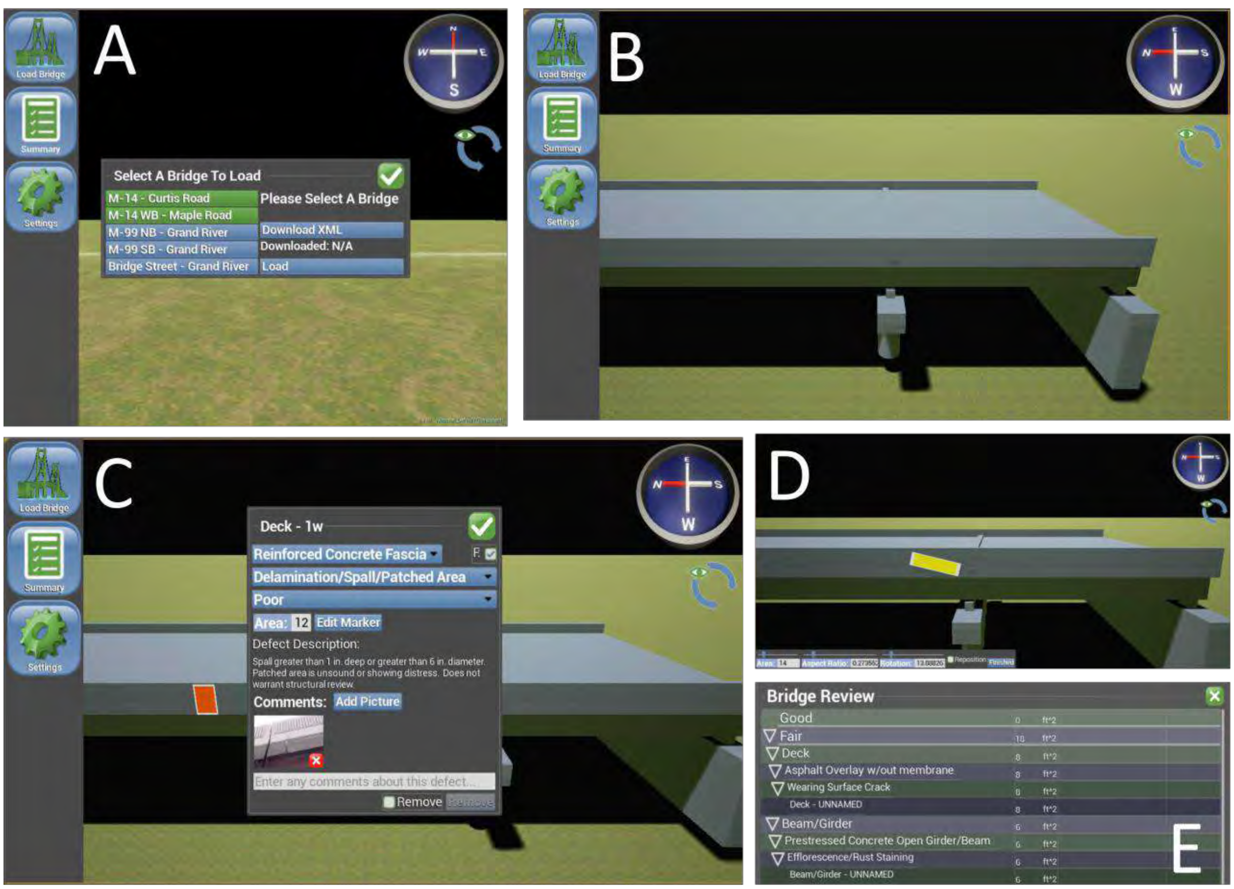


Figure 1.21 - Screens shots from the 3DB^{RIDG}E tool. A. The bridge load menu, B. Loaded bridge showing camera cylinder to move view orbits around and along bridge, C. The defect popup menu, D. The marker editor to position the defect, and E. The bridge summary view.

1.5.6 MDOT's UAV Project

In 2015, MDOT funded a project to evaluate the use of Unmanned Aerial Vehicles (UAVs) for transportation purposes (Brooks et al., 2015). The project evaluated five main UAV platforms with a combination of optical, thermal, and LiDAR sensors to assess critical transportation infrastructure and issues such as bridges, confined spaces, traffic flow, and roadway assets. Advances in unmanned aerial vehicle technology have enabled these tools to become affordable and easier to use. In a budget-limited environment, these flexible remote sensing technologies can help address transportation agency needs in operations, maintenance, and asset management while increasing safety and decreasing cost. One of the UAVs investigated, a hexacopter built by Bergen RC Helicopters, was very effective in creating high-resolution imaging of transportation infrastructure including creating the automated calculation of the locations and volumes of spalls as well as locations of likely delaminations on bridge decks.

UAVs could be very useful when inspecting complex bridges as defect information could be collected rapidly on large deck surfaces or hard to access areas. The report also illustrated that UAVs can help to improve safety. Micro-UAVs were able to send live video from inside two MDOT pump stations, which allowed the agency to inspect the pump stations without the dangers of sending a person into one of these confined spaces. Similarly, UAVs could greatly increase the safety of big bridge inspections. UAV's could increase the safety of inspections of taller and complex bridges that contain elements such as cables, towers, or other difficult areas to inspect. Agencies could remove the dangers of an inspector having to evaluate these difficult areas in person, while also providing a detailed view of the desired element.

1.6 Concluding Remarks

Big bridges, or those with dedicated maintenance and management programs due to size, complexity, or importance, are currently subjected to the same inspection and reporting criteria as non-complex bridges. Current research in the U.S. regarding consideration of big bridges as a series of interactive networks is limited, but a rich history of SHM provides methods likely to be applicable to assessing and monitoring big bridges. European and Asian efforts can also provide lessons learned and guidance, particularly towards SHM in long-span cable structures. Remote sensing tools providing location-specific distress information afford opportunities for application to big bridges.

CHAPTER 2 - REVIEW OF BIG BRIDGE INSPECTION AND MANAGEMENT REPORTS

2.1 Introduction

2.1.1 Element Level Inspection

The introduction of element level condition assessment in the early 1990s represented a significant advancement in the practice of bridge inspection. The original philosophy of the Commonly Recognized (CoRe) Elements, which were first established by the American Association of State Highway and Transportation Officials (AASHTO) during that time, remains the basis for the elements which have been developed over time and are listed in the Manual for Bridge Element Inspection (MBEI) used by inspectors today. As stated in the introduction to the MBEI, “the goal of this manual is to completely capture the condition of bridges in a simple, effective way that can be standardized across the nation while providing the flexibility to be adapted to both large- and small-agency settings” (AASHTO, 2013).

Element level evaluation of bridges assists bridge owners and agencies by providing a more risk-based bridge assessment of their inventory and has proven invaluable for the management of a majority of the structures in the National Bridge Inventory (NBI). By having inspectors quantify the bridge elements and their respective defects with condition state ratings of good, fair, poor, and severe (numbered 1 through 4), bridges can be effectively quantified, evaluated and ranked by their specific conditions, life cycle costs, and vulnerability/risk to help provide more detailed schedules for required repair and replacement of bridge components, such as the replacement of deteriorated deck joints or the deck itself, or cleaning and repainting steel superstructure members. The value of this element level data is supported by the FHWA’s modifications to the National Bridge Investment Analysis System (NBIAS) to use the element data reported by the states in development of the estimates of national bridge needs contained within the 2015 Report to the Congress on the Status of the Nation’s Highways, Bridges, and Transit. These modifications were performed for the purpose of substantially improving the accuracy of the information used by the federal policy-makers in their decision making.

While the methods of element assessment contained in the MBEI have proven to be very effective for risk-based assessment of more typical bridges, there are significant challenges in its implementation for larger bridges. Many owners have established their own unique management systems, some of which already incorporated element level assessment, so it may seem that there is less to gain by compiling the element level data as defined in the MBEI. However, big bridge owners who were not previously utilizing element level assessment stand to benefit disproportionately from the new FHWA requirements to use the MBEI for collecting and reporting of bridge element level data for NHS bridges. When appropriately applied, element level inspection and data collection efforts can be used to better manage large bridges and more accurately forecast future maintenance and capital costs. The use of element level data over the course of repeated annual inspections will lend itself to more accurate prediction of the expected life cycles for each bridge component and ensure the most efficient use of funding by the responsible agency. Maintenance and repairs on large bridges require more time and incur higher costs, therefore, scheduling of component replacements or full-scale maintenance for a big bridge require more careful consideration and should be based on solid data. Maintenance or replacement of a single component, such as a deck replacement on a simple one span structure which may take months, becomes a project that could span years for a big bridge and may require costly traffic disruptions.

2.1.2 Element Categories

There are three types of elements that comprise the elements listed in the MBEI. The first is the National Bridge Elements (NBEs). These elements consist of the primary structural components of a bridge which are crucial to its structural integrity, namely the deck and railings, superstructure, bearings, and substructure components.

The second type of elements is the Bridge Management Elements (BMEs). These elements represent secondary members or components whose deterioration or failure may not directly affect the structural integrity or load carrying capacity of the structure, but may severely affect the longevity of the structure if these elements are not maintained. These elements are typically more frequently rehabilitated or replaced, relative to the NBEs which they protect due to their greater exposure to environmental factors including sunlight, weather and vehicle loads. Their proper management may involve more frequent or specialized inspection and evaluation followed by repairs or replacements in order to provide the desired protection from the elements and vehicular traffic and therefore extend the service life of the critical NBEs which they are associated.

For all NHS bridges, the FHWA requires biennial submission of element condition state summaries for each NBE and the majority of the BMEs, excluding the approach slab elements and concrete reinforcing steel protective system. The use of element level data as a performance measure provides the FHWA with greater accuracy for evaluating the overall health of the nation's bridges as demonstrated by the use this data in the NBIAS calculations for the nation's infrastructure planning.

Several types of BMEs currently defined in AASHTO's MBEI include joints, which in the case of big bridges are often key components of the deck as they accommodate the range of expansion movement required by the lengthy main spans while providing a surface for traffic to traverse between deck sections. Another BME category includes approach slabs, which may be necessary to ensure the smooth transition of vehicular traffic onto the structure. The last category of BMEs includes wearing surfaces, steel and concrete protective coatings, and concrete reinforcing steel protective systems (e.g. epoxy coatings on steel reinforcement or cathodic protection systems). Because of the relatively short lifespans of most BMEs, many big bridges have established regular replacement/rehabilitation schedules for the common protective elements of their bridges (e.g. steel paint protection and wearing surfaces). These are often established through experiential evidence over the lifespan of the bridge and are modified through inspection observations which may prolong or shorten rehabilitation timeframes.

The last element category, Agency Defined Elements (ADEs), as its name suggests, are customizable elements which are developed by the individual state agencies to accommodate their unique needs and structure types. ADEs can include elements that are effectively NBEs but that are not represented specifically in the MBEI or sub-elements of existing NBEs. Many ADEs can also be considered BMEs such as crash protection for substructure elements or deck drainage systems. From big bridge owner survey results, it appears that a majority of the ADEs developed to date have been classified as additional BMEs. However, many agencies have created ADEs which could be considered additional NBEs in order to cover the variety of types of substructure, superstructure, and roadway elements that exist beyond the simplified list that has been defined by AASHTO in their MBEI. In fact, some agencies have maintained or only slightly modified many of the original CoRe elements to represent more specific element types that have been generalized in the current MBEI by simply appending the original CoRe element numbers and listing them as ADEs. Some of these ADEs may also be considered sub-elements of NBEs, which represent critical parts or components of the primary NBE, and are created in order to more accurately capture the condition of the structure in its element level data. One example of this is separating the lower chord of a truss from the main truss NBE. Quantities for these sub-elements are incorporated into the parent elements for national reporting purposes.

Each element is quantified by an assigned unit of measurement; the simplest of which is “each,” used for enumerated elements such as bearings, columns, piles, secondary suspension cables, pins or pin and hanger assemblies, and gusset plates. The second unit for element quantification is length, used for railings, expansion joints, primary suspension cables, and superstructure members such as a girder, truss, arch, or floor beam. Length is also used to quantify substructure units other than simple columns or piles, such as abutments, pier walls, pier caps, as well as height of a built-up or framed tower support such as a trestle or main suspension tower. The last unit for quantification is area, used for decks and slabs, approach slabs, wearing surfaces, concrete and steel protective coatings, and concrete reinforcing steel protective systems.

2.1.3 Defining “Big Bridges”

It is important to define the term “big bridge” as it is used herein. There are many criteria which could be used to make the distinction, such as the overall structure length, the length of the main span, the number of spans, the area of the deck, or the type of structure. For instance, the Missouri Department of Transportation classifies big bridges as any with a total length greater than 1,000 feet. Pennsylvania DOT uses a length of 500 feet to classify big bridges. The New York State Department of Transportation considers any bridge with a deck area greater than 27,000 square feet to be a big bridge. With many of the proposed criteria being purely quantitative, it may be difficult to determine a value that is appropriate for the wide range of bridge sizes to properly categorize big bridges. Using only one or too few quantitative criteria could result in a bridge being considered big or not based on a difference of only several feet of span length, for instance.

The type of structure is the most commonly used criteria for big bridge designation, due to the use of unique or complex elements in big bridges. Coincidentally, these types of structures have already been defined as complex bridges by the state agencies responsible for them, as required by the National Bridge Inspection Standards (NBIS). NBIS defines complex bridges as “movable, suspension, cable stayed, and other bridges with unusual characteristics.” There are a number of other qualities which can be used to designate big bridges, such as bridges that require a full-time management staff and maintenance crew, those that are managed as networks of structures, the collection of tolls for the structure, or geographical location as is the case for structures which cross state or international borders and may be managed by multiple agencies. Since there are so many criteria that can be used to designate a big bridge, it may be prudent to create a list of requirements of which a bridge must only meet one or several to be included. For example, Virginia DOT designates their "special structures" as any with one or more of the following traits: high traffic volume in conjunction with long detour, critical and non-redundant link for communities with significant population, structural complexity, or high maintenance and/or operational demands.

For the purpose of this study, examples of big bridges include suspension bridges, cable stayed bridges, cantilever or continuous truss bridges, arch bridges, and open girder or box girder bridges with long spans or a high number of spans. Movable and floating bridges are excluded from the study.

2.1.4 Implementation of Element Level Inspection

Since the enactment of MAP-21 in 2012, many big and complex bridge owners have had to put forth varying levels of effort in order to comply with the element level reporting requirements. Some owners were already collecting element level data under the CoRe system while others were only performing the required NBI level inspections. For owners using the CoRe system, a conversion of elements from one system to another was only required, sometime aided by translator programs. For those who previously did not perform CoRe element inspections, the determination of elements to be used and the calculation of respective quantities represented a significant effort. To save time on the initial element inspections, it is possible to use pre-existing defect descriptions contained within bridge inspection reports provided that detailed notes exist that accurately locate and quantify defects. The Maryland Transportation Authority (MDTA) successfully performed this conversion in order to provide inspectors with more accurate baseline for their initial element level inspection.

The following sections of this final report will review each of the various types of complex bridges and discuss the details of their inspection and management reports in regards to the NBEs and BMEs which exist and the ADEs which have been created by individual agencies, including other common elements which are not currently represented in AASHTO's MBEI. Unique access methods employed and the methodologies for the inspection and collection of element level data for each of these typical big bridge types will also be presented.

2.2 Suspension Bridges

Suspension bridges usually constitute the longest of the long-span bridge types. The main suspended span deck is supported by vertical suspender ropes which transfer the load to the longitudinally oriented main cables that drape over tall towers and are anchored at each end. There may be adjacent spans similarly supported by main cables and suspender ropes or the backstays may be unloaded. Between the suspender ropes, the floor system is usually longitudinally stiffened by truss members. The approaches to suspension bridges usually consist of multiple spans of various bridge types ranging from truss spans to multi-beam spans.

2.2.1 Suspension Bridge Elements

As indicated in Chapter 1 of this final report, there are currently only three elements listed in the MBEI pertaining to suspension bridge cable systems: Element 147 (Steel Main Cables), Element 148 (Steel Secondary Cables), and Element 149 (Other Secondary Cable). There are numerous other common components which are critical to the structural integrity of a suspension bridge which are not currently represented in the MBEI. Since main cables of a suspension bridge are not typically thought of as replaceable, preventing and maintaining the proper protection against corrosion of the wire strands becomes a critical priority for owners and agencies responsible for such structures. Main cable sub-elements could include the cable bands which fix the secondary suspender ropes to the main cable, as well as the main cable saddles which are located on top of the main towers and at cable bents and any other clamps and/or connections between the cable and the superstructure or towers.

While Element 515 (Steel Protective Coating) usually is considered the appropriate BME for the main cable wrapping and corrosion protection, there are several aspects unique to cable protective systems which likely necessitate the establishment of a separate element for main cable protection systems. For example, wrapping wires which compact the main cable wires are not addressed in the defect language for the main cable element. The wrapping wires could be considered part of the main cable element or as part of a new element for the main cable protection system. Cable wrapping systems may include a waterproof wrapping materials as well which can split and tear, defects not applicable to the steel protective coating element described in the MBEI. The MDTA includes Element 59.27 (Cable Wrapping) in their Facilities Inspection Manual which describes typical cable wrapping configurations, common defects, and a customized rating scale which incorporates specific and typical defects that may be observed.

The additional element could also account for defects pertaining to the cable wrappings required for state of the art dehumidification systems which have been installed on main cables of some suspension bridges, such as the Eastbound and Westbound spans of the Chesapeake Bay Bridge. With the number of aging suspension bridges in the US, these systems may be commonly installed in the future in order to arrest corrosion of the main cable wires to prolong the lifespans of the structures.

Suspension bridge anchorage systems are another area under represented by the current MBEI. Similar to the main cable systems, many of the anchorage components are not typically thought of as replaceable. All suspension bridge inspection reports reviewed had large sections of the report devoted to the condition of the anchorage chambers and the various components contained within. Some specific components identified were eyebars, eyebar pins, strand shoes, splay castings, strand separator structures, strand anchors, deviation saddles and embedment concrete. The accurate representation of these and additional components within the MBEI would help represent these critical components of suspension bridges and aid their owners in the management of these unique structures. Dehumidification systems specific to anchorage chambers are also becoming more prevalent in the preservation efforts of suspension bridge owners. These may be present for the entire anchorage chamber or limited to areas only around the strands and anchors. In the current MBEI no specific elements exist to record the condition of anchorage enclosures, and are usually categorized as Element 210 (Reinforced Concrete Pier Wall). This element uses linear feet measured along the longest plan dimension of the component to record defects that occur anywhere within the 3-dimensional space occupied by the pier. Since anchorage chamber enclosures are usually massive structures that may encompass many levels and/or internal chambers separated by internal walls and floors, the use of the 1-dimensional representation provided by the pier wall element becomes problematic. The Rhode Island Department of Transportation (RIDOT) has created Element 8120 (Anchorage Chamber) and Element 8121 (Anchorage Chamber Interior), quantified as the perimeter of the anchorage chamber exterior and sum of the lengths of all interior anchorage chamber walls, respectively, to account for their concrete anchorage chambers in their element level condition assessment. Self-anchored suspension bridges utilize anchorage elements similar to a cable stayed bridges which will be presented in the following section.

Large steel suspension bridge towers are usually comprised of numerous vertical cells separated by diaphragms at various levels and access through access hatches and internal ladders. Inspection of these towers is often time consuming due to the large numbers of cells which must be climbed while utilizing confined space entry requirements. Steel towers are currently quantified in Element 207 (Steel Tower) as the "sum of the heights of built up or framed tower supports," meaning that an entire tower is quantified by a single linear height. This makes the compilation of defect quantities from numerous cells within the tower legs difficult and can result in an inaccurate representation of the overall condition of the tower. For example, the isolated leakage of water on a single wall of a cell of a tower that has caused minor section loss, would lower the condition state for the entire cross-section of the tower for the affected height, despite all other cells being in good condition. While such generalizations may be desired by the NBIP, the condition state assessment of such elements could be improved for accuracy. The tower legs or even individual cells could be more easily rated individually; doing so would eliminate the necessity to perform the additional step of comparing the defects from many cells to determine the governing defect and condition state for each cross-sectional foot. Additionally, the tower struts between the legs, while a secondary element, can be sizable on a suspension bridge tower and are crucial to the stability of the tower structure. They are currently represented within the single tower height quantity, being horizontal or inclined elements, and could possibly be added to the MBEI as a separate tower sub-element.

There are typically several pin and link systems required to accommodate movement due to live load and thermal expansion of a suspension bridge which connect the stiffening truss to towers, and sometimes the cable to the truss. These link and pin elements can become quite complex and may not be accurately represented by Element 161 (Steel Pin and Pin & Hanger Assembly or both). Also, the term "Pin & Hanger Assembly" is usually associated with fracture

Figure 2.1 - UBIU used to access the floor system and stiffening truss of the main suspension span of the Bear Mountain Bridge.

critical members, a designation that does not typically apply to tower links due to the fact that they are load path redundant and, depending on design, may actually be compression members. Additional elements that were discussed at length in almost all of the reviewed inspection reports include false chord expansion devices, suspender rope sockets and associated connection and wind tongues or other lateral restraint systems.

2.2.2 Suspension Bridge Inspection Methods

Figure 2.2 - View of motorized traveler system used on the Benjamin Franklin Bridge.

Access for inspection and calculation of defect quantities for suspension bridges is relatively simple for the main suspension elements. Main cables are quantified as a length, measured longitudinally along the travel way. A continuous system of hand lines and stanchions are often installed along the length of the cables allowing access to the cables for maintenance or inspection using a standard construction harness and two lanyards for fall protection. A mirror can be used to inspect the underside of the cable, which is the most likely location of potential indicators of interior defects, such as signs of moisture or corrosion staining. The suspender ropes are quantified as each and can be viewed from the main cables, or from the deck where they are anchored, the likely location of section loss where moisture may accumulate. Suspender ropes can be inspected full-length through the use of technical rope access techniques or mechanized bosun's chairs or baskets. Anchorage chambers located on land may be accessed from the ground, maintenance catwalks, or the main cables. Above water portions of anchorage chambers located in water may be accessed through the use of boats, barges with manlifts or bucket boats, and the subaqueous portions can be accessed during diving inspections. Equipment such as underbridge inspection units (UBIUs) may be employed to inspect the suspended span floor system and higher approach spans (see Figure 2.1). Lower approach spans may be more efficiently inspected from ground-based equipment such as a manlift. Many larger suspension bridges, such as the Mackinac Bridge and Mid-Hudson Bridge, have integrated permanent motorized inspection vehicles on rails beneath the main and side spans of their suspension bridges called travelers (see Figure 2.2), eliminating the otherwise costly and hazardous need to close lanes on the structure to accommodate UBIUs. The travelers greatly reduce the time and cost required to access the below deck portion of the stiffening truss for annual inspections and maintenance operations by its staff.

While applicable to all bridges with submerged substructure elements, including the other types which will be presented in this document, underwater inspections of the submerged components are required on a five-year basis by the FHWA. Defects recorded during underwater inspections should be considered in the element data and compilation of defect quantities submitted to the FHWA for elements which may be partially submerged, as well as those elements which are completely submerged. Some agencies, such as the MDTA, have elected to create separate ADEs for underwater elements or portions of underwater elements to distinguish the above and below water defects.

2.2.3 Main Cable Investigations

Due to the importance of the main cable system to the integrity of the structure, special cable investigations are periodically undertaken by the bridge owners in order to ascertain the condition of the cable interior wires. Such inspections are accomplished by removing the cable protective system and wedging open the wires to visually inspect those at the interior. Samples of wires are removed for testing in order to determine their properties. The National Cooperative Highway Research Program (NCHRP) Report 534, Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel Wire Cables, provides direction for performing such inspections. Guidelines for the selection of internal inspection locations are provided; which would first be locations of suspected broken wires or external signs of internal deterioration such as loose cable wrappings or corrosion staining, then low points in the main and side spans, and last at mid-height points in the main and side spans.

Additionally, bridge owners may utilize the passive non-destructive evaluation (NDE) method known as acoustic monitoring. Prior to internal investigations, this structural health monitoring (SHM) system can be used as a risk-based assessment to determine locations of potential wire breaks along the entire length of the main cables. This greatly increases the value of subsequent internal investigations which after all only allow the visual inspection of a very small percentage of the thousands of wires within the cable cross section and at only a few selected points along the total lengths of the cables.

2.3 Cable Stayed Bridges

Cable stayed bridges represent the second longest classification of long span bridge types. The cable stayed bridge is optimal for spans longer than cantilever bridges, and shorter than suspension bridges. They have one or more towers or pylons, from which multiple cables support the bridge deck. There may one or multiple rows of main cables. The cables may continuously pass through the tower and anchor each end at or near deck level, or each cable end may be anchored at the tower and at deck level. The towers or pylons may take on a wide variety of shapes and may be hollow or solid. These bridge types usually have multiple approach spans of various types and materials.

2.3.1 Cable Stayed Bridge Elements

Representing the stay cables, Element 147 (Steel Main Cables) are also a key element to cable stayed bridge inspection and reporting. Each of the main cables is connected directly between the tower and the deck, eliminating the need for secondary suspender ropes and considerable ground-based anchorages. Due to the variations in cable stayed bridge design, various systems of cable anchorages, cable arrangement, and tower configuration are represented in the bridge inventory. Nonetheless, the basic methodology for the inspection of both cable-supported structures remains the same despite substantial differences in accessibility for inspection.

As inspection of the stay cables is more difficult for a cable stayed bridge when compared to a suspension bridge, the accurate quantification of the main cable element defects for a cable stayed bridge presents a challenge. The MBEI currently quantifies main cables as "the sum of all of the lengths of each main cable measured longitudinally along the travel way." Cables near the pier often extend much more vertically compared to their longitudinal length along the travel way resulting in a relatively small quantity which does not accurately represent the element. Additionally, quantification of defects along the length of the cables in the field on these primarily vertically oriented cables becomes more difficult. The inspector must either consider the length of the horizontal component projected from the actual length of the defect, or the quantities must be converted post-inspection, with consideration for the angle at which each cable is oriented to determine the ratio of the horizontal component to the actual length. This issue is much less apparent on suspension bridge main cables, but nonetheless, quantification of the main cable defects would be more accurate for both structures if they were measured along their actual length, as well as more conducive to the inspection. The actual length of stay cables is already a required calculation as it is needed to compute the area of the steel protective coating element on the cables. Again, the steel protective coating element is ill-suited for the protective system used on cable stayed bridges since it generally refers to paint protection. The main cables of cable stayed bridges are usually protected by a rigid sheath (commonly polyethylene or steel) that is filled with a corrosion protection barrier for the cable strands, usually grout. If the sheath is constructed of polyethylene (PE) it is usually coated with a UV resistant, light colored tape to prevent unwanted expansion of the black colored pipe and UV damage. If the sheath is steel, more conventional painting is used to protect the sheath.

There are several specific common sub-components of the stay cables for cable stayed bridges, just as there are for suspension bridges. Due to the potentially long lengths of stay cables, wind induced oscillations are usually a major concern. For this reason, many cable stayed bridges employ damping systems to help reduce or eliminate these concerns and these systems should be included in the MBEI. Dampers may be tuned weights, shock absorbing pistons, cross-ties or even aerodynamic controls. The only one of these damping methods that may be accurately categorized in the MBEI is the cross-ties method which may be recorded as Element 148 (Secondary Steel Cables).

The BME for the cable protection system is the same as that used for a suspension bridge main cable as well as all other steel element coatings, Element 515 (Steel Protective Coating). As was mentioned in the previous section on suspension bridges, a new element could be established which would be specific to stay cable protection systems to account for typical cable defects as well as the unique coatings and other materials which are often used. Additionally, with the increasing number of new stay-cable bridges being constructed, much research has been done on optimal cable surface treatments to reduce the vibrations induced by rain and wind loads on the cables.

Several of the possible new elements which were proposed for cable anchorages of suspension bridges could also be applied to the numerous anchorages required for stay cables. The steel guide pipes and neoprene boots which are located at the stay cable anchorages to protect the cables, dampen vibrations, and prevent intrusion of moisture are also important components and could be considered part of Element 515 (Steel Protective Coating) or developed as new elements quantified as each.

2.3.2 Cable Stayed Bridge Inspection Methods

Figure 2.3 - Inspectors using technical rope access techniques.

Compared to suspension bridge main cables, stay cables are generally too small and steeply inclined to be able to access them by the placement of hand lines and stanchions along their length. This requires the use of technical climbing and rope access techniques (see Figure 2.3) or equipment such as a manlift positioned on the deck capable of reaching the full height of the cables to make the visual inspection required possible. This makes the inspection of cable stayed bridges much more time consuming. Rather than the inspection of the ground-based anchorage chambers of suspension bridges, there are numerous anchorages located along the length of the bridge to inspect which can often be inspected from the deck or with the assistance of UBIUs or pre-installed access travelers or maintenance walkways. Hollow towers for cable stayed bridges are inspected similarly to those for a suspension bridge, sometimes requiring confined space entry and a significant amount of climbing, although cable stayed bridge tower designs can vary greatly in geometry. Tower anchorages are typically accessed from inside the tower.

2.3.3 Main Cable Investigations

Special investigations beyond simple arms-length and visual inspections which are the extent of typical inspections may be performed on the stay cables, similar to those for suspension bridge main cables. Visual inspections of the internal wires are more difficult due to the presence of the sheaths and grouting and higher tension, but there are numerous NDE methods which can be used, including cable tension measurements using accelerometers, magnetic flux leakage testing, ultrasonic testing, and radiography. Similar to suspension bridge cables, acoustic monitoring can also be installed as a passive structural health monitoring system to detect wire breaks in the cables as they occur.

2.4 Truss Bridges

Truss bridges comprise a significant number of long-span bridges in the national bridge inventory. Truss span lengths vary significantly depending on need but usually do not extend beyond a 1000 foot main span length. A wide variety of truss designs and configurations exist from simple short-span pony trusses to extremely complex long-span cantilever trusses.

2.4.1 Truss Bridge Elements

Many elements of steel truss bridges are also used for parts of other types of complex bridge structures discussed as part of this task, such as the stiffening trusses of suspension bridges. The arches of many steel arch bridges are also composed of a truss. For some designs which are a combination of a through-truss and an arch, it can be unclear whether complex bridges of this type should utilize Element 120 (Steel Truss) or Element 141 (Steel Arch). For example, the Sault Ste. Marie International Bridge uses Element 120 (Steel Truss) to quantify its main span truss arches despite the spans being called arch spans throughout the written portions of the formal inspection report.

Quantification of Element 120 (Steel Truss) is defined as the "sum of the lengths of each truss panel measured longitudinally along the travel way," meaning that for each truss line of the structure, the defects in the bottom chord, top chord, verticals, and diagonals, must be projected onto a single length along the travel way. Similar to the issues presented previously pertaining to the defect quantification for suspension bridge towers, this is often conducive to neither the inspection of the truss nor the representation of defects, as locations of defects along the longitudinal length of the truss must be carefully noted by inspectors to ensure that overlapping defects are not counted twice and can be compared to determine the governing defect. This makes compiling the defect quantities post-inspection for the truss element time consuming and requires engineering judgement for defect comparison. The process is further complicated by the use of multiple pass inspection techniques utilizing different access methods, commonly performed by separate inspection teams to efficiently inspect the structures. Furthermore, defects in vertical members are inadequately represented in the element data as their projected longitudinal length is only the width of the member. There are typically numerous defects at the panel points where the vertical members are located which can require much comparison to determine the defect quantities for the truss.

It may be prudent to separate the truss element into elements for each truss member, quantified as the actual length of the member, to provide a more detailed representation of the condition of the truss. Doing so would also alleviate the need to carefully note defect locations along members in order to compare and compile the defect quantities post-inspection. Each of the members must be individually inspected in order to determine the condition state for the truss element as it is currently defined, regardless. For a structure supported by one or two trusses, the tension members are fracture critical, requiring that these members be inspected closely on a biannual basis. Some state DOTs have already created their own ADEs for these purposes. For example, within their own internally developed bridge element inspection manual, MDOT has created Element 824 (Steel Truss or Steel Arch Tension Members), quantified as each, which can better represent the findings from the detailed fracture critical inspections required for these elements. The MDTA has created Element 8121 (Steel Bottom Chord of Through Truss) and Element 8126 (Steel Through Truss, Excluding Bottom Chord) to separate defect quantities for the top and bottom chords for their through trusses.

Another unique element for truss bridges is NBE 162 (Steel Gusset Plate), which is quantified as the "sum of the number of primary load path gusset plate assemblies." As a sort of sub-element of the greater Element 120 (Steel Truss), this element serves to better represent the condition of the gusset plates which hold the individual truss members together, located at each panel point. Gusset plates exhibit a number of typical defects such as missing fasteners and crevice corrosion between the gusset plates and truss members. With such defects often pertaining to both the truss member and the gusset plate equally, it can be unclear whether the defect should be represented as defects in both elements or only one. While there is no element commentary in the MBEI on the subject, in the case of a missing fastener in the gusset plate, it could be assumed that the defect should only be represented with the gusset plate element, as missing fastener defects listed under the truss element could likely only apply to fasteners missing in built-up truss members. However, for crevice corrosion between a gusset plate and truss member, the section loss or deformations for each element should be analyzed and attributed to each appropriately. Details such as this are seldom illustrated in the element defect or commentary text, requiring the common sense or engineering judgement of the inspector to interpret and determine the best practices for element condition assessments.

While they have already been discussed as part of the review of suspension bridge elements, Element 161 (Steel Pin and Pin & Hanger Assembly or both) is present on most cantilever truss main spans. The wind tongues and slotted false chord expansion devices which accompany the pin and hanger locations to restrain lateral movements while allowing expansion of the truss could be added as two new elements to represent these important components in the element level evaluation of such structures.

2.4.2 Truss Bridge Inspection Methods

There is much variation in the access methods used for truss bridges which depends on the types and sizes of the truss spans. A significant portion of the upper and lower chords can be walked with a standard construction harness and lanyards using hand lines which are typically installed along the length of the trusses to allow easy access for maintenance and inspection (see Figure 2.4). In the absence of hand lines, technical sling-protected climbing by wrapping webbing around members can be accomplished with relative ease, and without the requirement of access equipment positioned on the bridge deck. Just as with other structures, elements that are not easily accessed by climbing require an UBIU or manlift to inspect the elements below deck such as the floorbeams and stringers comprising the deck floor system and deck soffit, or members of the through-truss or cantilever truss located above deck.

Figure 2.4 - Inspector using permanent hand lines installed along lower chord of the Newburgh-Beacon Bridge.

As can be used on most steel bridges, many methods of NDE exist which can be used to determine the extent of cracks and section loss in the steel superstructure. Typical methods include dye penetrant testing which can be used to indicate the extent of surface cracks in steel, magnetic particle testing which can also be used to indicate surface as well as shallow subsurface deficiencies, and ultrasonic testing which can be used to easily measure member thicknesses and the depth of cracks in steel and other subsurface defects.

2.5 Arch Bridges

Similar to truss bridges, arch bridges can take on many different forms and lengths. Arch bridges can also be constructed of various materials including masonry, reinforced concrete, steel and a combination of materials.

2.5.1 Arch Bridge Elements

As mentioned in the previous section on truss bridges, many modern steel arch bridges make use of trusses, making distinguishing between the use of Element 120 (Steel Truss) or Element 141 (Steel Arch) difficult. Typical modern steel arch bridge designs include through-arch bridges and tied-arches, such as the second Blue Water Bridge. The components of each type of arch bridge are essentially the same, except the tied-arch bridge is designed to resolve the compression forces in the arches through tension in the deck or tie girder, rather than into the ground at the supports at piers or abutments. These designs make use of tension members, often steel cables similar to the secondary steel cables of suspension bridges (Element 148), to suspend the center portions of the deck below the steel arch such as those used on the Francis Scott Key Bridge in Baltimore.

Similar to Element 120 (Steel Truss), the arch elements are quantified as the "sum of all the lengths of each arch panel measured longitudinally along the travel way." Just as trusses must combine defects for the top chord, bottom chord, verticals, and diagonals, defects at the steel arch diagonals and spandrel columns or walls must be projected into the longitudinal arch length. For large concrete deck arches which may only be comprised of one rib, represented as Element 144 (Reinforced Concrete Arch), the defects for the entire arch rib as well as the spandrel columns or walls must be projected into a single longitudinal length on the arch. This can lead to trivialization of severe defects which may include a widespread area of spalling and exposed reinforcing steel with section loss oriented transversely beneath a leaking deck joint, greatly reducing the capacity of the arch. In comparison, a single isolated spall with exposed corroded reinforcing steel would result in the

Figure 2.5 - Second Blue Water Bridge being inspected with a UBIU.

same condition state rating for that linear segment of the arch despite being largely insignificant in regard to the integrity of the structure. For the same reasons that steel trusses would be separated into individual truss members, it may be desirable to create separate elements for the spandrel columns or walls and steel arch diagonals to better represent and account for the defects in these members, as was expressed by Minnesota DOT in their response to the survey performed as part of this task.

Although not typically a modern design choice in favor of more economical beam/girder spans, many older viaduct structures exist which are comprised of numerous short solid-spandrel arch spans. Quantifying elements and defects for these structures is much simpler than for larger arch structures due to the simple resolution of defects to a single length quantity and the absence of spandrel columns, walls, and diagonals, similar to the more economical choice of girder/beam bridges which are the final specific bridge type in this study.

2.5.2 Arch Bridge Inspection Methods

Inspection access for an arch bridge is similar to that of a truss bridge. Typically much of steel arch bridges can be inspected by walking with the use of handlines or staircases at the steeper ends of the arch such as those on the Second Blue Water Bridge, but UBIU or manlifts on the deck are required to inspect the floor system, soffit, or other inaccessible areas without travelers or other pre-installed systems for access.

2.6 Girder/Beam Bridges

Girder/beam bridges are a unique big bridge type included in this study, as these structures are composed of numerous relatively short simple or continuous spans and do not typically make use of as many complex elements which are crucial components of some of the other big bridge types. However, the overall size of girder and beam bridges is almost limitless. Take, for example, the nearly 24 mile long Lake Pontchartrain Causeway which consists of thousands of short spans. The proper recording and reporting of the elements of this structure alone can significantly influence the state bridge inventory. Since bridges of this type generally use the more well-defined elements commonly used throughout most of the national bridge inventory, they are more suited for analyses using methods employed for smaller bridges; however, due to their overall size, the separation of these very long structures becomes increasingly important to more efficiently manage them with respect to maintenance, repairs and planning.

A separate, more complex type of girder bridge is the segmental concrete bridge. These types of bridges often use precast or cast-in-place box members that may vary in depth and follow either straight alignments or curved alignments. These structure types usually employ post tensioning systems to achieve longer lengths.

Many of the preceding complex bridge types reviewed also employ simple or continuous girder/beam spans with relatively short piers in their approaches.

2.6.1 Girder/Beam Bridge Elements

Quantification of elements and defects during inspection for these structures is simplified by the use of simple and continuous beam/girder spans. Typical NBEs include Element 107 (Steel Girder/Beam), Element 109 (Prestressed Concrete Girder/Beam, Element 102 (Steel Closed Web/Box Girder), and Element 104 (Prestressed Concrete Closed Web/Box Girder). Each element is quantified as the "sum of all the lengths of each girder," making quantification of the elements fairly straightforward in comparison to some complex elements such as main cables which are defined as their longitudinal length along the travel way, instead.

Although spans of this type typically use numerous beams making the spans redundant and non-fracture critical, built-up systems of two girders or widely-spaced floorbeams which may have only limited internal redundancy can be used which makes those members fracture critical and thus requiring hands-on inspection which greatly benefits the detailed element level inspection.

Figure 2.6 - View of Quintana Beach Bridge under construction in Texas.

Segmented concrete box beam bridges are one type of girder/beam bridge for which compilation of defect quantities may be more difficult due to their large size and complex geometries. Concrete box segments are often composed of numerous cells and can be very wide which makes determination of defect quantities difficult due to the need for the precise locating of internal and external defects to prevent defect overlap and the potential amount of comparison required to determine governing defects for a given length of box girder. AASHTO helped addressed these issues in their 2015 Interim Revisions to the MBEI by revising the quantity calculation definition for Elements 104 (Prestressed Concrete Closed Web/Box Girder), 105 (Reinforced Concrete Closed Web/Box Girder), and 106 (Other Closed Web/Box Girder) from "number of girders multiplied by the span length" to "sum of all the length of each box girder section." The number of box girder sections "can be determined by counting the visible web faces, [and] dividing by two," effectively separating the box girder into each of its cells to be rated individually. The post-tensioning strands which are a crucial component of bridges of this type are not currently represented in the MBEI and could be added as a new element. Although the majority of the length of the post-tensioning element is often not visible for inspection, the ends where the rods or strands are anchored are inspected for signs of distress. Post-tensioning systems are also frequently used on other bridge components, especially pier caps, either as a retrofit repair or as an integral part of the original design. These other applications would also benefit from a new element to represent them.

2.6.2 Girder/Beam Bridge Inspection Methods

Since spans of this type are low-lying, manlifts are often used to inspect the land-based spans when the ground below the structure is suitable. For spans situated over water, bucket boats can be used to simultaneously inspect the substructure elements at the water level and the superstructure elements from the bucket in lieu of an UBIU to minimize traffic disruptions.

2.7 Additional Common Elements

There are numerous bridge elements which are not currently represented in the MBEI and are common to many of the complex structures reviewed as part of this task. Several such element categories could be considered BMEs as they are providing protection to NBEs and have been created as ADEs by several agencies to ensure that they are properly inspected and accounted for in the element level data. Others include miscellaneous elements that are common to most structures that have been created as ADEs by their respective agencies and owners, as well. Of course, inclusion of such elements may be more detail than is necessary as these elements may not be critical to the structural integrity of the bridge, but nonetheless, are customarily included in the inspection reports with accompanying detailed lists of defect locations and descriptions just as would be done for any other NBE or BME. Their inclusion in the MBEI could present a more detailed representation of the overall condition of the structure.

2.7.1 Secondary Bracing Members

Secondary elements, such as diaphragms and lateral bracing members could be included in the MBEI. On curved structures, these members are considered primary load bearing members in order to resist the lateral loads but are currently not represented in the MBEI. MDOT has already created an ADE listed in their Michigan Bridge Element Inspection Manual to account for such members; Element 825 (Steel Diaphragm/Cross Frame). Similarly, MDOT has also created ADE 847 (Steel Lateral Bracing) which are to be measured each.

2.7.2 Crash Protection Elements

One element category which could be considered a BME is crash protection elements, such as barriers to deter collisions with substructure elements at roadways beneath the structure, placed riprap surrounding the element, or lower concrete struts between pier columns which doubles as a crash wall to brace the columns against collisions at the water level. Also typically used at water-based piers or towers for the main spans spanning a navigable waterway are a system of dolphins and fenders to deter any possible collisions with the substructure NBEs. The MDTA has created four ADEs to account for such water-based elements: Element 8270 (Timber Dolphin) and Element 8271 (Steel Dolphin), both quantified as each, and 8272 (Steel Fender) and 8274 (Timber Fender), both quantified as linear feet.

2.7.3 Drainage Elements

Another crucial element category which can be found on any bridge are drainage devices, necessary to collect runoff on the deck and direct it downward without draining onto and subsequently deteriorating the superstructure and substructure elements below. Joint drainage troughs could also be included in this category. The MDTA has created ADEs 8307 (Neoprene or Fiberglass Joint Trough), 8308 (Steel Joint Trough), and 8344 (Drainage Devices) to account for such elements. RIDOT has created ADE 8060 (Scupper) to capture the condition of the drainage devices on their structures.

2.7.4 Lighting, Signage, and Other Miscellaneous Elements

There are numerous other miscellaneous elements commonly found on bridges which are not necessary to the structural integrity or protecting other elements, but are components which require inspection and maintenance. Their failure can pose a hazard to pedestrians, vehicular traffic, and marine traffic below, and can also be required for the continued maintenance of the structure. This miscellaneous element category could include appurtenances on the deck, such as signs, overhead sign structures, and light standards which are often mounted to NBEs of the structure, such as floorbeam or cantilever bracket ends or reinforced concrete protrusions from the deck which are subject to crevice corrosion or fatigue at the connections, or spalling, respectively. This category could also include electrical elements such as conduits or conduit trays and their supports which carry power for deck or underbridge lighting, security camera systems, navigational lights at the tops of towers and pier bases which are subject to stringent international conventions and requirements, maintenance lighting within enclosed piers and abutments, or even artistic lighting systems such as necklace lights along suspension bridge cables or spotlights to illuminate the bridge superstructure or substructure elements. Other conduits could carry important communication infrastructure or resources such as water or gas across the bridge. Often, similar to the deck mounted appurtenances, these miscellaneous elements are attached to NBEs of the structure and can be the sole cause of severe defects in the NBE, such as crevice corrosion occurring between the connection plate of the support and the bottom flange of the stringer or floorbeam to which it is fastened.

2.7.5 Access Elements

One important part of any inspection, inherently performed by inspectors, is the inspection of the existing access systems. Access elements could be its own category within the MBEI as they are present on nearly all complex structures, and could include maintenance walkways or catwalks, ladders and ladder cages, staircases, handlines and stanchions, and the rails and the travelers which ride upon them through the stiffening trusses of suspension bridges. Similar to the miscellaneous elements attached to the structure, the access elements often require even larger connection plates to be properly secured and able to support considerable live loads for maintenance operations, and thus are more prone to crevice corrosion between the plates where they are fastened. Closely associated with the access elements, security for these structures which can carry thousands of vehicles simultaneously requires many locked access doors, fences, and other security elements which are often an utmost priority of the bridge maintenance staff and could also be included within the access element category.

2.8 Big Bridge Organization

2.8.1 Division Into Sub-units

Throughout this review of numerous big bridge inspection and management reports, there was an opportunity to compare the formats and methods of organization which are typically used. The most commonly used and obvious method coincides with the practice of dividing large structures into smaller sub-units consisting of the different span types and materials which comprise the structure. Large complex structures often employ large numbers of shorter, low-lying approach spans such as prestressed concrete I-beam spans or steel beam spans; longer and higher approach spans transitioning to the main spans, such as simple deck truss or box girder spans; and the main spans. The MDTA manages several very large and complex structures by dividing the structure into multiple sub-units based on structure type. Each of these structures is then independently inspected and reported on as if it were a stand-alone bridge with separate executive summaries relevant only to that sub-unit, NBI and element data, plan and elevation drawings, etc. The results of all of these inspections are then totaled and summarized in one overall summary report. For example the Eastbound and Westbound Chesapeake Bay Bridges are each divided into nine sub-units (see Figure 2.7); two low-lying approach beam span sub-units, two girder span sub-units, a deck truss sub-unit, a through truss sub-unit, two cantilever deck truss sub-units and a suspension span sub-unit. This method becomes especially useful by clearly separating immense structures to be inspected into parts, with the added benefits of having the opportunity to inspect each sub-unit on an individual schedule, providing flexibility in the management of the structure. However, management of sub-units does require some planning on the bridge owner's part to ensure that elements located at the transitions between sub-units are properly attributed to the adjacent sub-units and inspected, with consideration for all possible structural interactions which may occur between adjacent sub-units.

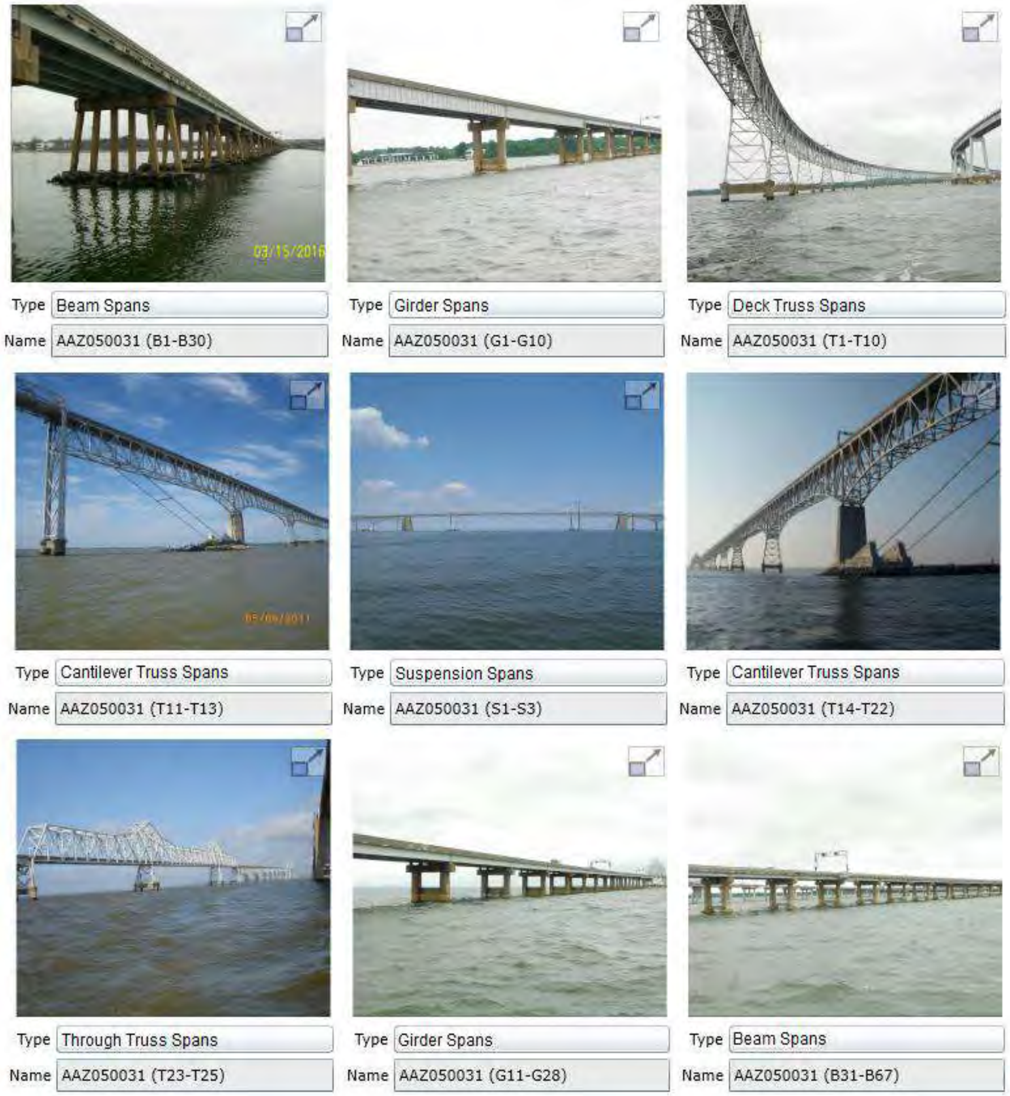


Figure 2.7 - Sub-units of the Eastbound Chesapeake Bay Bridge. *Source: MDTA's ASIR program*.

The second tier for organization of inspection reports is listing the parts of the structure by component, i.e. the substructure, superstructure, and deck. While this is often used as the second tier below the sub-unit organization of varying structural or geographical sections, it can also be interchangeably used as the top tier for organization, with the sub-unit sections each listed under the primary component. This type of organization is often used in order to simplify the inspection reports for structures which may have similarly structured components across sub-units, such as a continuous deck construction, or concrete pier columns and caps which may have little variation despite the varying superstructure elements they support. One example of such a report would be that for the Kingston-Rhinecliff Bridge, which has a uniform exodermic deck and concrete barrier in very good condition with few isolated defects along its 1.48 mile length despite transitioning between 87 ft to 150 ft two-girder approach spans and simply supported and cantilevered deck truss spans up to 800 ft long.

2.8.2 Border Bridges

Several inspection reports for international bridges located over waterways and borders between the United States and Canada and interstate bridges that cross state boundaries were reviewed as part of this task. For many of these international structures, bridge authorities have been created to handle the specific intricacies of dealing with governmental/legislative regulations and requirements of the adjacent governments. Many of the interstate border bridges do not have established authorities to manage these bridges. Instead they often rely on specialized departments within the state DOT to manage these crossings, and may have one or two individuals who manage and coordinate inspection, maintenance and repair planning with their counterparts in the adjacent states. The subdivision of border bridges largely follows the conventions used by other non-border big bridges with respect to the physical makeup of the structure, construction materials and components.

The Blue Water Bridges, which are jointly maintained by both the Michigan Department of Transportation (MDOT) and Blue Water Bridge Canada, the division has the purpose of dividing the inspection findings and recommendations to be delivered to each owner for the individual maintenance operations on their halves of the two bridges. If not separated for the purpose of individual maintenance operations, the international bridges were still found to use geographic naming prefixes. For example, the Sault Ste. Marie International Bridge uses the prefixes American and Canadian to differentiate its symmetrical span configurations, but is maintained entirely by the International Bridge Administration, an entity created within the MDOT. However, operational and policy direction is led by the Sault Ste. Marie Bridge Authority, a partnership between Canada's Federal Bridge Corporation Ltd. and the MDOT. Fortunately, the spans are also numbered sequentially with Span 1 located at the American side and Span 63 located at the Canadian side.

The practice of naming spans or utilizing reversed numbering systems for each approach rather than simply numbering from end-to-end presents minor challenges in regards to the element level assessment of big bridges, as the calculation and management of the inspection data for the numerous spans may require some extraneous programming for conventional spreadsheet processing or other data management systems. The issue could also be remedied by renumbering the spans, but would require modification of pre-existing bridge drawings and other documents.

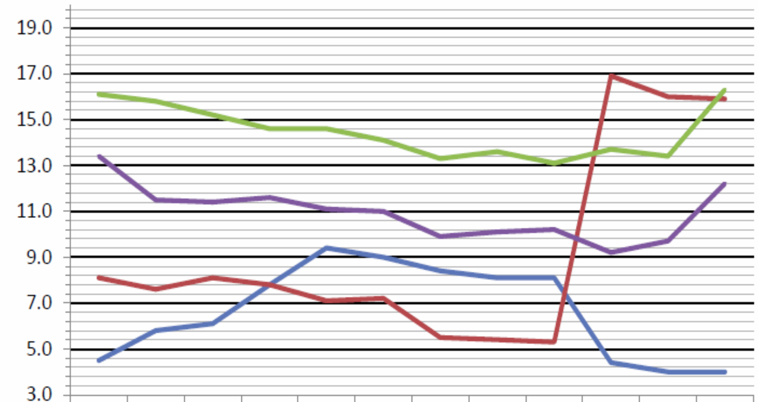
2.9 Big Bridge Management Strategies

The management of bridges becomes increasingly more complex as the size and complexity of the bridge increases. When multiple bridge types and materials are used the interactions between these components also become more complex from an engineering standpoint, and when the structure crosses jurisdictional or even international boundaries the regulatory, fiscal and legislative intricacies add to the management difficulties. For these and many other reasons, many big bridges have established their own authorities or specific management groups to look after big bridges. Several management reports for complex bridges were reviewed as part of this task in addition to the inspection reports for the structures. These documents included transportation asset management plans, long-term and short-term rehabilitation/replacement schedules, future needs reports, historical repair cost reports, capital improvement plans, etc. As element level data is still in development for most agencies and state DOTs, there are very few agencies making using of the MBEI data to estimate expected life spans of components at this time. However, many respondents to the survey performed as part of this task indicated that they will be using the data for risk-based analysis, deterioration modeling, identifying costs, and scheduling structure maintenance. The collected element level data from the periodic inspections of the bridge components may be indispensable in determining the expected life spans of the components. Analysis and extrapolation of the collected data can reveal the rates at which each element is deteriorating and serve as part of the life cycle cost analysis and risk-based assessment required to efficiently manage and preserve these structures.

2.9.1 Big Bridge Performance Measures

Performance measures which have been historically used for bridges are based on the NBI ratings for the major components of the structure; namely the deck, superstructure, substructure, and culverts. The components are each rated on a scale from 0 to 9, with 0 indicating a failed condition and 9 representing excellent condition, and are assigned based on the overall condition of the component. Any bridge with any of the major components rated 4 (poor condition) or below is considered to be structurally deficient, indicating a significant defect which often requires speed or weight limits be placed on the bridge to ensure safety.

Recent changes to the FHWA MAP-21 performance thresholds limit the amount of deck area allowed on structurally deficient NHS bridges to less than 10% of total deck area. When considering the very large deck areas associated with big bridges, this policy change can have a significant impact on the statewide inventory of bridges. Prior to the enactment of these regulations, the Louisiana Department of Transportation and Development (LADOTD) recognized the potential impact that individual bridges having very large deck areas could have on the state bridge inventory. LADOTD has 118 bridges with deck areas over 175,000 square feet. These bridges constitute only 1.5% of their total inventory of bridges but account for over 47% of total deck area in the state inventory. Because current measures indicate that the entire deck area for a structurally deficient bridge be reported for the deficient bridge, when one of these 118 very large deck area bridges becomes structurally deficient, it has an immediate and noticeable negative impact on the performance target. For example, in 2011 Louisiana had 5.3% of their State NHS bridges considered structurally deficient based on deck area, and in 2012, this percentage increased to 16.9% due to one of these very large deck area bridges becoming structurally deficient (see Figure 2.8).



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Interstate	4.5	5.8	6.1	7.8	9.4	9.0	8.4	8.1	8.1	4.4	4.0	4.0
State NHS	8.1	7.6	8.1	7.8	7.1	7.2	5.5	5.4	5.3	16.9	16.0	15.9
SHS	16.1	15.8	15.2	14.6	14.6	14.1	13.3	13.6	13.1	13.7	13.4	16.3
RHS	13.4	11.5	11.4	11.6	11.1	11.0	9.9	10.1	10.2	9.2	9.7	12.2

Figure 2.8 - LADOTD percentage of structurally deficient bridges by deck area for various bridge categories. *Source: LADOTD Initial Transportation Asset Management Plan (Pilot Version February 2015)*

Another performance measure that, in the past, has been used to represent the overall condition of a bridge is the sufficiency rating. Sufficiency rating was the numerical performance measure ranging from 0% to 100% developed by the FHWA which was calculated based on the NBI data collected for each structure to obtain a value indicative of the bridge's sufficiency to remain in service. 55% of the sufficiency rating is based on the structural adequacy and safety, 30% is based on the serviceability and functional obsolescence, and 15% is based on the essentiality for public use, with special reductions for detour lengths, traffic safety features, and structure type. This now discontinued measure of overall bridge condition relied heavily on the global ratings for the major bridge components and likely would not accurately represent the true condition of a very large bridge.

Even when the size of the bridge is factored into performance measures used to determine rehabilitation or replacement needs, it is often advantageous to adjust the guidelines for big bridges. Many states and authorities have adopted percentage based criteria for various major bridge preservation activities (see Figure 2.9). These criteria view the bridge in its entirety, so, for big bridges, very large areas must be in fair or poor condition to trigger rehabilitation. While typical bridges such as highway overpasses may benefit from a value such as 10% of deck area being structurally deficient or in condition states 3 or 4 to constitute the need for rehabilitation, a bridge such as the Lake Pontchartrain Causeway would require nearly 500,000 square feet of deteriorated deck to meet the same metric. For this reason, and because structures of this size are often critical non-redundant links in the transportation system with high traffic, viewing a big bridge as a network of smaller bridge units may allow more timely repairs due condition state thresholds to trigger rehabilitation.

Steel elements	More than 15% in Condition State 3 or 4
Steel protective coatings	More than 20% in Condition State 3 or 4
Reinforced concrete elements	More than 10% in Condition State 3 or 4
Prestressed concrete elements	More than 10% in Condition State 3 or 4
Timber elements	More than 10% in Condition State 3 or 4
Concrete deck or slab elements	More than 15% in Condition State 3 or 4
Wearing surface elements	More than 15% in Condition State 3 or 4
Joint elements	More than 10% in Condition State 3 or 4
Bearing elements	More than 10% in Condition State 3 or 4

Figure 2.9 - MnDOT's major rehabilitation condition criteria. *Source: BRIDGE OFFICE MINNESOTA DEPARTMENT OF TRANSPORTATION Fiscal Year 2016 through 2020 Bridge Preservation and Improvement Guidelines*

2.9.2 Coordination of Element Rehabilitation

Despite the many factors which can affect the rates of deterioration for each element, an approximate time frame for applying preservation activities or scheduled replacements can be estimated using deterioration models. With the use of element level data, deterioration models can become more accurate and targeted to specific parts of the bridge when compared to the use of the major components of the NBIS. These models are then continually refined and adjusted based on regularly collected inspection data and the effects of preservation activities. Another major aspect needed for accurate deterioration modelling, which current element level inspection requirements are not collecting, is environmental conditions which the element is exposed. Routine maintenance procedures such as washing the structure and joints, sealing cracks and patching spalls, and cleaning and spot painting the steel superstructure elements help to reduce the effects of these environmental factors and generally prolong the life of the bridge. Since many big bridge owners are currently not generating deterioration models for their bridges, they often rely on historical information, close monitoring and detailed information from routine inspection reports to predict timelines for preservation, major rehabilitation or replacement of bridge elements. Again, these timelines are often adjusted based on regular inspection data and routine maintenance activities.

For instance, the New York State Bridge Authority (NYSBA) provides approximate time frames for rehabilitation of components. Estimates include that a deck replacement is required every 35-40 years, cleaning and repainting of superstructure steel is required every 15-20 years, replacement of joints and wearing surfaces is required every 12-15 years, routine maintenance of substructure elements is required approximately every 5 years, and suspender rope replacement is required every 80-100 years.

The Mackinac Bridge Authority (MBA) uses a similar method for determining time frames for repairs, listing the life expectancy of the bituminous wearing surface at 12 years and cleaning and repainting the superstructure elements approximately every 35 years, which is currently being performed. The MBA plans to replace the deck and floor system of their suspension spans in approximately 10 years, noting that the components are in good condition despite the historical average expected life of suspended span decks being approximately 50 years.

With the use of enhanced deterioration modelling provided by the more detailed element level inspection data, many of these timeframes may more accurately be predicted, and long term cost planning be adjusted.

2.9.3 Deck Replacements

Figure 2.10 - Repair patches in the deck of the North Newburgh-Beacon Bridge.

One particular interest of this study is the efficient scheduling of deck replacements on big bridges. There are many factors which must be considered in order to determine the appropriate life cycle of a bridge deck. The varying types of deck constructions and the rate at which they deteriorate due to climate and live loads are primary factors. The quality of the isolated and sometimes widespread deck patches and repairs required to extend the service life of the deck and ensure the safety of motorists is another important factor which must be considered in the life cycle analysis. For decks with a numerous areas of full-depth repairs which commonly differ from the original deck construction, it may be prudent to quantify and rate the repaired areas separately with defects applicable to the repair type. This would better represent the conditions and defects of the repaired areas and assist in determining the feasibility of continued deck repairs in lieu of full deck replacements, or vice versa. The element level condition state data resulting from repeated inspections can be used to model the deterioration and perform a risk analysis, allowing the appropriate life cycle cost for the deck and an appropriate strategy for repair or replacement of the deck to be determined.

With the use of detailed element level inspection data and the subdivision of big bridges into smaller, more manageable units, major rehabilitation or replacement efforts may be targeted to specific portions of the bridge identified as having localized deficiencies.

2.9.4 Importance of Formal Inspection Reports

There are a number of reasons why the written portions of formal bridge inspection reports are required to supplement the element level data, and even more so for the more important large and complex bridges which are the focus of this study. The total element quantity and condition state summaries which are submitted to the FHWA do not indicate the proximity of related defects. Isolated minor defects which would be a non-issue could in actuality be defects at the same location, such as the common deterioration of elements located beneath a leaking joint, which is not apparent in the total condition state summary for the elements and makes the defects considerably more serious. For example, Sault Ste. Marie International Bridge exhibits isolated areas of deterioration beneath leaking joints resulting in Condition State 3 and 4 corrosion of stringers, floorbeams, and stringer bearings. However, only the element condition state summaries for each element which were submitted to the FHWA for the entire structure are provided in the inspection report, preventing a detailed analysis of the deterioration occurring at these locations.

BCZ472001(S17-S19) - Bridge - Biennial - Final Show details

Info | Inspection | Repairs | Photos | Inspection documents | Audits | Routings | Summaries | Reviews | Warnings | Element level data

Display mode ○ *Percentage ⦿ Quantity — Filter: Not filtered

Number	Name	Unit	Quantity	*QuantityCalculated	*Percentage	CS 1	CS 2	CS 3	CS 4
515	BCZ472001(S17-S19) > Steel Gusset Plate (EA) > Steel Protective Coating (SF)		53342	53342	100	53250	4	83	5
330	BCZ472001(S17-S19) > Steel Bridge Rail (LF)		2880	2880	100	1920	960	0	0
515	BCZ472001(S17-S19) > Steel Bridge Rail (LF) > Steel Protective Coating (SF)		24570	24570	100	17199	0	7371	0
305	BCZ472001(S17-S19) > Assembly without Seal (LF)		122	122	100	122	0	0	0
313	BCZ472001(S17-S19) > Fixed (EA)		2	2	100	2	0	0	0
515	BCZ472001(S17-S19) > Fixed (EA) > Steel Protective Coating (SF)		410	410	100	410	0	0	0
148	BCZ472001(S17-S19) > Steel Cable-Secondary (EA)		66	66	100	65	1	0	0
515	BCZ472001(S17-S19) > Steel Cable-Secondary (EA) > Steel Protective Coating (SF)		2926	2926	100	2864	62	0	0
161	BCZ472001(S17-S19) > Steel Pin, Pin and Hanger Assembly, or Both (EA)		132	132	100	122	10	0	0
515	BCZ472001(S17-S19) > Steel Pin, Pin and Hanger Assembly, or Both (EA) > Steel Protective Coating (SF)		290	290	100	279	1	10	0
8307	BCZ472001(S17-S19) > Neoprene or Fiberglass Joint Trough (LF)		61	61	100	61	0	0	0
210	BCZ472001(S17-S19) > Reinforced Concrete Pier Wall (LF)		53	53	100	53	0	0	0
234	BCZ472001(S17-S19) > Reinforced Concrete Pier Cap (LF)		76	76	100	73	0	3	0
12	Span 17 > Reinforced Concrete Deck (SF)	SF • Square foot	44040	44040	100	42954		1086	
331	Span 17 > Reinforced Concrete Bridge Rail (LF)	LF • linear foot	2160	2160	100	2010	150		
8070	Span 17 > Reinforced Concrete Median (LF)	LF • linear foot	720	720	100	714	6		
302	Span 17 > Compression (LF)	LF • linear foot	367	367	100			367	
311	Span 17 > Movable (roller, sliding, etc.) (EA)	EA • Each	4	4	100		4		
515	Span 17 > Movable (roller, sliding, etc.) (EA) > Steel Protective Coating (SF)	SF • Square foot	880	880	100	440	440		
205	Span 17 > Reinforced Concrete Column (EA)	EA • Each	4	4	100			4	
8271	Span 17 > Steel Dolphin (EA)	EA • Each	2	2	100	2			
8274	Span 17 > Timber Fender (LF)	LF • linear foot	353	353	100	353			
113	Span 17 > Steel Stringer (LF)	LF • linear foot	6485	6485	100	6476		9	
515	Span 17 > Steel Stringer (LF) > Steel Protective Coating (SF)	SF • Square foot	36429	36429	100	36428	0	0	1
152	Span 17 > Steel Floor Beam (LF)	LF • linear foot	1585	1585	100	1532	49	4	

Figure 2.11 – Element Level Data for Francis Scott Key Bridge as it appears in MDTA's ASIR program. Note summaries for main span sub-unit (S17-S19) at top and summaries for Span 17 below.

Several agencies, such as the MDTA and NYSDOT, are combating this issue by requiring that element level quantity and condition state data be separated by span or panel for each structure, in addition to the summaries provided for each span as well as the individual sub-units of the structure (see Figure 2.11). This method greatly increases the utility of the element condition state data by providing defect locations and allowing detailed analysis of specific locations.

For the 18,000 fracture critical structures located throughout the United States, only one defect in a tension member could potentially cause a structural failure. Considering only the element level data, this could be one isolated Condition State 3 defect among the thousands of other linear feet recorded for the element which is propagating at an accelerated rate. The defect could be overlooked when considering only the element level data if not for being assessed by a professional engineer and prioritized as one of the few immediate repairs required in the inspection report. The repair could be as simple as sealing or replacing a leaking drain pipe which was accelerating corrosion on the web and bottom flange of a fracture critical floorbeam and subsequently spot cleaning and painting the steel. For vital big bridges, properly priority-coded repair recommendations become essential to the owners to ensure that the most severe defects are repaired first, whereas, for management of numerous small bridges, the question of the responsible agencies becomes which bridge to repair first.

2.9.5 Technological Advances

Advances in construction techniques and development of materials for complex bridges affect the costs of future rehabilitations or upgrades, an important consideration in bridge management. The use of precast and prestressed concrete elements greatly increased the speed at which rehabilitations can occur, as was recently seen in the deck replacement of the south span of the Newburgh-Beacon Bridge using precast grid reinforced concrete panels. While the cost may have increased for producing and transporting these elements, the time required for installation using innovative construction sequences decreased dramatically, negating the needs for costly traffic disruptions.

New technology can greatly reduce inspection time, as well. Portable tablet computers are utilized by many consultants and inspection agencies which can alleviate the need to transfer inspection data from handwritten notes by having the word processor in the field. This method is also more secure than traditional note taking on paper as inspection data can be automatically backed up and is immediately viewable by all members of the inspection team when using collaborative software. Bridge management software can also be installed on the portable devices allowing existing inspection data in the system to be reviewed and new data to be entered in the field.

2.9.6 Management Software

With the large amount of data resulting from element level inspections, agencies require software to manage and analyze the data. A majority of respondents to the survey performed as part of this task indicated that they currently use software packages such as AASHTOWare Bridge Management (BrM) or Bentley InspectTech. Others use customized software or spreadsheets which were developed in-house to manage the data, such as MDTA's Authority Structures Inspection and Repair (ASIR), MDOT's MiBRIDGE, PennDOT's BMS2 and iForms, NYSDOT's Bridge Data Information System (BDIS), and Wisconsin DOT's Wisconsin Structure Asset Management System (WISAM).

Most of these software packages perform similar functions. They record and store bridge inventory and inspection data to assist bridge owners in tracking the condition of their bridges, selecting appropriate repair or maintenance activities, and achieving performance goals. Some packages also provide various levels of bridge analysis; however, most big bridge owners have developed specialized analysis tools and spreadsheets to capture the unique characteristics of their specific bridges. Most bridge management software packages are web-based databases, allowing them to be accessed virtually anywhere.

2.10 Big Bridge Owner Survey Results Summary

As part of this study a nationwide survey was conducted in which responses to questions pertaining to the element level analysis of big bridges were solicited from numerous big bridge owners and state DOTs across the country. Responses were received from 22 state DOTs and 4 organizations which manage big bridges.

2.10.1 Summary of Responses

Respondents were asked what features should be used classify a structure as a big bridge. A majority of respondents listed numerous criteria, but the most common responses were structure type, deck area, and overall or main span length. See Figure 2.12 for a graph of the results. Specified 'other' criteria included superstructure height, bridges crossing a border, those with separate funding, and movable bridges.

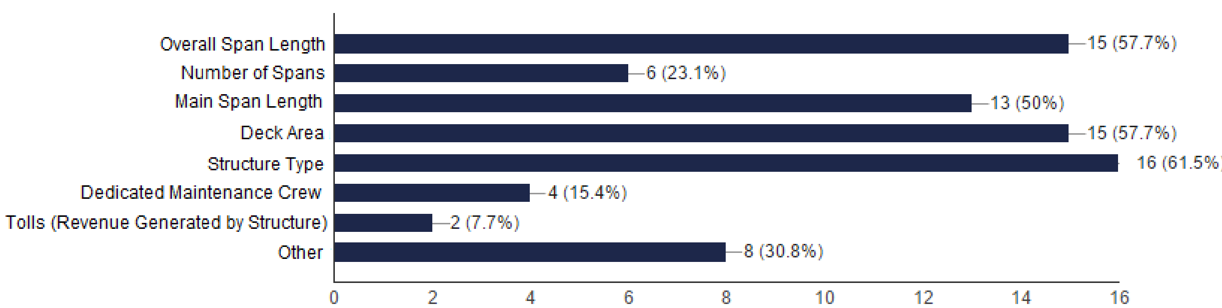


Figure 2.12 - What features do you think classify a structure as a Big Bridge?

Respondents were asked whether element level inspections of their big bridges are currently being performed; all answered yes or responded that element level inspections are to be started within the near future or during the next inspection. Another question went on to ask what challenges the respondents are facing in collecting the data; a variety of responses were received, including the additional time and expenses required to collect the data, lack of a comprehensive list of elements in the MBEI, means to electronically document the location, quantity, and type of defects, learning curve of the inspection team, and the practicality of or justification for collection of the data. A minority of respondents reported that they faced no issues or have been collecting element level inspection data for a number of years, several since the CoRe elements were introduced in the mid 1990's.

The survey asked how element level data will be collected in the field and what software will be used if collected electronically. Approximately half of respondents indicated that data will be recorded on paper forms with the remainder using tablets or computers or a combination of paper forms in field and electronic data entry post-inspection. Half of the respondents did not indicate what software will be used; the majority of respondents are using AASHTOWare Bridge Management (BrM) or Bentley InspectTech software packages and several are using applications developed in-house such as MDOT's MiBRIDGE, MDTA's Authority Structures Inspection and Repair (ASIR) database software, and PennDOT's iForms. Respondents were also asked if they currently use any software or customized spreadsheets to manage their big bridges. Nearly all of the 26 respondents indicated that they do or will use software packages, spreadsheets, other customized tools, or a combination for management of their big bridges. Respondents were then asked for what purposes do they use their management software, spreadsheets, or customized tools. See Figure 2.13 for a graph of the results. Common responses included inventory and inspection data management, deterioration modeling, repair tracking, and repair/rehabilitation planning or prioritization.

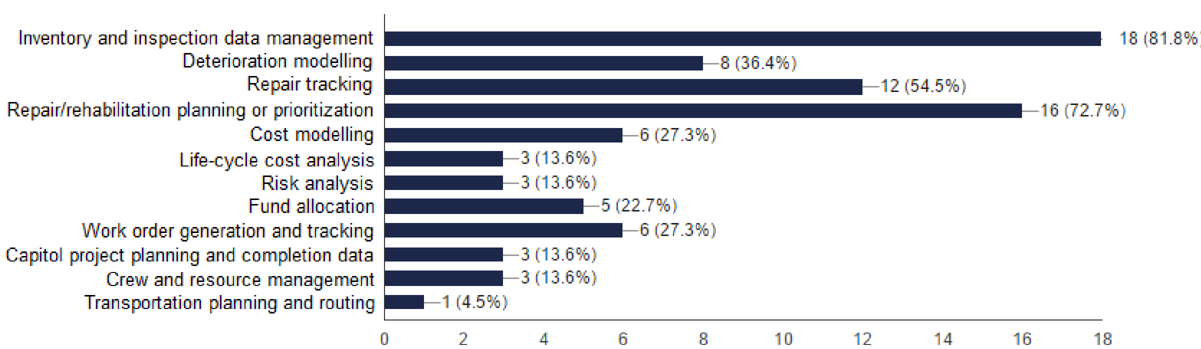


Figure 2.13 - For what uses do you use your management software or spreadsheets?

Respondents were asked whether the current list of NBEs and BMEs sufficiently represent their big bridges. See Figure 2.14 for a graph of the results. Another question asked what elements/details the respondents feel are lacking from the current list of element level information being collected; responses included primary truss members, secondary bracing members such as diaphragms and those for trusses, backwalls and other specific abutment related items, elements for components which are combinations of different elements, more elements for specific material and member types, cathodic protection systems, and movable bridge elements.

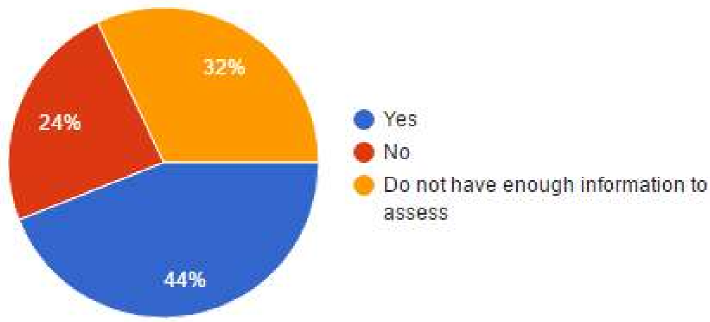


Figure 2.14 - Do you feel that the current list of NBEs and BMEs sufficiently represent you Big Bridge(s)?

The survey asked whether any ADEs had been developed by their organization to better record details of big bridges. See Figure 2.15 for a graph of the results. Respondents were then asked for examples of ADEs which were developed; examples included specific joint types, bearing pedestals, secondary members, beam ends, retaining walls, wingwalls, anchorage chambers, separate elements for deck soffit and fascia, sidewalks and curbs, post tensioning members, and movable bridge elements.

Figure 2.15 - Have any ADEs been developed by your organization?

Respondents were asked if they are currently using or plan on using collected element level data for analysis, planning, or management of their big bridges. Over 90% replied that they will use the data, that it was not applicable, or that they do not have enough information to assess. Of the few that replied that they will not use the data, it was expressed that they believe that the effort required to collect the element level data is not justified for big bridges and prefer to use written inspection reports or other inspection data in customized spreadsheets for management of big bridges. Those that said they will use the element level data listed maintenance planning, performance tracking, deterioration forecasting, and calculating cost-benefit ratios for prioritizing bridge replacement/rehabilitation projects as the primary uses.

Respondents were asked if they routinely divide their big bridges into sections for the purposes of better management of inspections and maintenance work and what criteria they use, if so. See Figure 2.16 for a graph of the results. 46% of the 26 respondents replied that they do not divide big bridges or that the question was not applicable as they do not consider any of their structures big bridges. Of the 54% which divide their big bridges, the most common criteria were structure and construction material type, followed by length/spans, and last geographic/municipal border or ownership.

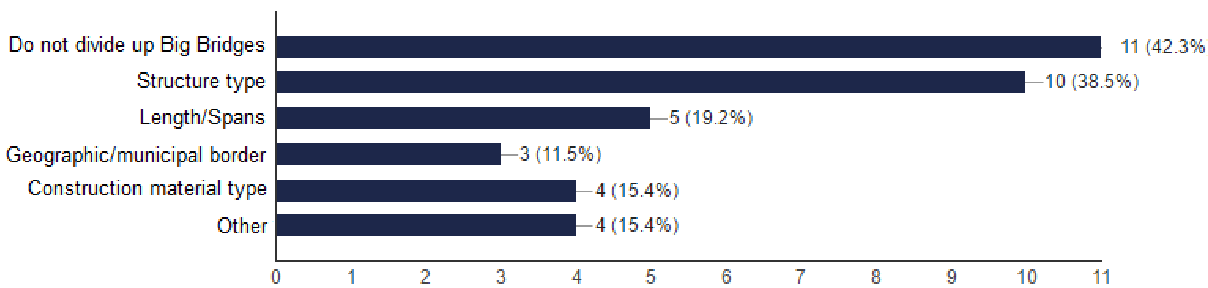


Figure 2.16 - What criteria do you use to divide your Big Bridge(s) into smaller units?

At the end of the survey, respondents were asked if they had any additional comments or concerns with respect to element level inspection data (i.e. data collection, use of the data for management purposes, other shortcomings, etc.). One respondent noted that consistency of data from various inspection teams over the years is important to result in accurate analysis. A few respondents commented that that the data is not practical for use in managing big bridges and modeling for big bridges is limited in accuracy and will only be marginally useful; therefore there is a lack of justification for the effort. One respondent who indicated that their organization has been collecting element level inspection data since 1995 commented that they would like more flexibility by being permitted to modify the condition state language for some defect elements in the MBEI and would rather have five condition states instead of four.

2.11 Chapter Summary

AASHTO's MBEI serves as an indispensable tool in the risk-based assessment required to effectively manage the multitudes of various sized structures comprising our transportation network. However, as expressed at the end of its introduction, "This manual not intended to supplant proper bridge and element inspection training or the exercise of engineering judgment by the inspector or professional engineer" (AASHTO, 2013). The MBEI is useful for the overall quantitative analysis of numerous bridges, but it is not possible to express all the unique and complicated defects through the condition rating based assessment. The simplified total defect quantities do not indicate proximity of defects, so a number of relatively minor defects which would be a non-issue if spaced far apart, could in reality be located at the same isolated area, making the defect considerably more serious.

With the current element quantity calculation definitions in AASHTO's MBEI, the typical details used to describe defects in inspection reports are often not sufficient to immediately convert to defect quantities. Furthermore, the element quantities are often not conducive to the inspection methods which are used, lending much importance to the proper preparation and developing efficient methods required for the initial inspections when defect quantities are to be established.

Throughout the world, increasing numbers of unique and complex structures are being designed and built which are combinations of many of the complex bridge components which were considered as part of this task. This further necessitates that the element level assessment of such structures be understood by the agencies, owners, and inspectors involved so that the proper quantification and condition assessment of the complex elements is performed in a standardized manner. This would ensure that the defect data properly represents the condition of the structures for their risk-based assessment, whether to compare the increasing number of complex structures, or for the assessment of the multitudes of complex elements for a single bridge; such as the hundreds of stay cables required for some cable stayed bridge designs.

CHAPTER 3 - REVIEW BIG BRIDGE MANAGEMENT METHODOLOGY

3.1 Background

Big Bridges require the same types of bridge management capabilities as all other bridges, but also may have some unique requirements of their own. Bridge owners typically include all of their big bridges within their bridge management systems (BMS), to the extent that such systems are in operation. Relevant BMS capabilities include (Markow and Hyman 2009):

- Inventory and inspection data management and process management
- Calculation of performance measures
- Deterioration and action effectiveness models
- Cost models
- Life cycle cost analysis
- Risk analysis
- Prioritization and program development
- Funding allocation
- Development of performance targets
- Various administrative reporting requirements, such as NBI reporting

In addition, a few agencies have added functionality to their bridge management systems to address certain workflow functions including:

- Work order generation and tracking
- Capital project planning and completion data
- Crew and resource management

In the USA and 18 other countries, most owners of big bridges maintain bridge management systems for all of their bridges, providing at least basic inventory and inspection capabilities (Mirzaei et al. 2014). Until recently at least half of the states were also using BMS analytical functionality for decision support, usually by means of the AASHTO Pontis bridge management system (FHWA 2010).

Proposed federal regulations in 23 CFR 515.007 require all states to implement bridge management systems having decision support capability (FHWA 2015):

> *(b) Each State DOT shall use bridge and pavement management systems to analyze the condition of Interstate highway pavements, non-Interstate NHS*

pavements, and NHS bridges in accordance with 23 U.S.C. 150(c)(3)(A)(i), for the purpose of developing and implementing the asset management plan required under this part. These bridge and pavement management systems shall include, at a minimum, formal procedures for:

(1) Collecting, processing, storing, and updating inventory and condition data for all NHS bridge and pavement assets;

(2) Forecasting deterioration for all NHS bridge and pavement assets;

(3) Determining the life-cycle benefit/cost analysis of alternative strategies (including a no action decision) for managing the condition of all NHS bridge and pavement assets;

(4) Identifying short- and long-term budget needs for managing the condition of all NHS bridge and pavement assets;

(5) Determining the optimal strategies for identifying potential projects for managing pavements and bridges; and

(6) Recommending programs and implementation schedules to manage the condition of all Interstate highway pavements, non-Interstate NHS highway pavements, and NHS bridge assets within policy and budget constraints.

Currently AASHTO is in the process of developing a successor to Pontis, called AASHTOWare Bridge Management software (BrM), which will have all of these capabilities. Most of the states have begun collecting data that is compatible with BrM but not with Pontis (FHWA 2014). AASHTO plans to release a completed version of BrM within the next year. In the telephone interviews conducted under the present task, it was found that most of the state DOTs contacted are planning to implement BrM, but some are considering the development of their own databases and software tools for some or all of the 23 CFR 515.007 requirements and related functionality. Many states have not yet decided how they will implement the requirements. Section 3.3 discussed BMS implementation in more detail.

Pontis and BrM, like most bridge management systems around the world, are designed to fit the needs of large agencies owning thousands of bridges. The requirements for these systems include very limited data collection, very quick analysis, and strength in network level information. BrM is adding a substantial amount of bridge-level and project-level functionality, but is still designed for large inventories of mostly small bridges.

Owners of large bridges generally find that they still must manage their inventory and inspection data in their enterprise BMS because of the need to satisfy a variety of administrative requirements such as NBI reporting. They work around the limitations of their systems to provide the additional information that big bridges require. For example:

- Agencies using Pontis and AASHTOWare Bridge Management have developed custom elements specific to Big Bridges, or have adopted inspection and data management procedures that better accommodate big bridge needs. For example, Florida DOT has a comprehensive set of special elements for the mechanical, hydraulic, and electrical features of movable bridges, as well as elements for fenders, dolphins, pile jackets, navigation lights, expansion joints, and appurtenances often found on larger structures. Washington State DOT has special elements for floating concrete pontoons, which support that state's largest bridges. New York, Pennsylvania, and Texas inspect all of their bridges span-by-span, and a few additional states inspect their big bridges by individual span or groups of spans.
- NCHRP Report 590 showed that all of the analysis functions of a bridge management system, at the bridge level and network level, can be provided in spreadsheet models. Michigan, Minnesota, Florida, and Quebec use spreadsheets as a significant component of their BMS. For big bridges, an advantage of this approach is the ability to easily customize the models. For example, newer and older parts of a bridge can use different deterioration rates and costs.
- The bridge management systems used in Switzerland and Finland have tracking of individual defects and damages, with a detailed description of location of each defect on each element of the bridge and the ability to report on progression of defects over time.
- Other countries have developed special bridge management systems specifically tailored for big bridges. Japan and South Korea have been leaders in this area. These systems have detailed design, inspection, and operational data but none have life cycle cost analysis or other forecasting capabilities so far.

The focus of the present task is to identify and describe management decision support methods and tools that agencies have developed to respond to the needs of big bridges, as distinct from the general inventory of bridges managed by every state. Special attention was devoted to finding methods to satisfy the 23 CFR 515.007 requirements for these bridges, since agencies were not previously required to have these capabilities. Emphasis was also placed on the use of element-level data in bridge management.

3.2 Research Activities and Methodology

Element level data collection became widespread in the 1990s largely because previous bridge condition surveys were found to provide insufficient detail to support management decision making. As a result, the development of element level inspection manuals was motivated by management requirements. The results of Chapters 1 and 2 indicate that the management requirements have not been met by the AASHTO Guide for Commonly-Recognized (CoRe) Structural Elements or the AASHTO MBEI.

Agencies identified in Tasks 1 through 3 to have potentially relevant processes or tools were contacted by telephone to supplement this information and gain a more in-depth understanding. In some cases these conversations uncovered additional examples of management reports related to big bridges.

3.2.1 Information from Earlier Tasks

The results of the Chapter 1 and 2 investigations were useful in structuring the management investigation, particularly for identifying agencies that might be able to provide valuable input to the study.

Literature Review (Chapter 1)

Extensive literature was found on general bridge management, covering all sizes of structures, not specifically big bridges. Literature was also found on the design and inspection of structure types typically found on big bridges, or focused on one specific big bridge.

Recent international conferences have begun to address the potential use of structural health monitoring in bridge management. So far these are focused on detecting problems that require immediate maintenance work, but some authors have commented on the potential for structural health monitoring data to be used in deterioration modeling. No examples were found of completed models of this type, however.

There are numerous publications on bridge-level management analysis of life cycle cost and risk. While these sources are typically not specific to big bridges, they provide a level of detail that agencies would not often devote to average or smaller bridges in their inventories. This makes them potentially relevant to the current study. A notable example is NCHRP Report

483 (Hawk 2003) which provides methods and software for a stochastic analysis of life cycle cost, and which investigates the effects of uncertainty in unit costs, deterioration rates, discount rates, condition data, and other inputs.

A related class of literature focuses on comprehensive bridge-level spreadsheet models of bridge work scoping and timing, incorporating preservation, functional improvement, risk mitigation, and replacement. Three prominent examples are Florida (Sobanjo and Thompson 2011), Quebec (Ellis et al. 2008), and NCHRP Report 590 (Patidar et al. 2007). These models are designed to be used on every bridge in an inventory regardless of size or complexity. Because they are quite detailed, agencies may wish to focus their use on big bridges as a supplement to the analyses conducted in their bridge management systems. These spreadsheet models can be customized to fit any individual bridge needs. One potential customization would be the ability to create separate analyses of the structure units or groups of spans within a big bridge. All of these models use element-level data as an essential input for deterioration and life cycle cost, for the planning of preservation work.

Search for Management Reports (Chapter 2)

Clear linkages were found between certain inspection-related procedures and management needs. In particular, several agencies divide up their bridges into spans, groups of spans, or structure units for inspection, and may use the same system for defining projects on their longest bridges.

Chapter 2 uncovered eight examples of planning documents, most of which were in the form of business plans or investment plans. An investment plan in each case was developed as a listing of capital preservation projects, for which funding has been identified. In most cases these projects are scheduled to be let within a five year timeframe. None of these plans attempted to project capital needs beyond 5 years, which might arise from deterioration, and none include a life cycle cost or risk analysis. All the business plan examples include investment plans but also contain strategic planning information about the agency, such as governance, mission statement, goals and objectives, and business processes.

All of the business plan examples found were from toll authorities, where big bridges were a significant part, or the entirety, of the agency's infrastructure. For State DOTs, the Statewide Transportation Improvement Program (STIP) generally covers the same timeframe and includes the same types of projects as the near-term portion of the toll authority investment plans. State Transportation Asset Management Plans (TAM Plans) generally include the same topics as the toll authority business plans, but have a consistent time frame of 10 years and address additional topics, especially life cycle cost and risk analysis.

Survey (Chapter 2)

A web-based survey received 26 responses from transportation agencies and owners. The information elicited in the survey focused on bridge inspection, but also asked a few screening questions concerning management processes and tools. Nine of the responses suggested management practices or tools that might be relevant to the present study, so the research team followed up with all of them by email and telephone, as described in the next section.

The other survey respondents did not have any practices or tools related to big bridges, usually because they did not have any structures that they would consider to be Big Bridges. This in itself was useful information.

3.2.2 Telephone Interviews

A total of 46 individuals in 29 states were contacted by email, and followed up with 17 telephone interviews lasting 30-60 minutes. In some cases multiple contacts were made within the same agency to gain a more complete perspective and to follow referrals. Some of the agencies were not survey respondents but were known to have relevant information to share. The following outline was used in each telephone interview to guide the conversation:

Transportation Asset Management Plans

- Do you have TAM Plans developed specifically for any of your individual big bridges, such as:
    - Risk analysis or risk register
    - Life cycle cost analysis
    - Investment plan over a long period such as 10 years
    - Owner's manual
    - Do you have a long-term target replacement year for any of your big bridges? Do you have any big bridges that you plan to never replace completely?
- Do you plan to call out any of your big bridges in your statewide TAM Plan?
- Federal condition targets are weighted by deck area. Will this affect the way you manage big bridges? For example, will you plan preservation work around the possibility of a big bridge moving from Good to Fair or Fair to Poor?

Other management activities

- Do you have any STIP items that focus specifically on preservation of any of your individual big bridges? (aside from replacement)
- Do you have an annual or biennial capital or maintenance budget dedicated to any of your big bridges?
- Do you have your big bridges permanently subdivided for the purpose of planning or contracting any of your preservation activities (especially deck work and painting)?
- Do you develop lists of preservation needs within individual big bridges, and prioritize those needs in relation to each other?
- Some have commented that big bridges could be managed as though they were a network of smaller bridges - do you see it that way, and is there any sense in which you manage big bridges in this way?

Bridge management system

- Have you developed any sort of deterioration model specifically for your big bridges?
- Have you conducted a life cycle cost analysis to try to optimize the painting or deck repair intervals (or any other type of preservation)?
- Do you track historical costs of painting and repair work related to big bridges, which would be used when planning future work?
- Do you monitor and track the effectiveness of your painting and repair treatments for use in planning future work? Are there any aspects of this that are different for big bridges than for other bridges?

Project planning

- Do you regularly develop maintenance of traffic plans for big bridge repair work, and do you have a documented methodology for doing this?
- Have you estimated the user costs associated with work zones, for example, to develop contractual incentives for early completion?
- When planning repair/rehab work on big bridges, what cost allowance do you make for traffic control costs, mobilization cost, and engineering cost? Does this differ from smaller bridges?

This outline was used for guidance only; in no instance was a respondent asked all of the questions in the outline. The questions were intended to lead as quickly as possible to information useful to the study in order to make best use of the respondent's limited time availability.

Eleven of the telephone contacts were found to have management procedures or tools specific to big bridges, at a level that would be useful for the present study. Several of these individuals provided additional information or reports by email following the telephone conversation. Big bridge methods or tools were obtained from the following states: California, Florida, Indiana, Michigan, Minnesota, Pennsylvania, Virginia, and Wisconsin. Additional information on the state of the practice was also obtained from Louisiana, Nevada, New York, and Washington.

3.3 Overview of Bridge Management System Capabilities

It is useful to gain an overview of the tools commonly provided in bridge management systems that may be used for any size of structure. Although AASHTOWare Bridge Management (BrM) is familiar to most US transportation agencies, there are other BMS in use within the USA and in other countries. All of these systems have a means of gathering and managing element condition data, and have analysis procedures to use element data in life cycle cost analysis and other decision support functions. Some of the systems that may be less familiar to the reader have functionality that big bridge owners may find valuable. This section describes four commercially-available products:

- AASHTOWare Bridge Management, widely used in the USA
- Stantec BMS 2016, widely used in Canada
- KUBA, used in Switzerland
- dTIMS for Bridges, used in Indiana

This is not a comprehensive survey. The International Association of Bridge Maintenance and Safety (IABMAS) conducts a biennial worldwide survey of the state of the practice in bridge management systems (Mirzaei et al. 2014). The current edition of the survey found 25 bridge management systems in 18 countries. Most of these systems are developed by transportation agencies for their internal needs and in their local language. In most cases the agency has obtained software development and research assistance from universities or consulting firms, but the product is not offered commercially to other agencies. New York is an example of a US State DOT that is in the process of developing its own BMS (provided by Agile Assets).

3.3.1 Inventory and Condition Data

A wide variety of data items are necessary to address all of the management needs of a transportation agency (Figure 3.1). These typically include:

- Identification of each object, usually including a name and numbering system.
- Location, usually in terms of latitude/longitude and a road network linear referencing system.
- Jurisdiction and responsibility, including ownership, maintenance and operations responsibility, and political districts.
- Structural classification, such as design type and material, and further detail of significance for maintenance planning such as deck wearing surface and waterproofing characteristics.
- Geometry, including length, outside width, sidewalk width, navigation clearances, and other relevant dimensions useful for cost estimation.
- Functional characteristics such as maximum load rating for various standard trucks, design loading, and type of service (vehicles, pedestrians, rail, water, etc.).
- Risk assessment information related to scour vulnerability, fatigue-prone details and historical fatigue cycles, storm vulnerability, seismic zone, and flood zone.
- Data for inspection process management such as recommended inspection interval, and special inspection requirements (underwater, fatigue, non-destructive evaluation, access equipment, etc.)
- Metrics useful for planning purposes such as year of construction, current replacement value, planned replacement year.

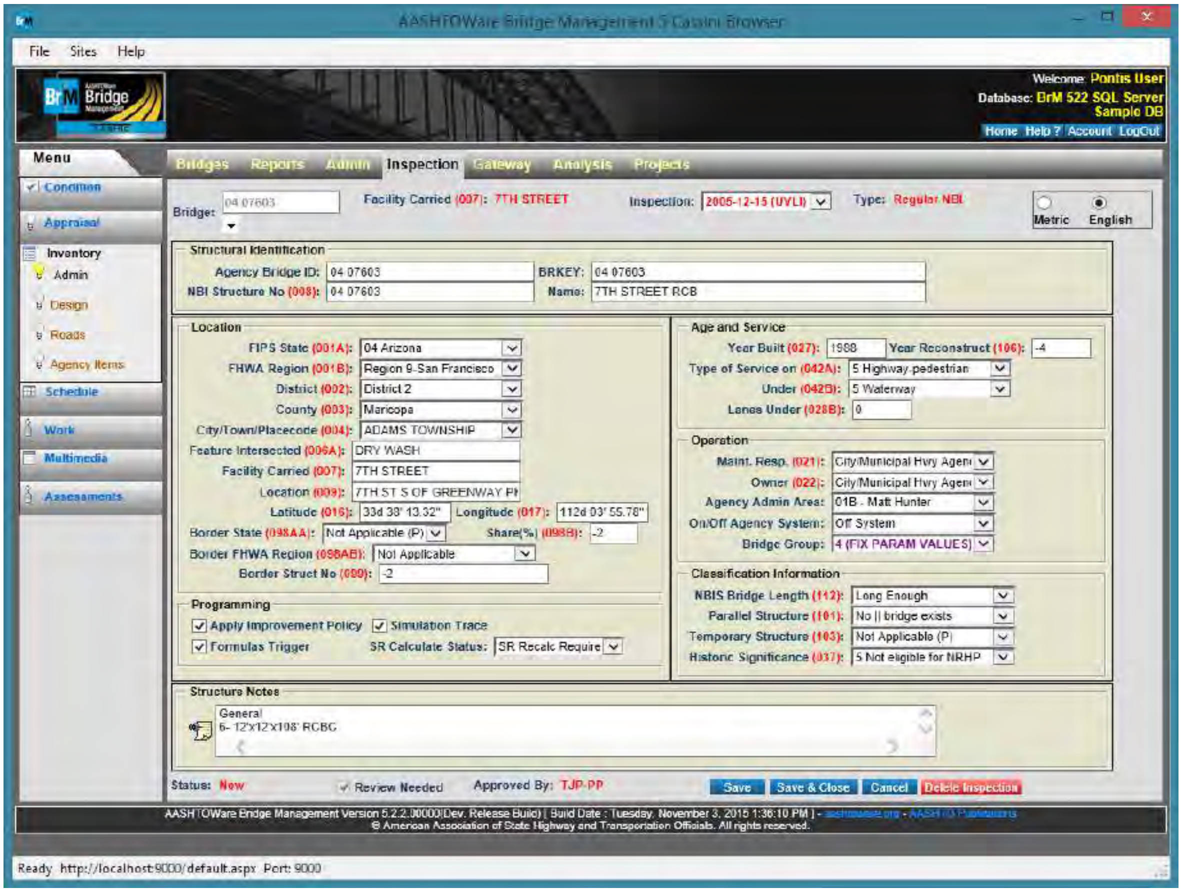


Figure 3.1 - Inventory screen in the AASHTOWare Bridge Management Software.

Bridge management systems typically include tools for navigating through the database and defining subsets for inspection and analysis (Figure 3.2).

Big bridges often consist of multiple structure types, multiple jurisdictions, and multiple roadways. Conventional BMS may have difficulty fully describing these characteristics. When BMS have been developed to fit big bridge requirements, their data models often have more complex schemas to accommodate complex structures. These schemas would often be considered too complex for agencies lacking such bridges, since a more complex database also makes the software user interface more complex. KUBA provides a graphical interface for showing how the properties of a structure vary along its length (Figure 3.3).

Roadway Data

Most bridge management systems have a separate database table for the roadways carried on and under each bridge. Certain long bridges may have many roadways passing under them. Some big bridges carry multiple roadways on the structure, but BMS typically do not support a full representation of this configuration. The data items typically needed at the roadway level include:

- Route and kilometer (mile) point, or other linear referencing system.
- Type of traffic (e.g. vehicles, pedestrians, railways, wildlife, waterway) and users of special interest (school buses, transit, freight routes, military uses).

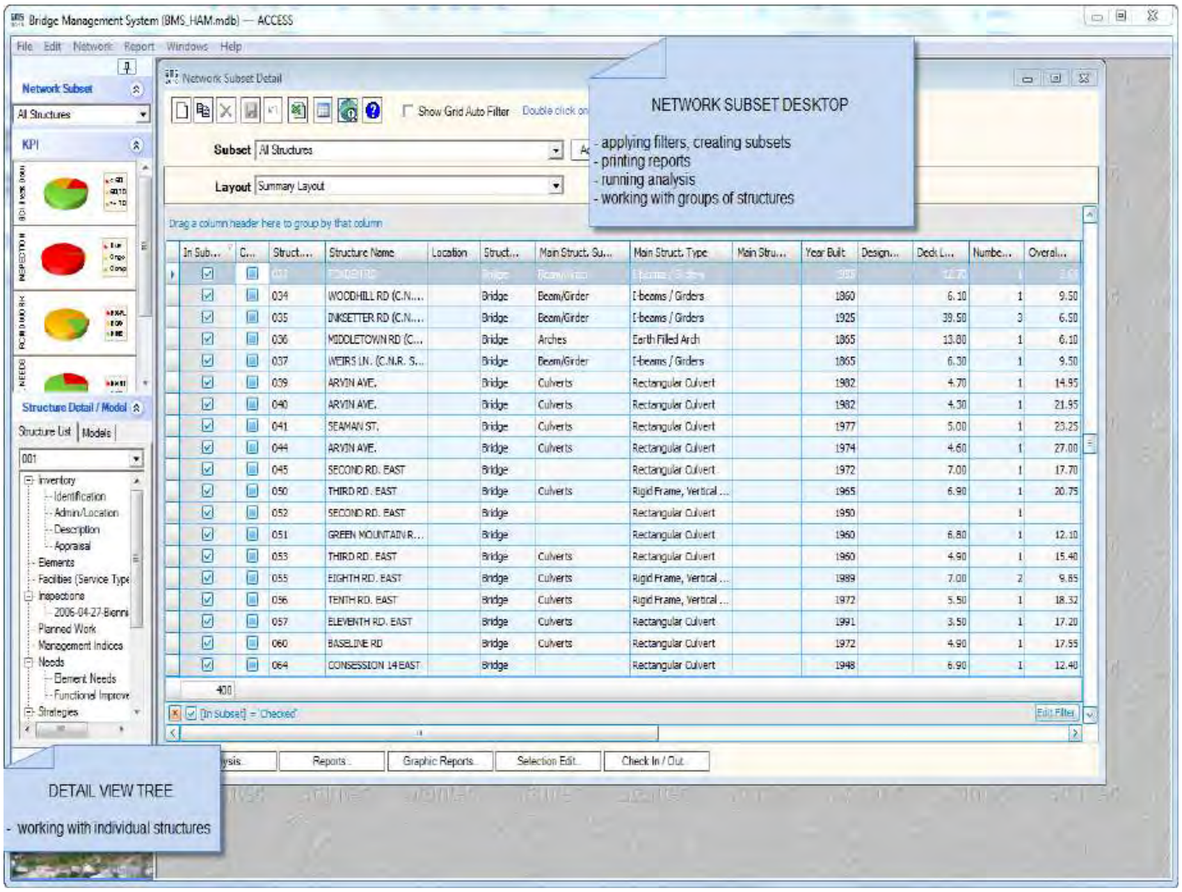


Figure 3.2 - Example inventory navigation screen from the Stantec BMS.

- Name or route signage identification.
- Traffic operations and enforcement responsibility.
- Traffic and truck volume, and growth rates.
- Number of lanes and special-purpose lanes (e.g. shoulders, bicycles, and pedestrians).
- Horizontal and vertical clearances, and width of roadway and lanes.
- Accident rates, actual or estimated.
- Detour distance and time.

Element Data

All of the commercial systems, and most custom-developed bridge management systems, support element-level data collection (Figure 3.4). Elements represent a subdivision of each structure that is significant for maintenance planning, especially for deterioration modeling, treatment identification, and cost estimation. Examples of elements are concrete decks, steel girders, timber stringers, concrete abutments, steel columns, strip seal joints, steel rocker bearings, steel coating (paint) system, deck wearing surface, deck membrane, cathodic protection system. A typical bridge management system may distinguish more than 100 different types of elements. Each type of bridge element is characterized by:

- Element number and name.
- Element category designating its role in the structure (e.g. deck, superstructure, substructure).

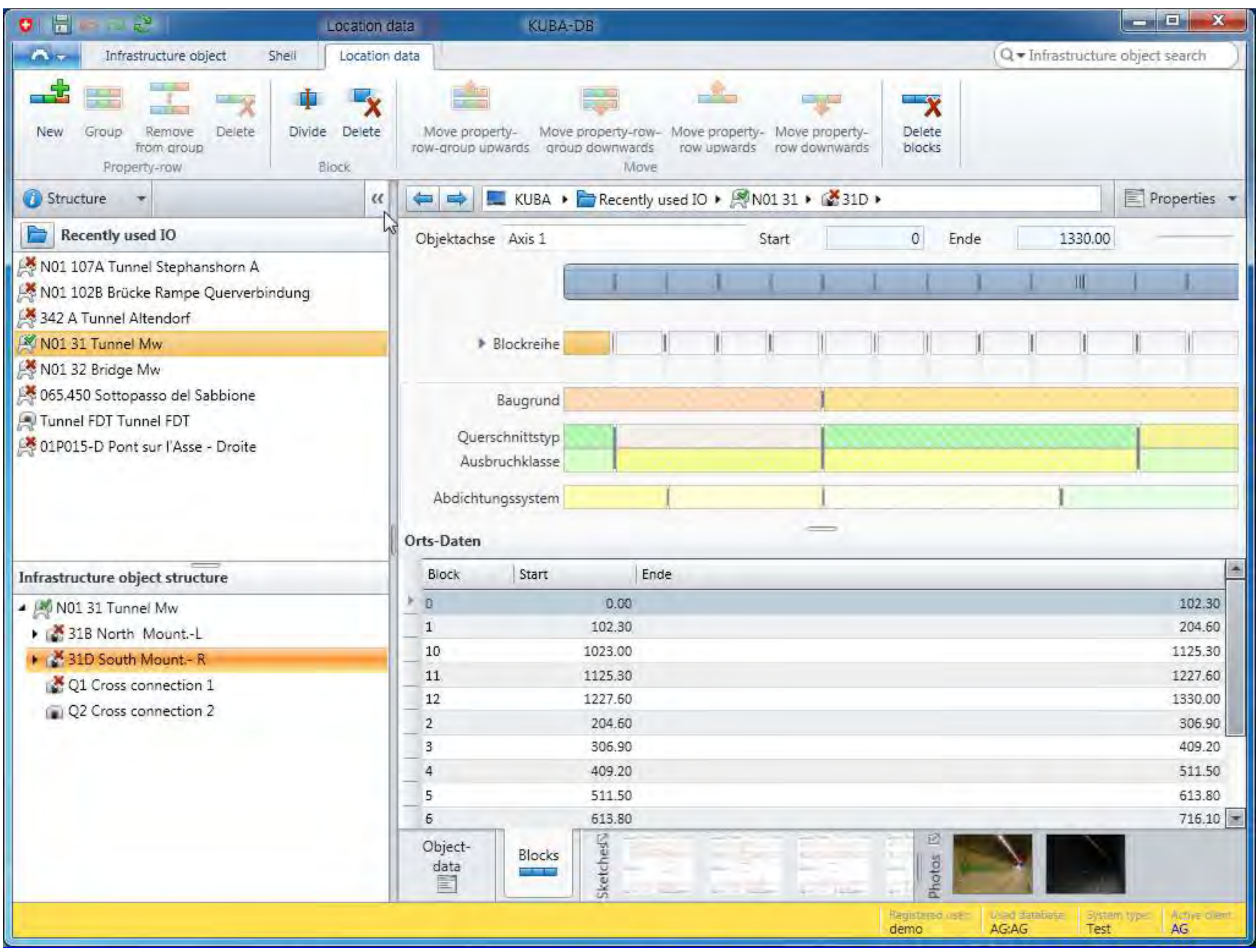


Figure 3.3 - KUBA presentation of features along the length of a structure.

- Material (reinforced or prestressed concrete, steel, timber, etc.)
- Definitions of condition states, usually four states of type and severity of defects that can be distinguished by visual inspection.
- Deterioration rates, usually the median number of years to transition from each condition state to the next.
- List of feasible treatment actions for each condition state, with a unit cost and effectiveness.

Each bridge has a list of the elements found on that bridge. Each of these bridge elements typically has the following information:

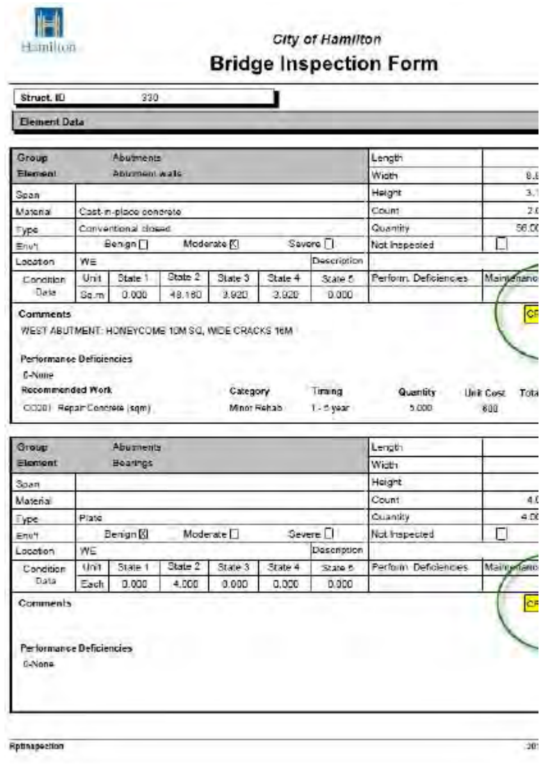
- Manufacturer and model or other relevant detail about the construction of the element.
- Environment - classification of climate or operating conditions affecting deterioration rates.
- Total quantity of the element on the bridge, possibly accompanied by other measurements useful for cost estimation.

Definitions of standardized elements are published in guidebooks such as the AASHTO Manual for Bridge Element Inspection (AASHTO 2013), and most state DOTs have their own customized element manuals.

Inspection Data

Each agency typically operates three levels of bridge inspection processes. The descriptions and characteristics vary, but a general classification can be presented as follows:

- Level 1 – Typically an annual or more frequent visit to each bridge by a maintenance supervisor to look for obvious signs of severe damage or safety-related deficiencies. Usually the supervisor does not make a written report unless immediate maintenance work is required.
- Level 2, often called a Principal Inspection – Conducted at an interval from 1 to 6 years (depending on condition and risk criteria, and local or national regulations) by an engineer or specially trained technician, to update all inventory and condition information. This inspection always produces a written report.


Hamilton

City of Hamilton

Bridge Inspection Form

Struct. ID 330

Element Data

Group	Abutments						Length
Element	Abutment walls						Width
Span							Height
Material	Cast-in-place concrete						Count
Type	Conventional closed						Quantity
Env't	Benign ☐	Moderate ☒		Severe ☐			Not Inspected ☐
Location	WE					Description	
Condition Data	Unit	State 1	State 2	State 3	State 4	State 5	Perform. Deficiencies
	Sq.m	0.000	48.180	3.920	3.920	0.000	

Comments
WEST ABUTMENT: HONEYCOME 10M SQ, WIDE CRACKS 16M

Performance Deficiencies
0-None

Recommended Work	Category	Timing	Quantity	Unit Cost
CO201 Repair Concrete (sqm)	Minor Rehab	1 - 5 year	5.000	800

Group	Abutments						Length
Element	Bearings						Width
Span							Height
Material							Count
Type	Plate						Quantity
Env't	Benign ☒	Moderate ☐		Severe ☐			Not Inspected ☐
Location	WE					Description	
Condition Data	Unit	State 1	State 2	State 3	State 4	State 5	Perform. Deficiencies
	Each	0.000	4.000	0.000	0.000	0.000	

Comments

Performance Deficiencies
0-None

RptInspection

Figure 3.4 - Example bridge inspection form from the Stantec BMS, as used in the city of Hamilton, Canada.

- Level 3, often called a Special Inspection – Generally conducted only on bridges having special requirements because of their configuration or condition. Usually special equipment is required, and often specialized contractors are used. Examples are underwater and fatigue inspections, and non-destructive evaluation of decks. A written report is always prepared.

Bridge management systems generally focus on the Level 2 inspection. None of the commercial systems support Level 1, but some of the custom-developed systems do offer basic support, at least for keeping track of when a structure was most recently visited. None of the commercial systems have detailed data storage, reporting, or modeling for Level 3, but all of them offer at least a basic function for storing one or more results of Level 3 events, in the form of overall risk assessments or element conditions. The Stantec system provides additional detail on automated bridge deck condition assessments. A few agencies have augmented their AASHTO bridge management systems to store Level 3 detail, especially riverbed scour profiles (such as Alabama's WebScour program) and fatigue detail or crack information.

All of the commercial bridge management systems have a database table for storage of all historical inspections including the most recent one. This table contains the following types of data:

- Identification of the bridge, inspection crew, crew leader, and date of inspection.
- Assessments of functionality and risk that may change from one inspection to the next, particularly vertical clearance, scour, and fatigue cracking.
- Overall assessments of condition. Usually this is in the form of a bridge condition index or health index computed from element-level condition state data.
- Identification of follow-up activities, which may include the recommended next Level 2 inspection date, recommendations for Level 3 investigations, and maintenance work recommendations.
- In a related table, a listing of elements with an assessment of the quantity of each element in each condition state, according to the relevant manual. A screen for entering this information is shown in Figure 3.5.

KUBA has a capability to prepare a graphical depiction of a bridge, which can then be used to show the specific location of damage within the structure (Figure 3.6). Finland's custom bridge management system also has the ability to store damage location (Söderqvist 2004).

The Stantec system also features a table for recording and tracking of the follow-up to critical findings. The AASHTO and Stantec systems both have systems for recording functional and risk assessments, and for tracking these over time. All of the systems have features to record the status of inspector work recommendations, which can be interfaced to outside systems such as maintenance management systems. KUBA has a built-in capability to analyze completed projects to update models of treatment effectiveness, which can then be used in estimating life cycle costs (Figure 3.7).

Inventory and Inspection Technology

All four of the reviewed systems can be configured to work with either Oracle or Microsoft SQL Server as their database platform. All can support multiple users (typically up to 5 or more simultaneous users) with an access control system integrated with the database manager's security system.

The Stantec system features a Windows Mobile smartphone-based inspection module. All four of the systems can provide tablet-based inspection support using Windows-based tablets. KUBA provides a mobile inspection system for the Apple iPad (Figure 3.8).

AASHTO offers either a desktop installation or a web server installation of its bridge management software, allowing all capabilities to be used from Internet Explorer. The developers of the Stantec and dTIMS systems indicate that web-based inspection capabilities are planned but are not yet available. KUBA provides a web interface for viewing (but not entering) bridge data. In all of these systems, bridges can be checked out of the main database to a portable computer for use in the field. Data entered in the field are later checked into the database in order to record a new inspection. All of the systems provide automated quality checks on incoming data, and also provide support for indicating the review status of each inspection.

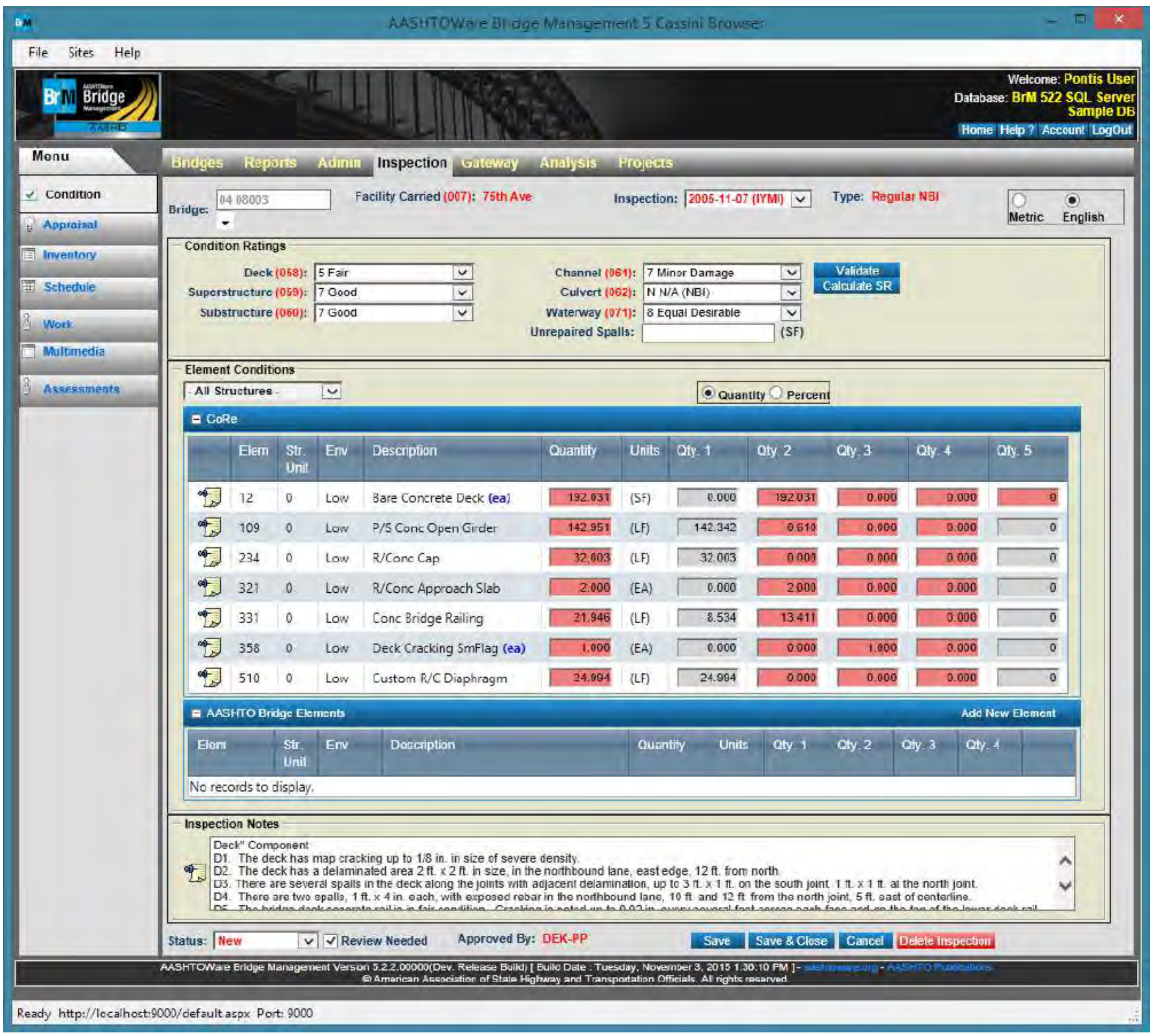


Figure 3.5 - Element inspection screen in AASHTOWare Bridge Management Software.

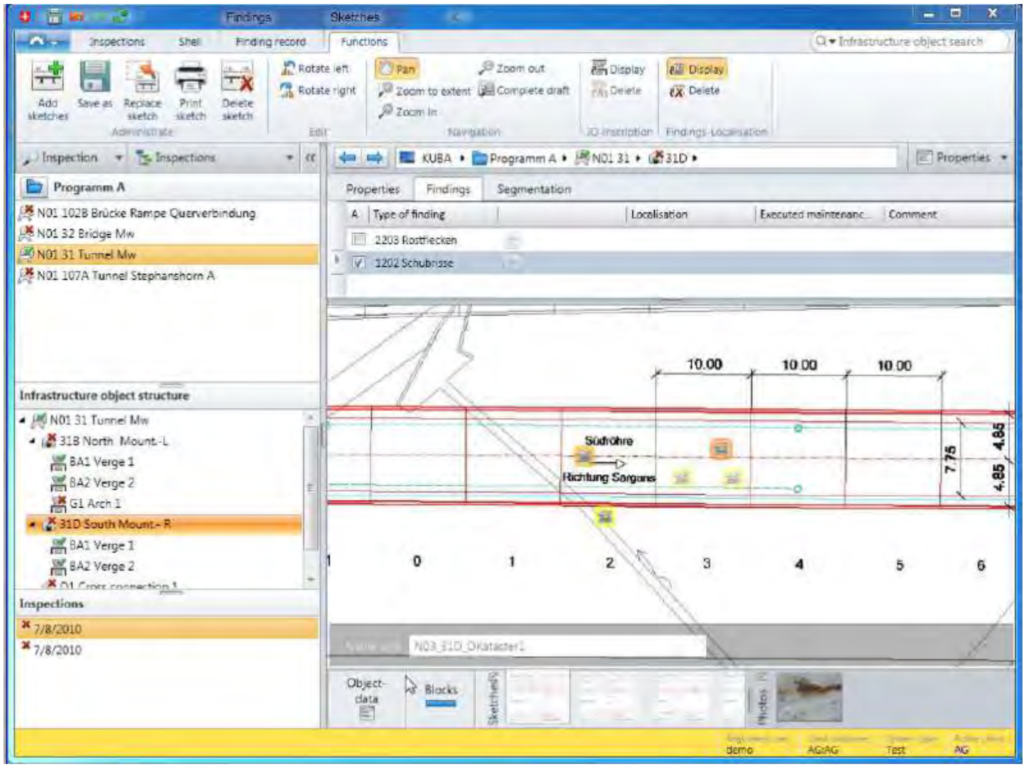


Figure 3.6 - Graphical depiction of the location of damage within a bridge in KUBA.

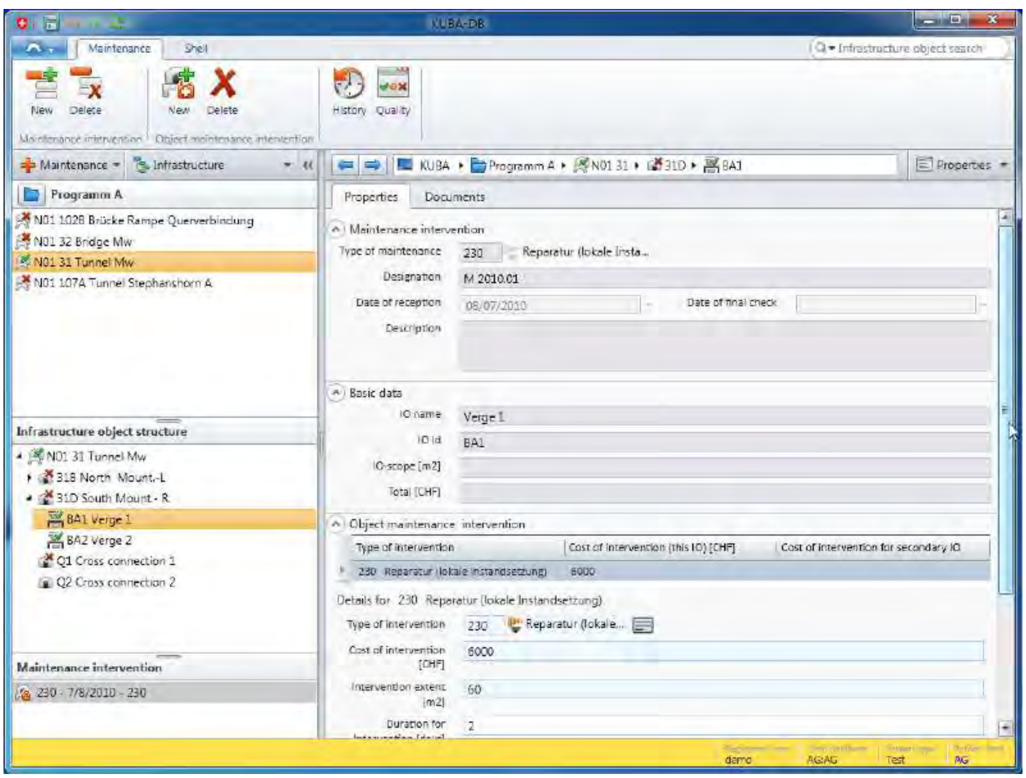


Figure 3.7 - Screen for recording recommended work and status in KUBA.

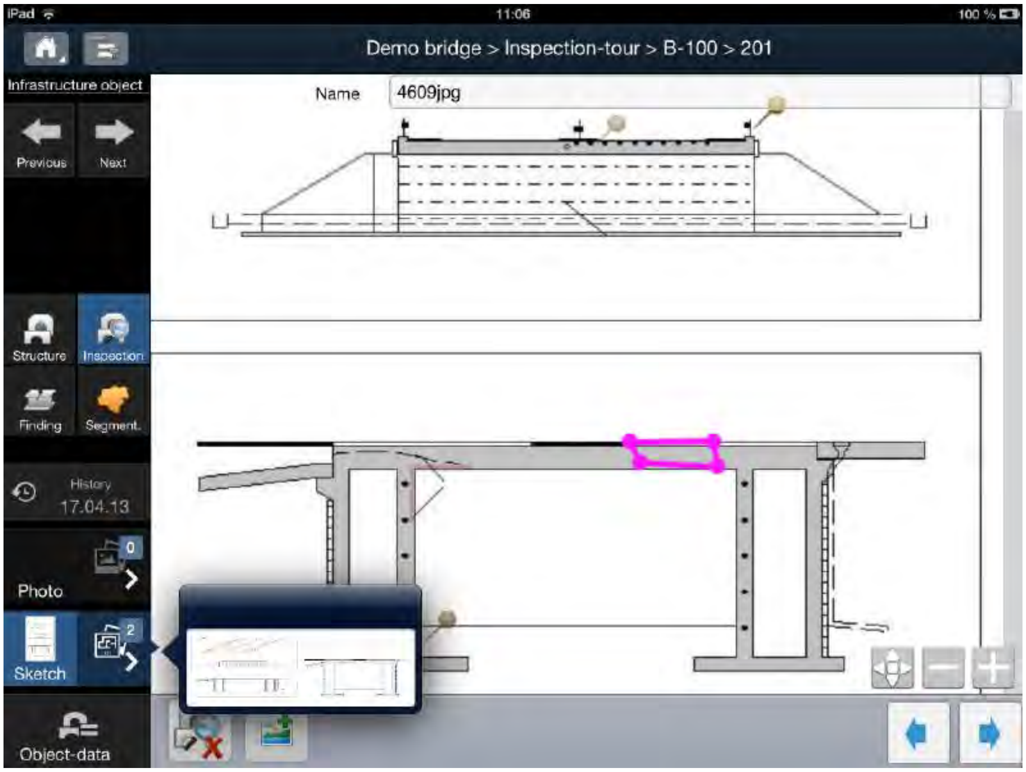


Figure 3.8 - KUBA mobile inspection application for the iPad.

3.3.2 Performance Measures, Reporting and Tracking

Most transportation agencies have enabling legislation, strategic plans, or other documents which state the major objectives that are to guide policy making and resource allocation (Gordon et al. 2011, NAMS 2006). For bridge management, the typical concerns are:

- Condition – particularly, maintaining conditions in a sufficiently good state that transportation service is not affected by damage or deficiencies. BMS, including all of the commercial systems evaluated here, have features to compute a bridge condition index, usually on a scale where 100 is perfect and 0 is the worst possible (Shepard and Johnson 2001). These systems also define generic condition states such as good – fair – poor and track the percentage of the network in good or poor condition.
- Safety – minimizing the potential for crashes and their resulting injuries and property damage. Over the transportation network as a whole, safety is typically expressed as the rate of traffic accidents per 100 million vehicle-kilometers traveled. This measure is difficult to use at the bridge level because traffic accidents are infrequent at most bridge sites, and because driver and vehicle characteristics have a greater effect on crash frequency than bridge properties. The AASHTO and Stantec bridge management systems use a modeled expected value of crash risk, in place of an

actual crash count, because this is more reflective of how infrastructure characteristics (such as roadway width, alignment, and deck condition) relate to safety.

- Mobility – minimizing travel time and maximizing the reliability of travel time. This concern is typically measured as a detour distance and travel delay time; however, for many big bridges, detours may not be feasible except in urban settings. It is also important to consider for trucks that are forced to use longer routes because of clearance or load capacity restrictions.
- Life cycle cost – minimizing the cost of keeping infrastructure in service over the long-term. One of the most fundamental features of a bridge management system is a model to estimate the future costs necessary over the life of a bridge to keep it in good repair, and to analyze decisions affecting the timing of these costs, especially the ability to delay large costs of rehabilitation and replacement.
- Risk – managing the resilience of the network so unexpected events do not disrupt the continuity and performance of transportation service. The AASHTO and Stantec systems provide functionality to compute a risk index based on characteristics of the bridge. A more general approach that some agencies are using quantifies the probability of service disruption scenarios and the cost incurred by the agency and road users if the disruption scenario occurs. Florida DOT has this type of model (Sobanjo and Thompson 2013).

All of these concerns are significant on big bridges because of their exceptional size and utilization. Of the four commercial systems evaluated, the AASHTO and Stantec systems have features to model all of these performance concerns. The KUBA and dTIMS systems model only condition and life cycle cost.

Much of the value of performance measures is in the ability to communicate the current state of the inventory and past or future changes. The following techniques are supported by all bridge management systems:

- Summary of current network conditions, usually by comparing geographic areas in terms of average condition index or percent poor. BMS also have the capability to report network conditions in more detail by element type.
- Trendlines of past conditions and forecast future conditions. Usually these are expressed as condition indexes, accident risk, travel delay, and infrastructure

resilience. These can be reported for subsets of the network or for the entire network.

- Geographic displays of performance levels on a map of the network. Usually conditions are color-coded as good, fair, or poor.
- Direct reporting of condition measures at the bridge or element level for individual structures, as tabular reports.

The Stantec bridge management system has mapping capabilities tightly integrated, allowing maps to be used for functions such as selecting bridges for inspection or analysis, and accessing site photographs (Figure 3.9). The other commercial systems are able to be interfaced with an agency's own GIS or with commercial mapping products such as Google Maps. These do not provide geographic access to the internal functionality of the BMS (Figures 3.10 and 3.11). Deighton indicates that capabilities to select multiple bridges on a map, and other geographic functions, are planned in the future for dTIMS. The AASHTO, Stantec, and dTIMS systems are able to export KML files which can be used to locate a bridge in Google Earth and other mapping programs.

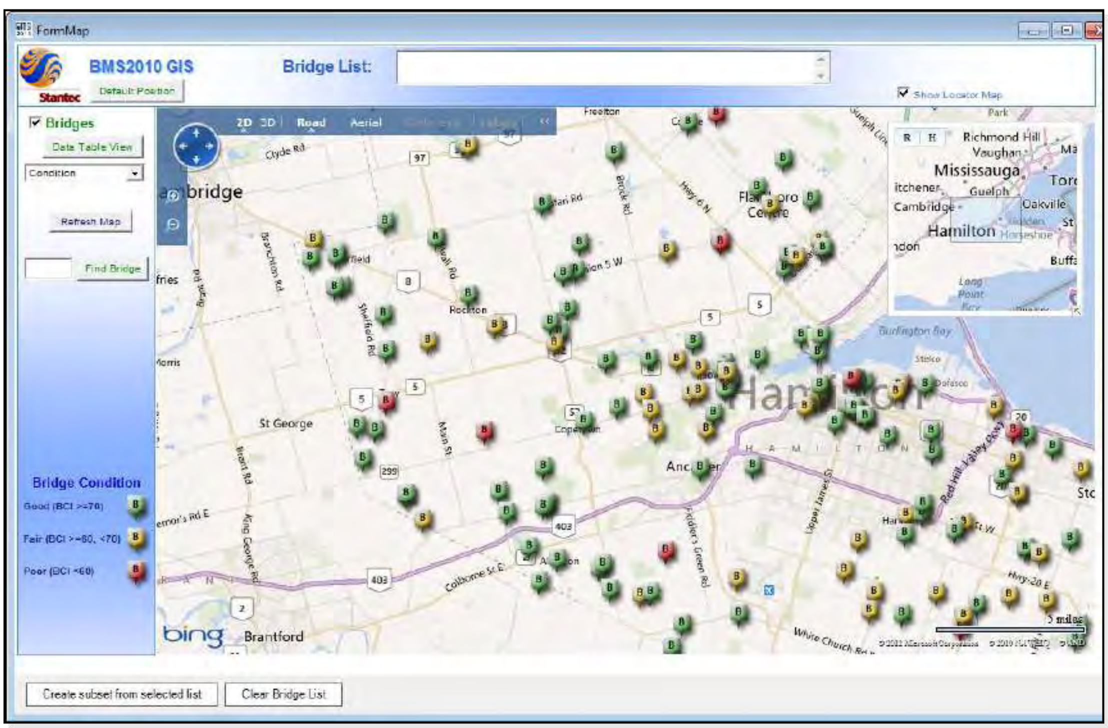


Figure 3.9 - Stantec geographic display is color-coded by bridge condition index and provides access to functionality.

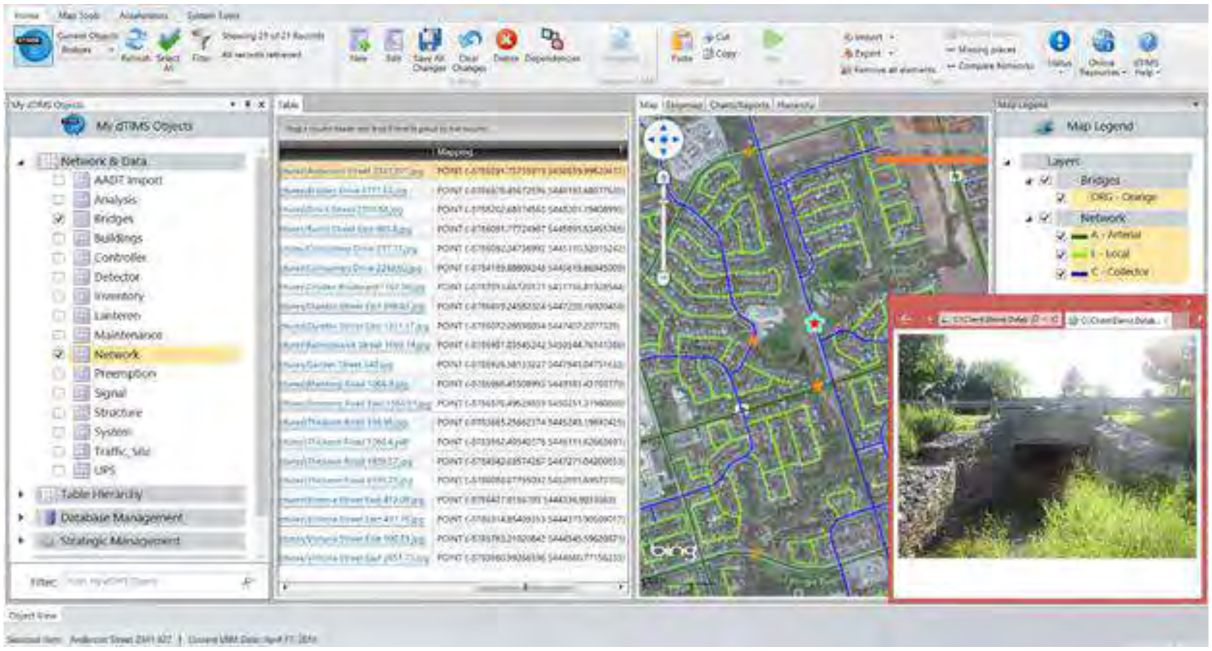


Figure 3.10 - Map-based display of bridges on a network, in the dTIMS software.

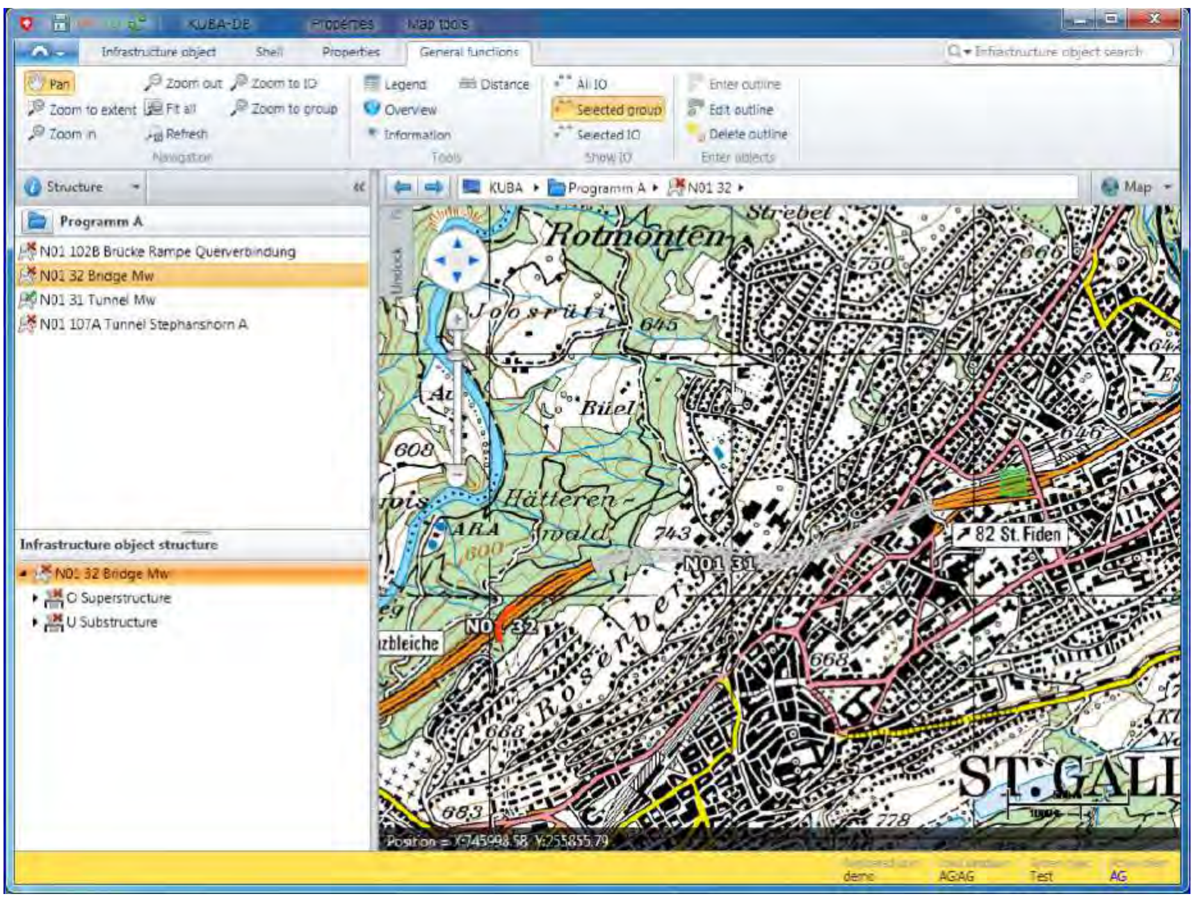


Figure 3.11 - Structure location in KUBA.

3.3.3 Life Cycle Cost Analysis

In order to decide on the optimal combination of rehabilitation, repair, and maintenance activities, the state of the art in bridge management systems is life cycle cost analysis (Hawk 2003). These methods are so widely accepted that they are now required by federal law in the USA (23 USC 119 (e)(4)).

In life cycle cost analysis, the near-term cost of a preventive rehabilitation, repair, or maintenance action is balanced against the benefit of delaying larger costs farther into the future. This preference is quantified as a discount rate. Although discount rates are sometimes confused with interest rates, they have an entirely different purpose, as they merely reflect the relative value of having money in hand today, rather than the uncertain value of money that might be available at some time in the future. Most transportation agencies use discount rates in the range of 1.9 to 3 percent, excluding inflation. The effect of a 2% discount rate, for example, is to divide any cost by a factor of 1.02 for each year that the cost can be delayed.

Although it is attractive to delay costs as much as possible and take advantage of the time value of money, there are limits. When repairs or rehabilitation are delayed, condition of each asset gets worse, eventually having an effect on the serviceability or even the safety of the infrastructure. Also, certain kinds of preventive maintenance actions are highly cost-effective, but only if performed at the optimal time. For example, painting a steel bridge at the right time is highly effective in prolonging its life. If painting is delayed, at some point it becomes ineffective at protecting the steel from section loss, and a much more expensive rehabilitation or replacement action is required.

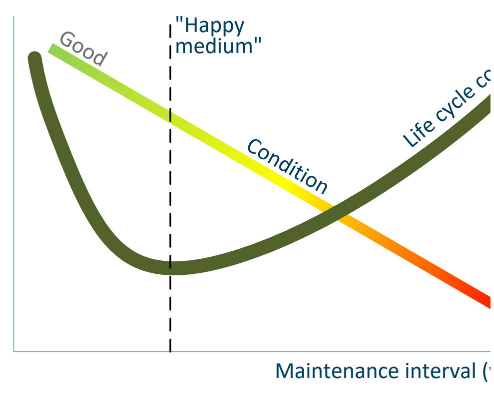


Figure 3.12 - Finding strategies which minimize life cycle cost

A key goal of life cycle cost analysis is to find the optimal level of maintenance where life cycle costs are kept to an absolute minimum, the “happy medium” where maintenance expenditures are neither too frequent nor delayed too long, as illustrated in Figure 3.12. Typically, when a bridge is maintained at a level which minimizes long term costs, it is kept in relatively good condition. Over the life of a facility, this can reduce long-term costs by more than half, compared to a strategy of letting facilities simply deteriorate until they have to be replaced.

Life cycle cost analysis depends on deterioration models and treatment models of cost and effectiveness. Deterioration rates and costs vary by element: for example, expansion joints deteriorate faster than abutments, and cost much less to replace. As a result, life cycle cost analysis is generally performed at the element level. The most common use of life cycle cost analysis is to compute the benefit of preservation activities such as painting of steel, patching of concrete, and sealing of joints. Since these activities don't affect road users directly, the life cycle cost savings of these actions is typically the only justification for these treatments that can be computed in a bridge management system.

Forecasting Deterioration

All transportation assets deteriorate over time. Bridges are degraded by corrosion, chemical activity, collisions, metal fatigue, and scour. All common bridge materials can deteriorate as they age, thus weakening their structural strength and admitting corrosive water and chemicals. The causes of deterioration can vary drastically from one site to another, and from year to year.

To quantify and predict deterioration, engineers use mathematical models at the element level. The most common deterioration model is called a one-step Markov model, which presents the deterioration rate as the median number of years to make a transition from one condition state to the next. For example, the median time for a concrete bridge deck to go from Good condition to Fair condition might be 15 years in a moderate environment, and 25 years in a warm, dry environment. These estimates of transition time are often developed initially using expert judgment; but ideally each agency should develop models using its own history of bridge inspections.

With a set of estimated transition times, a Markov model converts these times to probabilities under the assumption that the probability distribution is uniform from year to year. Changes in condition in future years are computed year by year, over a period as long as necessary for life cycle cost analysis (Figure 3.13). Although the analysis is very detailed at the element and condition state level, the computations are performed very quickly by management system software, and can be made sensitive to causal factors such as climate.

The AASHTO, Stantec, and KUBA models all use the same type of Markov deterioration models. The dTIMS system uses a linear deterministic model which is estimated using judgment but does not have a foundation in statistical research (Figure 3.14). dTIMS has a limited capability to incorporate Markov models but is not able to perform this analysis with a full-size inventory at the element level. As a result, it does not have the capability to compute the life cycle benefits of element level treatments such as painting of steel elements, patching of concrete, or sealing of joints.

The AASHTO system provides several mechanisms to make the forecasts more precise, such as the ability to slow the onset of deterioration using a Weibull model, and the ability to model the interactions among elements. For example, leakage of an expansion joint can accelerate the deterioration of the steel girders on a bridge. KUBA also provides refinements to the deterioration model, using a mechanistic model of chloride-induced corrosion of steel reinforcing in concrete decks (Hajdin 2002). While these innovations make the models more complex, it is found to be valuable for large agencies or large structures where optimal timing of work might save substantial amounts of money. NCHRP Report 713 (Thompson et al. 2012) has a thorough discussion, including mathematical equations and examples, of deterioration models used in bridge and asset management.

Preservation Treatments

By means of its local forces and contractors, each agency has a variety of bridge preservation capabilities at its disposal, such as:

- Patching of concrete
- Repair of corroded steel
- Spray liners for culverts
- Paving of the bottoms of culverts
- Replacement of bridge decks
- Installation or replacement of deck waterproofing systems
- Replacement of deck wearing surfaces
- Patching of deck wearing surfaces
- Spot painting
- Total repainting
- Sealing and repair of expansion joints
- Repair or replacement of bridge bearings
- Placement of rip rap or other slope and stream bank protection

In a BMS, each of these treatments has a unit cost, expressed in money per unit of element. Each treatment also has an effectiveness, expressed as a probability of improving to each possible condition state of each element. These are developed in the same manner as deterioration models, first using judgment and later using statistical analysis of inspection and maintenance data. Again, the AASHTO, Stantec, and KUBA systems use the same forms of probabilistic models, and dTIMS uses a deterministic model at the bridge level. Effectiveness models tend to be quite similar among agencies, since there is much commonality in methods and equipment all around the world. It is important, however, to develop unit costs that are specific to the agency where they will be used.

An NCHRP Report (Hearn et al. 2010) and its accompanying online resources provide an overview, classification, and comparison of effectiveness and cost models in agencies across the USA, based on a detailed analysis of data from their maintenance management systems. Florida DOT also has a complete set of statistically-derived models (Sobanjo and Thompson 2011).

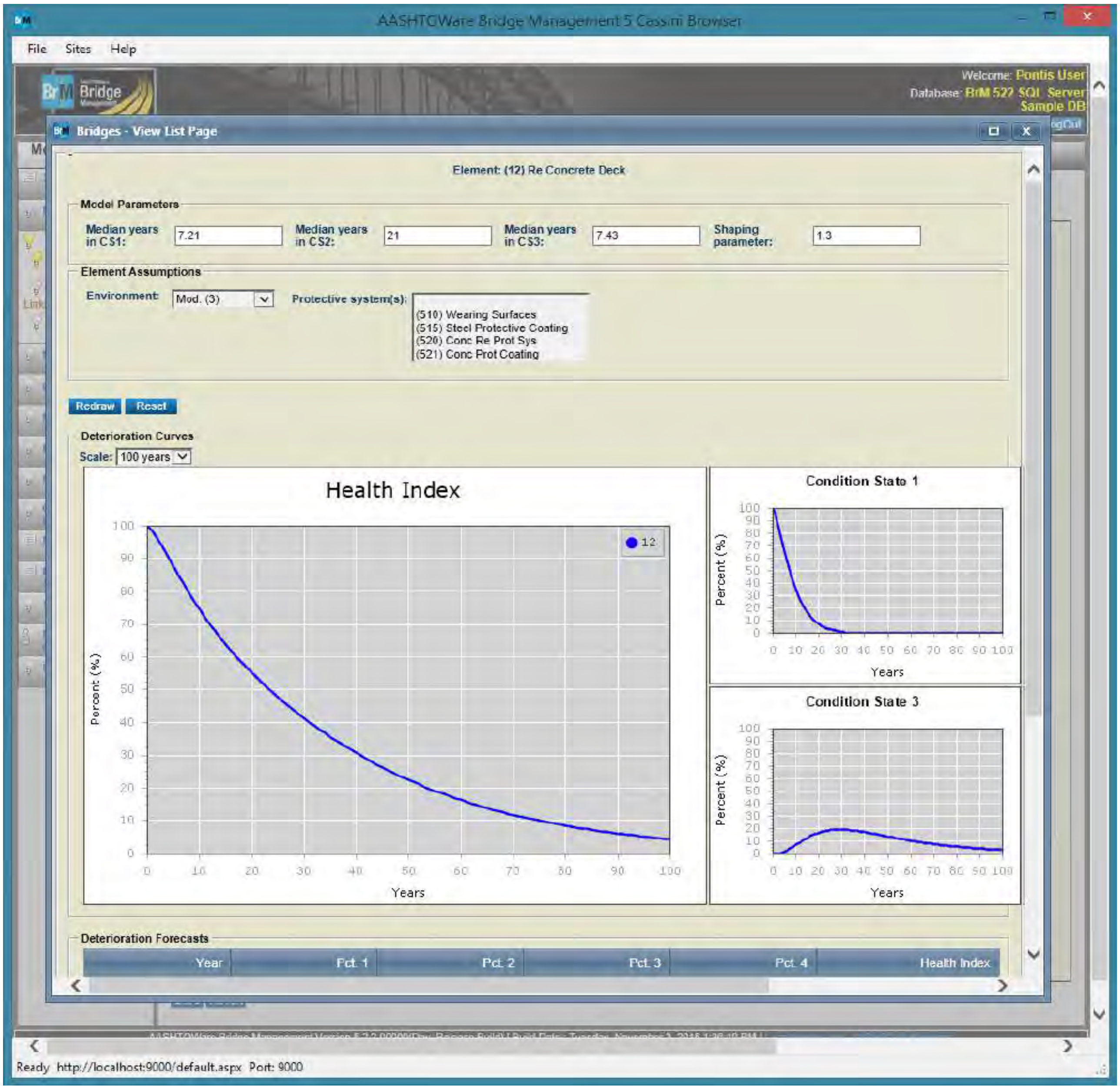


Figure 3.13 - Screen for defining deterioration models in the AASHTOWare system.

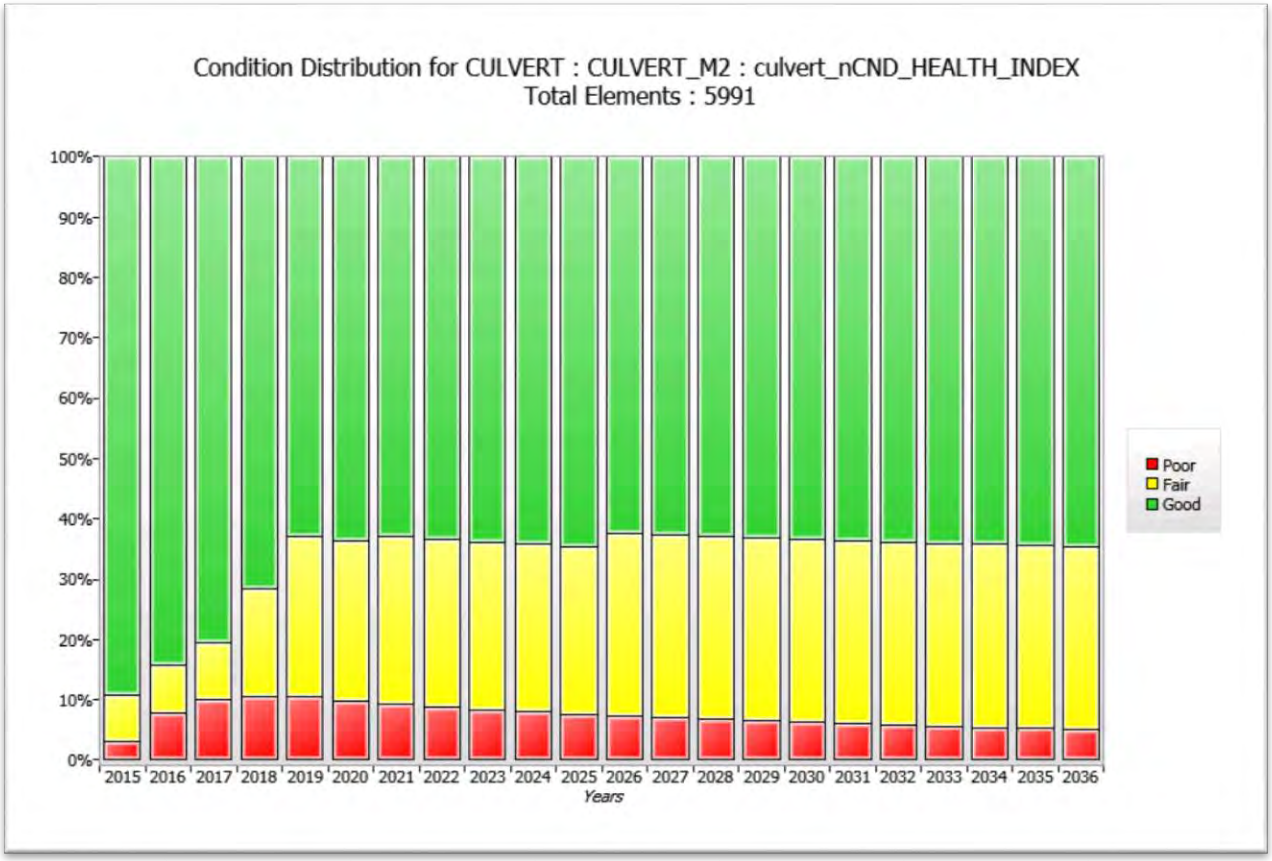


Figure 3.14 - Example of culvert deterioration from dTIMS.

Life Cycle Activity Profiles

Using the deterioration and treatment models, a bridge management system develops a set of alternative life cycle activity profiles representing different choices of treatment scope and timing, including the possibility of taking no action at all. Each life cycle activity profile is developed by forecasting the deterioration of the bridge and the actions that become necessary to overcome the deterioration. The costs of these actions are computed and discounted to present value. Figure 3.15 shows a comparison of two life cycle activity profiles, one representing a policy of replacement only (orange), and the other representing a policy where preservation work prolongs the life of the bridge and postpones the need for replacement (green).

In general, the life cycle activity profile with the lowest present value of costs is optimal, subject to performance constraints. Under fiscal constraints, it may be necessary to downscope or delay actions, which a BMS does by selecting the alternative with the smallest increase in life cycle cost caused by the delay.

On a big bridge, some agencies have found that it is necessary to downscope projects by limiting work to selected spans or structure units because of fiscal constraints. Other portions of the bridge are delayed until funding becomes available. For this reason, a capability to generate life cycle activity profiles for portions of a bridge is a useful capability for big bridges that would not normally be found in a BMS. This is one example where a big bridge might be managed as a set or network of smaller bridges.

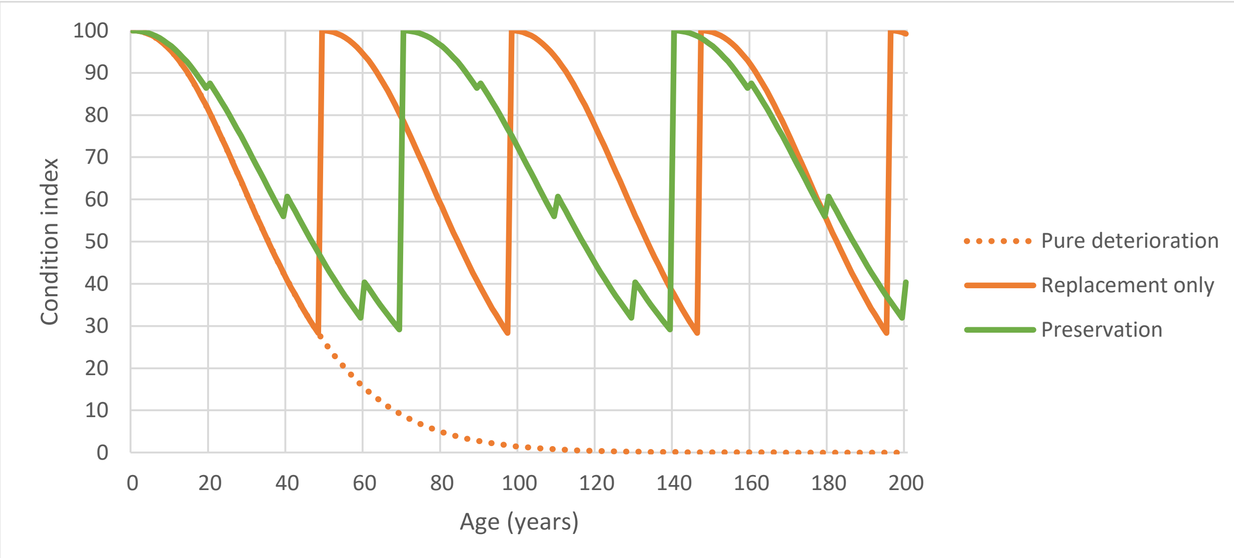


Figure 3.15 - Bridge life extension achievable with increased emphasis on preservation, using the AASHTOWare models.

Across the network as a whole, a BMS can compare the life cycle cost savings that comes with a preservation policy, against an alternative policy involving different, perhaps less expensive preservation strategies. The annualized life cycle cost savings divided by the initial added cost of preservation, is the return on investment of preservation. Equalizing the return on investment among treatment categories can help to determine the optimal allocation of funds among different types of preservation work. A bridge management system (including any of the four commercial systems) considers these tradeoffs automatically as a part of its analysis.

3.3.4 Risk and Functional Performance Analysis

There are many different kinds of risk in a transportation system, so it is important to be clear on the types of risk that are part of bridge management. Specifically, the risk is the possibility that transportation service on a link of the network will be disrupted (blocked or severely impeded) by an unexpected failure of a bridge or bridge element. The disruption may last for days or weeks while the road is cleared and repaired. By nature the hazardous event is unpredictable at any given site, and uncommon across the inventory. Yet, road segments are disrupted one or more times every year by such events, such as floods or over-height truck collisions, somewhere in the network, leading to substantial economic losses to the public as well as injuries and property damage.

The nature of the hazards can vary, but all transportation agencies have risk concerns and need risk management strategies. To support this need, AASHTO has published a Guide to Highway Vulnerability Assessment (SAIC 2002) and a series of technical guides to help implement a risk management plan (SAIC and PB 2009). A Guideline for Risk Assessment in Bridge Management Systems is slated to be published under NCHRP Project 20-07(378) by early 2017.

In risk analysis it is helpful to define specific concepts to increase understanding and provide a basis for risk-based asset management (Seville and Metcalfe 2005, Sobanjo and Thompson 2013):

- *Likelihood* of hazard. Bridge failures are typically triggered by natural events, such as earthquakes, floods, scour, and settlement; by man-made events such as collisions of over-height trucks or marine vessels; or by age-related events such as advanced deterioration or fatigue cracking. These events are inherently uncontrollable, although agencies in some cases can take steps to reduce the likelihood of failure. For natural hazards, one approach is to quantify the total number of failures for a given category of bridge over a historical time period, then divide by the number of bridges in the category and number of years in the historical record. Categories could be defined by structure type, seismic zone, flood zone, or other readily measurable criteria. The likelihood of disruption caused by advanced deterioration and fatigue is typically derived from element-level data in state of the art risk models (Sobanjo and Thompson 2013).
- Direct *consequence* of hazard. A bridge hazard event is recognized if it causes damage requiring an agency response. This damage may be to the bridge itself, and may also encompass surrounding features, including a road or other transportation facility. It may also damage the property of others, and may cause personal injury. All of these consequences may be represented by costs in a risk computation. Alternatively, some risk assessment procedures use a scoring procedure (basically, a utility function) to represent the disbenefit of a failure. Agencies can often limit the consequences of a hazard event by making assets less vulnerable, or more resilient.

The recovery cost of bridge damage caused by extreme events is often derived from element level data in state-of-the-art models (Sobanjo and Thompson 2013).

- *Impact* of hazard. If a hazard event occurs and causes damage to a bridge or other transportation facility, there may be social, environmental, and economic impacts that extend far beyond the bridge itself. Traffic may be forced to take a longer route, or use a different mode of travel, for an extended period of time while the facility is repaired. Road users then incur costs for travel time, vehicle operating costs, and fares. Added traffic on detour routes may cause congestion on those routes, with further inconvenience. Businesses may be disrupted; some may even fail due to changes in traffic patterns. In the longer term, businesses may not want to locate in areas they perceive to be vulnerable, thus depressing economic conditions and/or property values. AASHTO has a standardized method for quantifying the costs of these impacts (AASHTO 2010).

Bridge management systems typically group the direct consequences and the impacts together and merely call them “consequences” (SAIC 2002). The components of risk are often analyzed using probabilistic models. Risk is usually considered to be a quantity computed as likelihood × (direct consequences + impacts) (Seville and Metcalfe 2005). The process of estimating this risk is called *risk assessment*. The agency usually tries to minimize risk by actions to make them less vulnerable, or more resilient. Sometimes it is possible to reduce the likelihood of a hazard, for example by increasing bridge underclearance, installation of fender systems or the retrofit of fatigue prone and fracture critical details. Risk reduction actions may

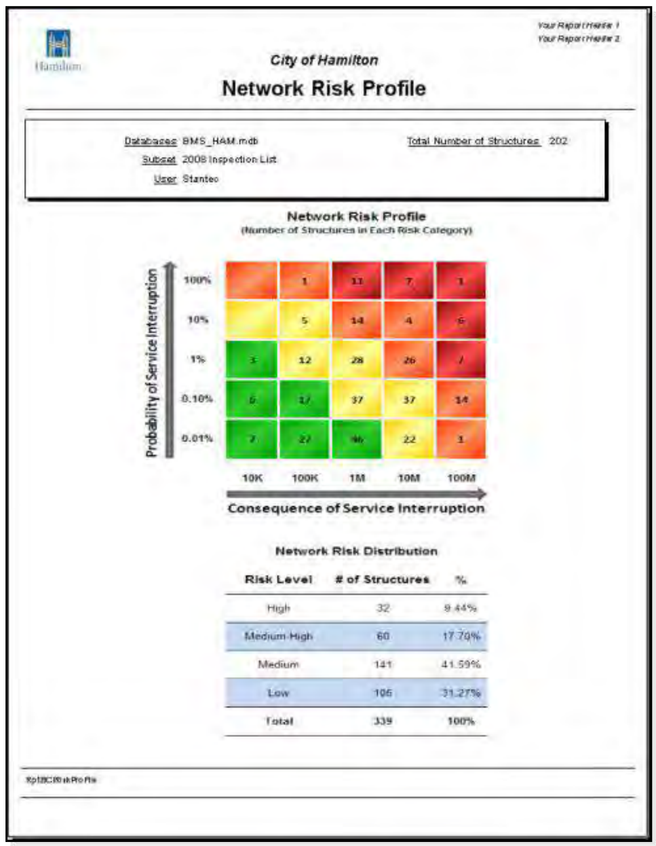


Figure 3.16 - Risk summary report in the Stantec BMS.

be costly, and they compete for funding with other project needs. It is necessary to prioritize and schedule these activities just like all other types of projects. This process is part of *risk management* (Figure 3.16).

Asset management procedures and tools are just as relevant to risk as to any other type of performance, so it is considered best practice to integrate risk management into asset management. Since performance measures are usually quantities of desirable attributes under the agency's control, it is becoming common for agencies to focus on asset resilience as the performance measure (Committees 2012). Risk assessment activities record data related to asset resilience, and actions are taken to increase resilience.

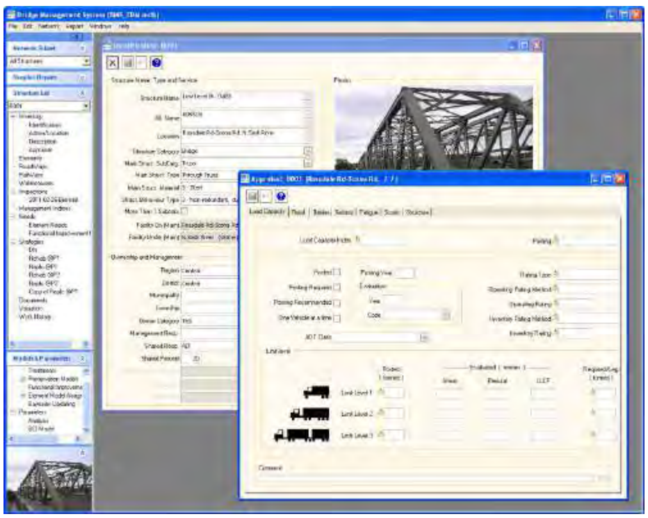


Figure 3.17 - Example of truck load limits in the Stantec BMS.

Resilience then is any attribute, or combination of attributes, which help an asset resist damage in the face of an external hazard. In a field risk assessment process, trained personnel make note of the resilience attributes of each asset (NYSDOT 2013). This information is used in a risk computation, which then participates in asset management decision support capabilities. When communicating with the public, the term "resilience" focuses attention on the positive outcomes of actions that the agency can control, and for which it can be accountable.

Functional deficiencies, while much more difficult or costly to correct for big bridges, are typically modeled in the same way as risk, except using an estimate of the fraction of the traffic stream impacted rather than the likelihood of a hazard event. Vertical clearance and load capacity restrictions are modeled based on the number of trucks that are forced to use a detour route each day. Excessive narrowness of a roadway is modeled based on a statistical analysis of excess vehicular crashes. Florida DOT has developed models of truck height and weight in its typical traffic stream, and the risk of traffic accidents as a function of bridge roadway characteristics. These models can be used in the AASHTOWare software, as Florida does, and are also provided in the Stantec system (Thompson et al. 1999, Sobanjo and Thompson 2011, Johnston et al. 1994). Figure 3.17 shows an example of a load rating screen for various truck classes.

3.3.5 Decision Support Functionality

All fully functional bridge management systems, including all of the commercial systems, have a capability to develop a project definition and cost estimate, using the most recent inspection and the deterioration and treatment models. All have the capability to develop more than one project alternative based on variations in scope and timing of work, taking into account the deterioration that may occur if a project is delayed.

Each project alternative in these systems is given an estimate of cost and benefit. The benefit/cost ratio is used as a way of comparing alternatives and setting priorities. The life cycle cost analysis and risk/functional analysis together address project benefits in terms of all of the essential performance objectives: condition, safety, mobility, cost, and risk. All of the bridge management systems provide some means of considering performance measures or bridge characteristics for each of these objectives separately. However, for certain purposes it is necessary to combine these concerns:

- When funding is constrained, it is necessary to select a specific set of projects by setting priorities among project alternatives. This should be based on the combined effects of each project on all of the performance objectives.
- Decision makers and stakeholders may have expectations about performance levels to be achieved for each performance objective. It is important for the BMS to provide information on the tradeoff between funding and performance, and between one objective and another. For example, investing more money in safety without increasing the overall funding level, necessarily requires a sacrifice in the other performance concerns.

These interactions among performance measures affect the scope and timing of individual projects, the overall allocation of funding among types of projects and subsets of the inventory, and the range of possible network performance outcomes. Figure 3.18 shows an example of the capabilities available in all of the commercial systems to project funding needs over a long time horizon, typically 10 to 20 years, and to compare alternative scenarios. Figure 3.19 shows a graph of overall network condition (percent of the inventory in poor condition) as a function of total 12-year funding. None of the commercial bridge management systems are currently able to produce this graph, but an analysis similar to this is likely to be necessary for the investment portion of Transportation Asset Management Plans. Figure 3.19 was produced using a spreadsheet based on AASHTOWare BrM data.

The AASHTOWare and Stantec systems support two ways of combining performance concerns:

- Social cost framework, where all risk and functional deficiency concerns are expressed in monetary terms and combined into the life cost analysis (Sobanjo and Thompson 2013).
- Utility theory framework, where separate performance measures are scaled and amalgamated into a unitless prioritization criterion (Patidar et al. 2007).

The dTIMS and KUBA systems set priorities based on condition and agency life cycle cost, and do not provide a means of including risk and functionality related to safety and mobility. However, AASHTOWare, Stantec, and dTIMS are able to be customized to incorporate risk and functionality, or any other desired considerations, into a prioritization index. Figure 3.20 shows the screen in the AASHTOWare system for defining a utility function to scale and combine multiple performance concerns into a single criterion for priority setting.

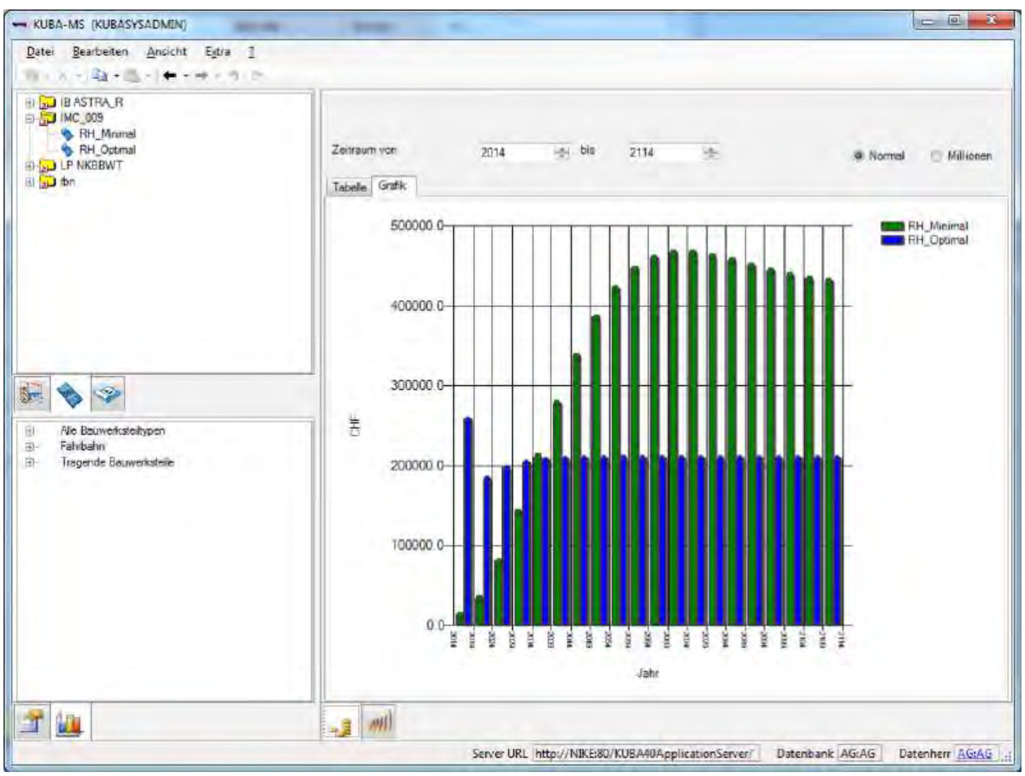


Figure 3.18 - Example of comparison of funding scenarios in KUBA.

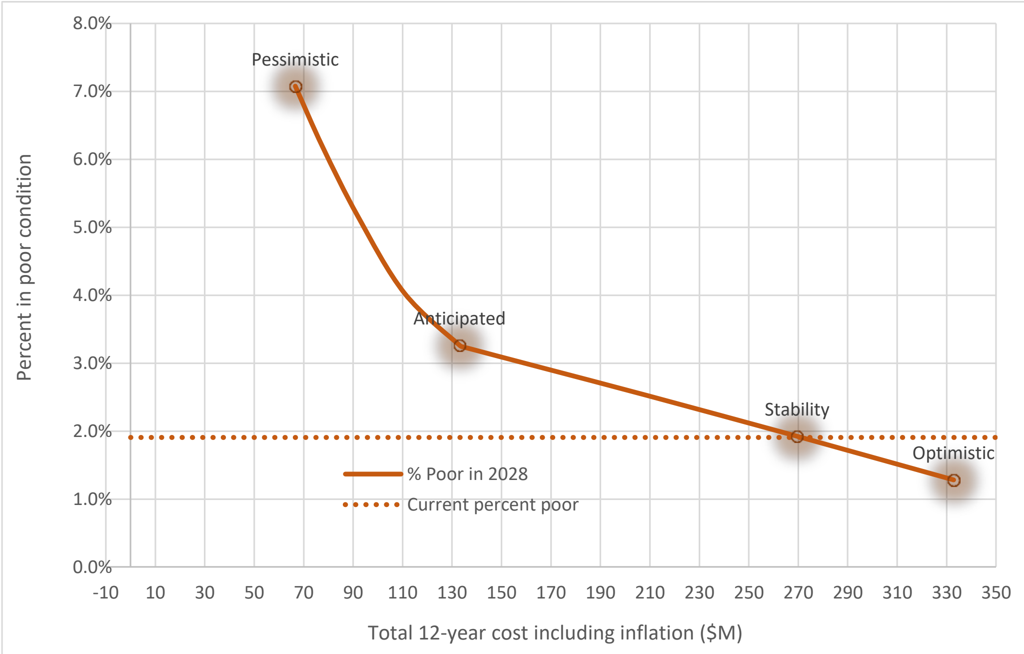


Figure 3.19 - Graph of network condition as affected by total funding level

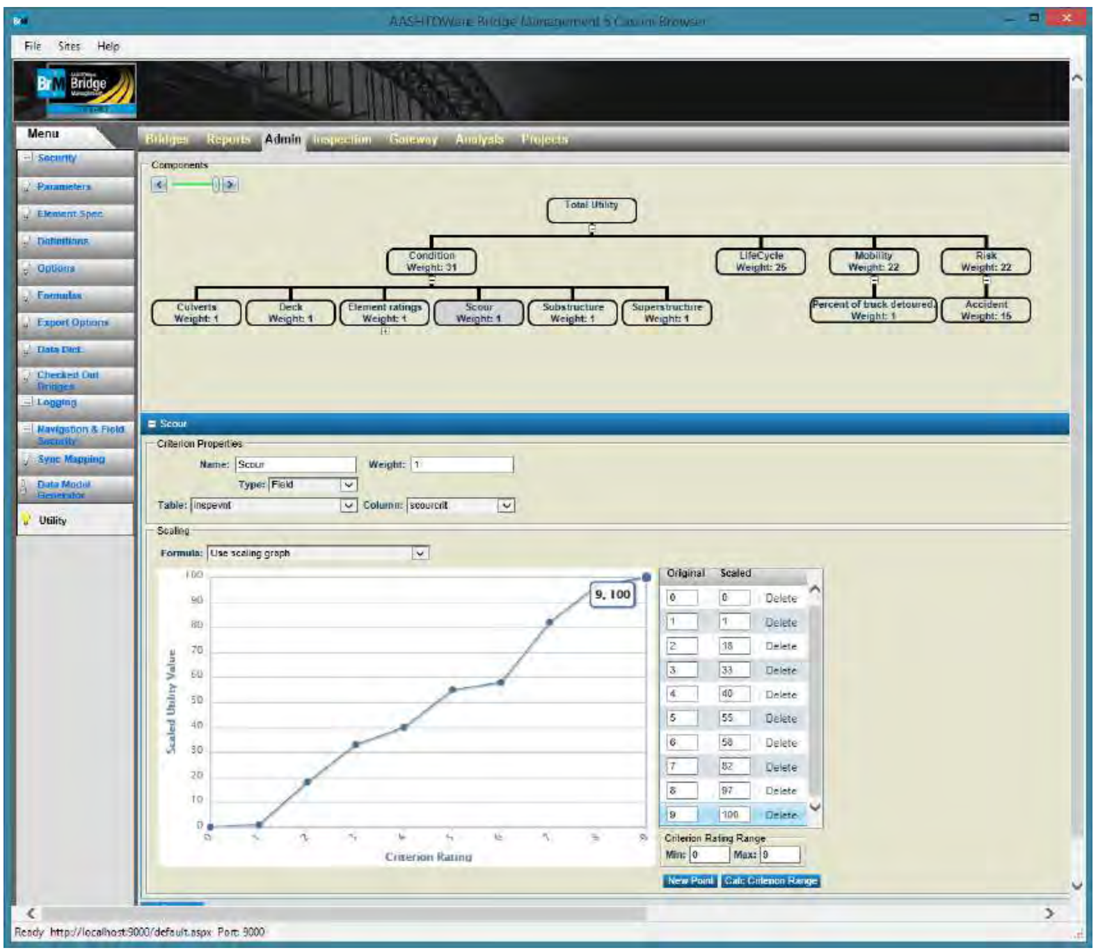


Figure 3.20 - AASHTOWare screen for defining a utility function.

3.3.6 Integration Features

Bridge management systems usually are developed separately from other asset management or engineering systems, and are not meant to be closely integrated with other systems. However, all of the commercially-available systems store their data in standard relational databases, which enables the sharing of data with other applications. The most common interfaces are with geographic information systems, maintenance management systems, and hand-held bridge inspection systems, all of which are available from commercial sources.

It is also common to use commercial report-writers (such as Microsoft Access or Crystal Reports) and spreadsheets (such as Microsoft Excel) to access bridge management system databases for analysis and reporting. Figures 3.21, 3.22, and 3.23 show examples.

A unique aspect of the dTIMS system is that it was initially developed as a pavement management system, which was later extended to bridges and other types of assets. The developer has incorporated some essential ingredients for bridge management such as element level inspection, but promotes its product as an asset management system for all infrastructure asset classes. As a result, there are no agencies which have implemented the system primarily for bridges without first implementing it for pavements.

A unique aspect of the AASHTOWare software is its close integration with AASHTOWare bridge design and load rating software packages in the same database. This is a very important concern for larger agencies where multiple new bridges are in the process of being designed and rated at the same time, and then must move reliably into the bridge management process once they are opened for service. The AASHTO framework facilitates the application of life cycle cost information to bridge design decisions, and enables its detailed model of bridge composition to provide accurate measurements of bridge elements. KUBA addresses a portion of this functionality by offering the ability to calculate the ability of a bridge or route to accommodate heavy trucks (Figure 3.24).

Figure 3.21 - Project level analysis spreadsheet developed for Florida DOT for use with the AASHTOWare bridge management software.

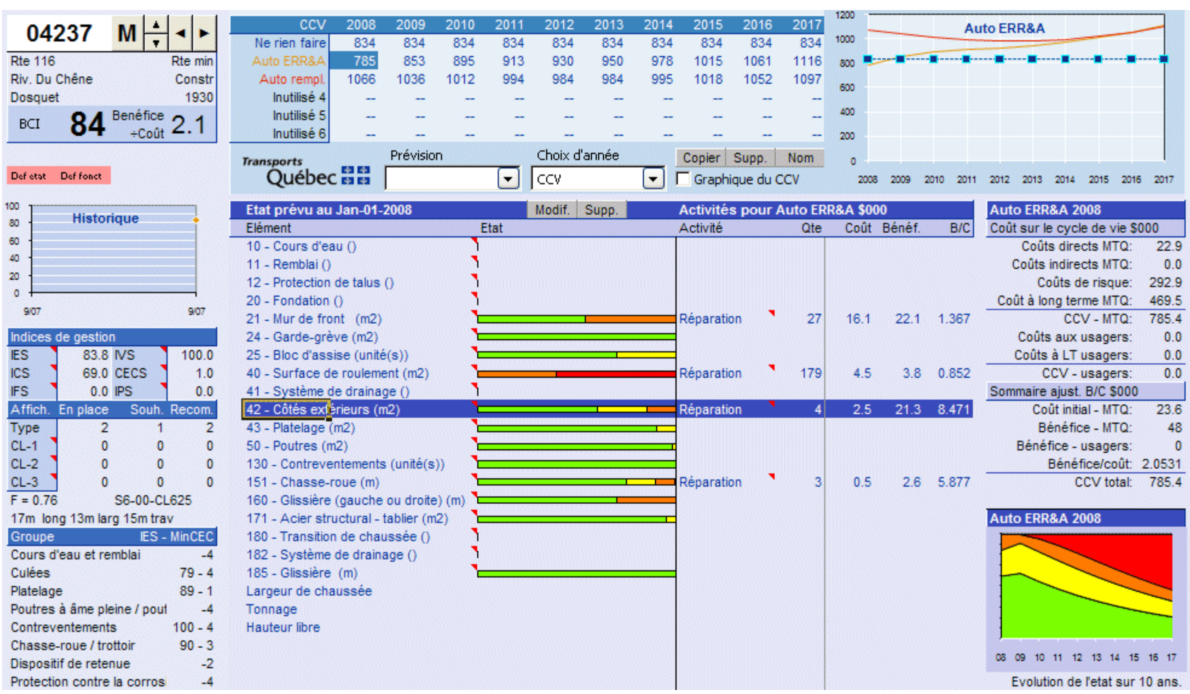
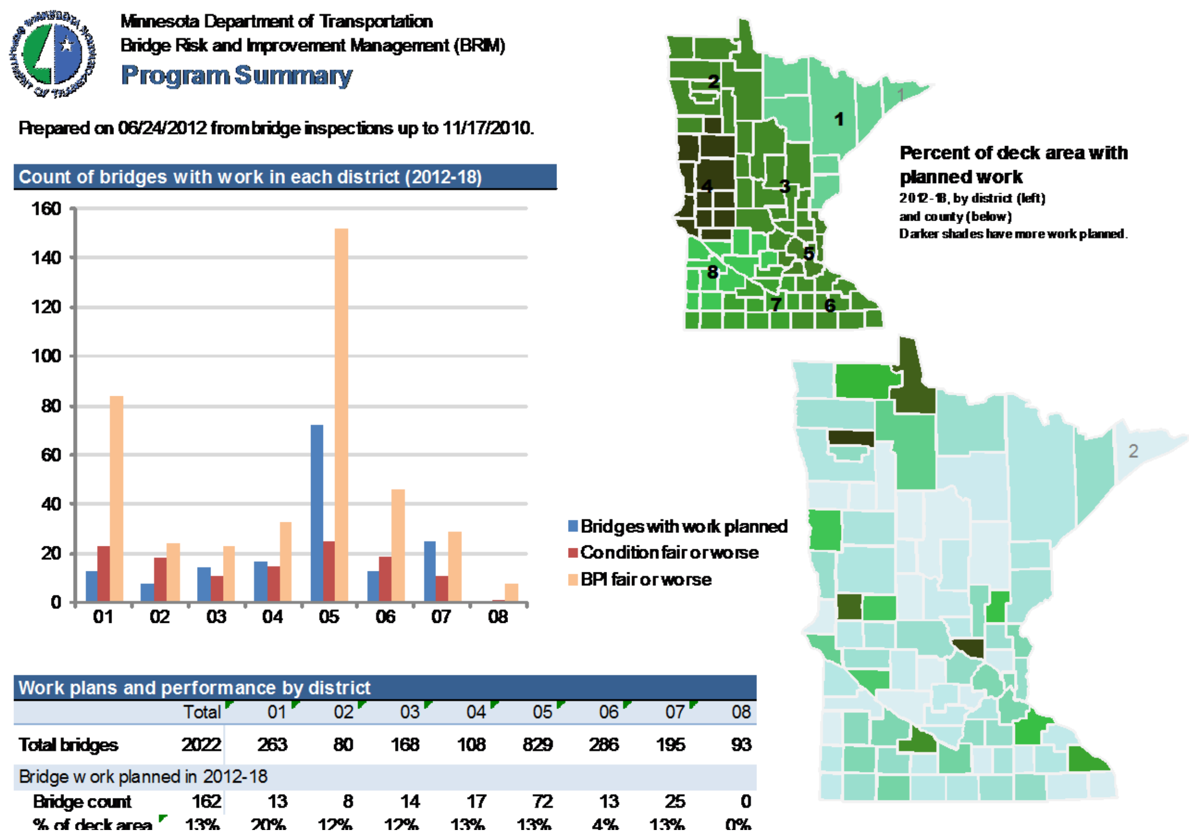


Figure 3.22 - Tactical planning dashboard developed for Québec for use with the Stantec BMS.



	Total	01	02	03	04	05	06	07	08
Total bridges	2022	263	80	168	108	829	286	195	93
Bridge work planned in 2012-18									
Bridge count	162	13	8	14	17	72	13	25	0
% of deck area	13%	20%	12%	12%	13%	13%	4%	13%	0%

Figure 3.23 - Risk analysis and work planning spreadsheet developed for Minnesota DOT for use with AASHTOWare BrM

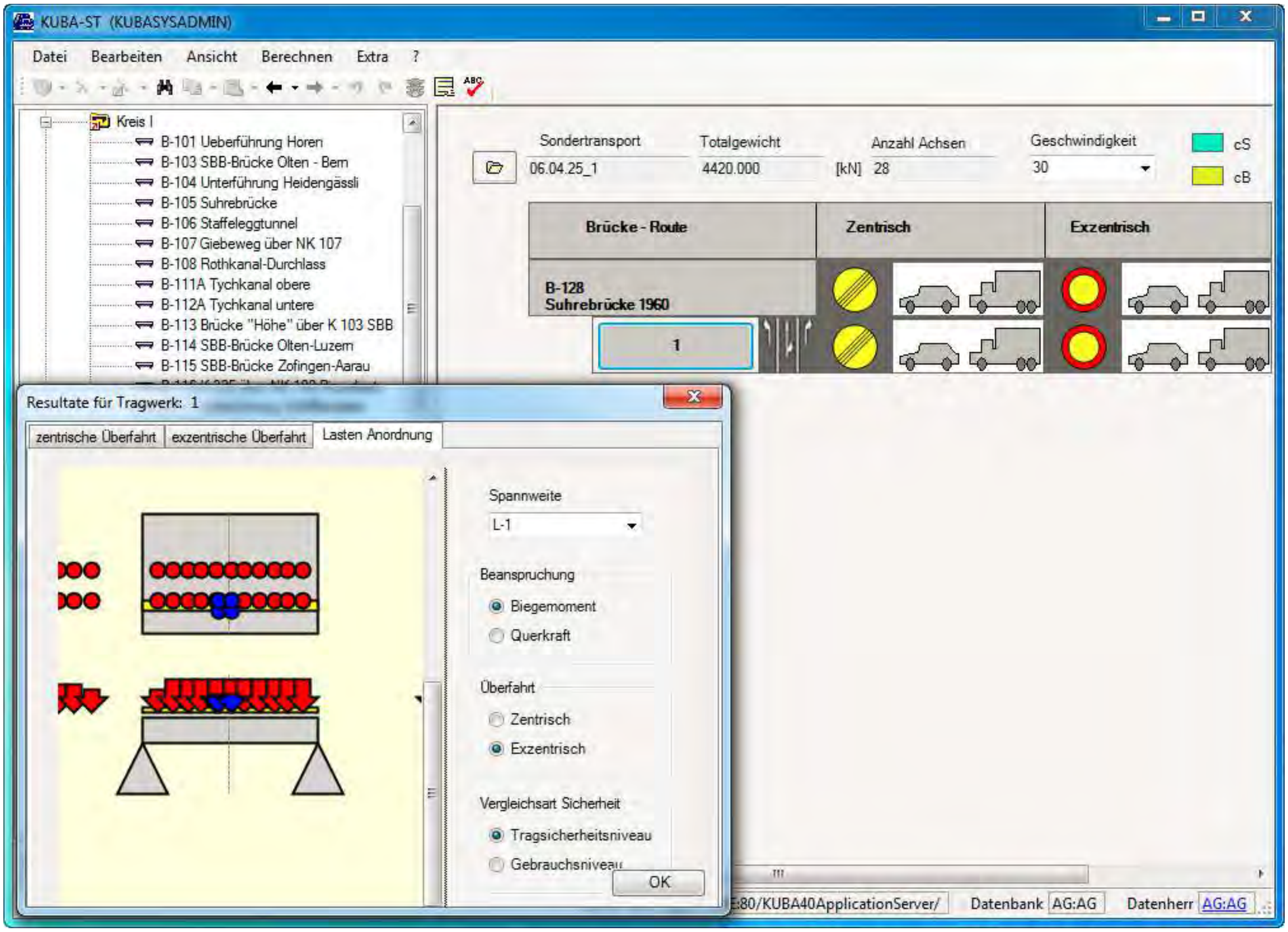


Figure 3.24 - Screen for evaluating heavy truck loads in KUBA.

For any of the four systems, certain system integration tasks will greatly enhance the accuracy and usefulness of the bridge management system:

- Traffic volume information. Most transportation agencies routinely gather traffic counts and store them in some type of database, usually as part of a geographic information system or a transportation planning system. Traffic data is essential for modeling safety and mobility benefits of bridge projects, so an automated linkage between the BMS and the traffic count database would be helpful.
- Detour information. Most transportation geographic information systems are able to compute detour route distance and time, information which is important for estimating mobility benefits of bridge projects.
- Maintenance and contract management. A live linkage to work accomplishment data can be useful in bridge management to support reporting on the status and completion of inspector work recommendations and capital projects planned using

the BMS. Each BMS has functionality to program projects based on the most recent inspection and funding constraints; but will not necessarily know whether a project is already funded or underway unless such information is provided from another system. For the long term, it is also important that each maintenance or capital project involving a bridge have clear data that identifies the affected bridges and the type of work done, information which can be used later to develop better deterioration and cost models.

- Document and image management. Many agencies have document management systems to organize engineering drawings, photographs, and other important documents. All four of the commercial bridge management systems offer features to link these documents to bridges. The AASHTO, Stantec, and KUBA systems have internal document management features which support linkages to inspections and element inspections, which make it easier to organize the large number of photographs that may be taken during an inspection (Figure 3.25). The Stantec system further supports keyword search features that make it possible, for example, to find commonalities in defects across multiple bridges over time in order to increase management understanding of bridge problems.

In the USA and several other countries, agencies increasingly are developing enterprise asset management strategies involving a comprehensive list of asset categories, extending beyond pavements and bridges to include unstable slopes, signs, traffic control devices, marine infrastructure, airports, water, and sewer systems (Gordon et al. 2011, Thompson 2013). Although bridge management systems have some unique requirements that may necessitate a separate information system, the need for building connections among asset management systems, especially for planning and programming purposes, is likely to increase in the future.

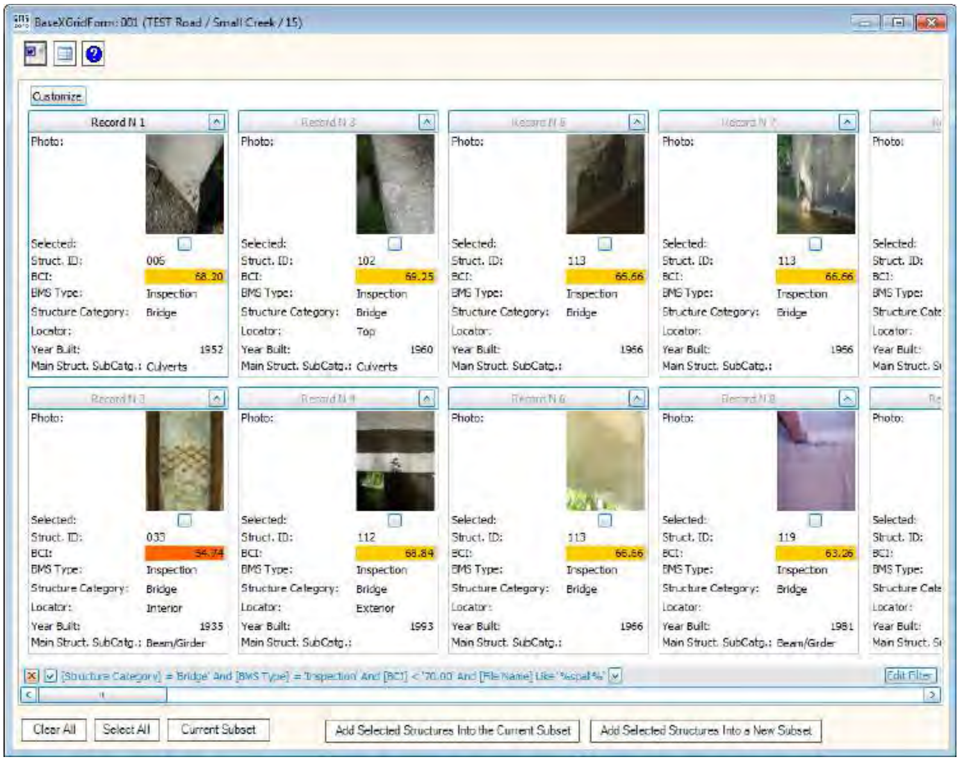


Figure 3.25 - Management of inspection photographs in the Stantec BMS.

3.4 Findings

In general, the research found wide variation among states in the methods used for managing Big Bridges. No one agency or type of agency had implemented every type of innovation. Therefore, a description of the state of the art is necessarily a composite of methods and tools found across a significant number of agencies. The following sections describe the most notable contributions in each area of bridge management.

3.4.1 Business Plans and TAM Plans

MAP-21 calls on state Departments of Transportation to prepare risk-based Transportation Asset Management Plans (TAM Plans) for the National Highway System (NHS) to "*improve or preserve the condition of the assets and the performance of the system*". The legislation mandates the establishment of condition and performance targets for at least pavements and bridges, and requires the TAM Plan "*to include strategies leading to a program of projects that would make progress toward achievement of the targets.*" Although only pavements and bridges are mandatory in the TAM Plans, states are encouraged "*to include all infrastructure assets within the right-of-way corridor in such plan*." (23 USC 119(e))

On 20 February 2015, FHWA published a Notice of Proposed Rule-Making (NPRM) to present its proposed regulations regarding the TAM Plan requirements (FHWA 2015). The

NPRM specifies in Section 515.009(f) that the TAM Plan shall cover at least a 10-year period, shall be made easily accessible to the public, and shall establish a set of investment strategies that improve or preserve condition and performance in support of the national goals in 23 USC 150(b).

The regulation explicitly links the TAM Plan to the Statewide Transportation Improvement Program (STIP), which is the primary vehicle for programming of transportation projects. Section 515.009(h) says "A State DOT should select such projects for inclusion in the STIP to support its efforts to achieve the goals" of the TAM Plan. Section 515.009(d) lists the minimum content of the TAM Plan:

1. TAM objectives, aligned with agency mission;
2. Performance measures and targets;
3. Summary of asset inventory and condition;
4. Performance gap identification;
5. Life cycle cost analysis;
6. Risk management analysis;
7. Financial plan;
8. Investment strategies.

Many state DOTs use pavement and bridge management systems to develop much of the preservation component of the STIP. If the TAM Plan is to drive major parts of the STIP, then it must also feed back into the management systems to ensure a consistent linkage.

Almost all big bridges in the USA are on the National Highway System and are therefore required to be included within the TAM Plan and within state performance targets, according to the proposed rules. In the Task 4 interviews it was found that most rehabilitation and replacement work on big bridges is included in STIPs, with the exception of a few toll agencies that do not receive federal funds.

3.4.2 Business Plan Contents

Many big bridges are owned and/or operated by independent or semi-independent authorities, many of which are wholly or partly toll-funded. Many of these agencies were found to have published business plans, which contain many of the same ingredients as are required in TAM Plans. In the business plans that were reviewed in the present study, the following ingredients were typically found:

- Description and history of the agency and/or facilities
- Description of the organizational structure and governance
- Statements of mission, vision, and values
- Listing of strategic goals, often with listings of strategies or management initiatives related to each goal. Some of the business plans also include performance measures relating to each goal.
- Competitive analysis and business partnerships
- Historical traffic, revenue, and toll rates
- Historical capital and operating expenditures
- History and status of debt financing
- Forecast of revenue over 5 to 30 years in the future
- Forecast of operating expenses over a time period ranging from 5 to 30 years
- Program of projects for capital expenditures, including preservation and service improvement, over a period ranging from 5 years to 40 years. Some of the business plans include capsule descriptions of each project, from 1/3 page to a full page for each project.
- Vehicle and equipment replacement schedule

Strategic Goals

All of the business plans reviewed include statements of strategic goals. For State DOTs, it is common for such goals to be stated in enabling legislation or strategic plans. At the federal level, national goals are stated in 23 USC 150(b) as:

- Safety
- Infrastructure condition
- Congestion reduction
- System reliability
- Freight movement and economic vitality
- Environmental sustainability
- Reduced project delivery delays

All of these national goals can be commonly found in toll authority business plans as well. In addition, toll authority business plans typically include goals of revenue maximization and customer satisfaction. When customer satisfaction is listed as an agency goal, it is sometimes used as a catch-all category for all aspects of performance affecting road users, including safety and mobility. Other times, it refers to services distinct from safety and mobility of general traffic. The Mackinac Bridge Authority, for example, lists the following customer services in its business plan:

- Escorting over width trucks
- Escorting heavy trucks
- Escorting trucks hauling hazardous materials
- Escorting wind susceptible vehicles during strong winds
- Providing drivers to motorists who wish not to drive themselves
- Transporting passengers
- Transporting bicycles
- Transporting snowmobiles
- Providing support to community sponsored events at the Mackinac Bridge Authority (i.e. bicycle, jogging, car parades, and truck parades)
- Coordinating special events and functions (i.e. Annual Bridge Walk)
- Patrolling the bridge and properties
- Weighing trucks
- Assisting stranded motorists
- Assisting law enforcement agencies
- Providing bridge information to motorists and other interested parties

It can be seen that these services are most relevant to big bridges and are less common on other bridges.

Performance Measures

TAM Plans are required to address performance measures, targets, current condition, and performance gaps. The draft TAM Plans currently available almost all contain summaries of statewide bridge condition, which includes the big bridges owned by the state and by special authorities within the state. Many of the states collect condition data at the element level and then use a translator program to derive other federally-mandated condition and performance measures.

The business plans of toll authorities have very little asset performance information, typically limited to safety statistics. The review in this study found no such plans that quantified bridge condition at the element or bridge level, and no information that might have been derived from element level data. The Maryland Transportation Authority does track the response rate to defects identified in bridge inspections, and also tracks a few measures related to vehicle throughput focused on toll collection operations, in addition to safety measures.

Network-Level Life Cycle Cost and Risk

TAM Plans are required to include analyses of life cycle cost and risk. Most of the draft plans currently available do this in a quantitative or semi-quantitative way. The state of the art is to use bridge management systems to perform these calculations for each individual bridge (as described in the previous chapter), then aggregate over the network to show how agency policies of preservation and risk management relate to quantitative measures of long-term cost and risk.

Clearly the size and utilization of big bridges give them a disproportionate impact on long-term cost and risk. This is reflected in state-of-the-art bridge management system analyses. None of the toll authority business plans address this issue, however, and none of the state DOT TAM Plans available thus far call out the special role of big bridges.

Network Performance Targets

MAP-21 and subsequent draft rules mandate that bridge condition be reported as the percent of total deck area on bridges in Good and Poor condition. Ten-year targets must be established by each state for these measures, and the legislation also includes a uniform target for percent of deck area on structurally deficient bridges.

The state-of-the art is to use bridge management system models, as discussed in Section 3.3, to project needs year-by-year, including future needs that are likely to arise because of future deterioration. Conditions are based on element-level data, and deterioration models operate at the element level. Needs are prioritized each year to fit a range of fiscal scenarios, with priority based on forecast performance outcomes including life cycle cost, safety, mobility, and sustainability, taking risk and functional needs into account. In general, higher fiscal scenarios yield higher levels of performance and more ambitious targets.

Most of the draft TAM Plans currently available show these targets. The targets are typically developed separately for National Highway System (NHS) bridges and for non-NHS bridges. Often there are also separate targets for state-owned and non-state-owned bridges. So far none of the states have published separate targets specific to big bridges. None of the toll authority business plans has condition targets, either.

In the interviews conducted as a part of this task, most of the respondents agreed with a statement that big bridges are, in general, a significant risk factor in the attainment of deck area weighted targets. Respondents agreed that there may be special management concerns attached to big bridges that are on the borderline between Good and Fair, or Fair and Poor. However, few agencies so far have identified specific management strategies for such bridges.

Michigan DOT is one exception. MDOT is targeting 100 percent of its big bridges to be in Good or Fair condition. Big bridges in Michigan entail 23 bridges having deck area over 100,000 sq.ft, plus 10 structurally complex bridges, and 11 movable bridges. Currently five of the bridges are in Poor condition, but once rehabilitation or replacement of these bridges is complete in 2021, MDOT projects that it will attain the 0% Poor target for these bridges. Provided that the Department is able to allocate sufficient funding, MDOT hopes to prevent any additional big bridges from moving to the Poor category over the next ten years.

Rhode Island DOT is in the process of developing a similar type of strategy. Currently it significantly violates the federal target of 10% of deck area on structurally deficient bridges, and its big bridges are a significant contributor to this problem. RIDOT has developed a special 10-year program of replacement and rehabilitation to reduce the percent structurally deficient to under 10%. Then the Department hopes to allocate sufficient funding to maintain performance at this level or better.

3.4.3 Needs Assessment and Project Planning

As discussed in the previous section, bridge management systems use element level data to identify preservation needs, develop alternatives for project scoping and timing, perform cost estimation and life cycle cost analysis, quantify risks and the risk reduction benefits of projects, and select among project alternatives. Most of the state DOTs surveyed intend to use AASHTOWare Bridge Management (BrM) for these functions, but Indiana is using dTIMS. Florida has its own software for this, to use in conjunction with BrM. New York and Wisconsin are developing their own software. This state of the art approach is used for all bridges in the inventory, including Big Bridges.

Toll authorities in principle have access to the bridge management systems licensed and operated by state DOTs, but the research team did not encounter any toll authorities that were actually using their states' systems for project planning. It was much more common that this activity was performed by consultants without the quantitative tools used by state DOTs.

A disadvantage of this informal judgment-based approach is the tendency to ignore events that are considered unlikely, without making an allowance for them in financial projections. This can cause needs to be chronically under-estimated. For example, if the probability of needing a $10 million deck overlay within ten years is 10%, a program of projects developed from judgment would tend to omit the deck overlay from a ten-year capital program. A fiscal projection using a formal deterioration model, on the other hand, would make an allowance of $1 million for this work within the ten-year period. The chronic under-estimation of needs can negatively impact the relationship between the agency and its governing bodies, as well as contribute to public cynicism.

A symptom of this problem that was observed in the financial statements of several agencies, was a decline in identified capital and preservation needs over time in projections 10 to 40 years into the future. A bridge management system, with its more consistent use of deterioration models, would be less likely to produce this pattern.

Dividing a Big Bridge into Smaller Ones

A few respondents have processes in place to divide up big bridges into smaller ones for project definition purposes. When element-level data is an essential input to the process, the agency would need to have separate element inspections for the parts of the bridge to be separated. Agencies that perform span-by-span inspection – such as New York, Pennsylvania, and Texas – have considerable flexibility to do this.

A bridge that is divided up into smaller bridges can be managed as if it were a network of smaller structures, with separate project scopes, different contracts and contractors, and different timing. Interviewees mentioned several potential advantages if this were to be done:

- The ideal timing of work might vary for different parts of a bridge, especially if past replacement and rehabilitation were performed at different times. The might minimize long-term costs.
- More contractors might be able to bid on work if the projects are smaller in scope. This might lead to lower costs.
- It is easier to identify funding, and opportunity costs are reduced, if projects are kept smaller.
- For bridges composed of multiple structure types or materials, the deterioration rates and needed construction capabilities may vary in different parts of the structure.

Interviewees also identified disadvantages of this approach:

- Construction timelines and traffic disruptions might be prolonged.
- Economies of scale might be lost.
- Bridge management systems have weak support for analyzing projects defined in this way.

Considering the diversity of agencies interviewed, it was found that agencies having bridges of length 8,000 to 12,000 feet or longer were more open to dividing up their bridges, and in some cases felt that they were compelled to do so because of fiscal constraints. Agencies having no bridges this large were more likely to avoid this strategy except as a last resort.

Louisiana DOT, which has some of the nation's longest bridges, indicated that it works around BMS limitations to some extent by permanently dividing bridges on district and parish boundaries. It does this in its AASHTOWare BrM database and in its National Bridge Inventory (NBI) reporting.

BrM allows bridges to be divided into separate structure units, which can have separate lists of elements. So even bridges that are reported in a single NBI record can, in theory, be divided into separate work candidates for project planning. BrM does not automate this process of defining projects along structure unit lines, however, so the partitioning would have to be done manually. Virginia is one of the states that does this. They prioritize among spans according to the risk of inaction, similar to the way they prioritize among bridges. So the choice of how to group parts of a bridge into projects is not permanent: it can vary based on what conditions and needs are observed by inspectors.

Work Zone Traffic Strategies

With high traffic volumes typical on big bridges, strategies for maintenance of work zone traffic play a major role in project definition. When fiscal constraints allow it, agencies commented that it is desirable to complete work on an entire bridge all at once. For deck and wearing surface replacement, many agencies in the survey try to complete one lane at a time across the entire bridge to minimize lost throughput capacity. However, if a big bridge has a cash toll plaza or customs facility at one end, it may be necessary to use all available space for storage of waiting vehicles. Two of the toll authorities noted this as a reason to divide work into smaller projects and postpone portions of a project.

California described its strategy to perform as much deck and joint work as possible at night and on weekends, using temporary work zones. The objective is to reopen all traffic lanes in time for the start of rush hour on weekday mornings. Given the availability of contractor skills and logistical limitations in moving materials to the work site, this may necessitate dividing projects into smaller increments of work spread over a longer period of time.

Most of the agencies interviewed use contractual incentives and disincentives to speed project completion. Many use user cost models, especially the AASHTO Red Book, to determine the size of the incentives or penalties. Since user costs are proportional to traffic volume, these contractual provisions can be very significant. Certain states, especially Virginia and California, noted an agency policy to make widespread use of these incentives even on smaller structures.

Project Evaluation

As noted above, agencies that have implemented bridge management systems (BMS) tend to be more consistent and complete in evaluating the benefits of bridge projects, regardless of the size of bridge. The majority of the agencies that routinely consider life cycle cost and risk in their project development decisions, are able to do so because it is a function built into their BMS.

An example of a customized, consultant-developed life cycle cost analysis is presented in Figure 3.26. The report used this worksheet to compare two alternatives. The example did not appear to provide a means of investigating timing alternatives or of generating any other alternatives other than the two that the consultant identified. The example provides information at about the same level of detail as would be generated in a bridge management system, and potentially could be generated by BrM with the ability to compare more alternatives in order to optimize the scope and timing of work.

2016 **BRIDGE LCCA WORKSHEET** REV. 12/15/2015

EPOXY OVERLAY, DECK PATCHING, SUPERSTRUCTURE & SUBSTRUCTURE PATCHING

REGION:	METRO	DATE:	10/16/2015	STRUCTURE ID:	SN 12092
ENGINEER:	Eric Rickert, P.E.	DECK AREA:	200,240 SFT	BRIDGE ID:	B01-82700
LOCATION:	Belle Isle Traffic over Detroit River	DECK DIM:	2,268'-4.5" x 88'-0" to 96'-6"	STR. TYPE:	Concrete encased structural steel arch

WORK ACTIVITY		UNIT	UNIT COST	Year 0 - 2019 EPOXY OVERLAY		Year 15 - 2034 CONCRETE OVERLAY & PATCHING		Year 40 - 2059 BRIDGE REPLACEMENT		Year 55 - 2074 HEALER SEALER		Year 85 - 2084 EPOXY OVERLAY W/ PATCHING	
				QUANTITY	TOTAL	QUANTITY	TOTAL	QUANTITY	TOTAL	QUANTITY	TOTAL	QUANTITY	TOTAL
NEW BRIDGE													
Multiple Spans, Concrete	(add demo & road approach & traffic control)	SFT	$220.00 /SFT					200,246.0	$44,054,120				
Multiple Spans, Steel	(as above)	SFT	$250.00 /SFT										
Over Water or Single Span	(add to replacement cost)	SFT	$75.00 /SFT					200,246.0	$15,018,450				
Precast 3-sided Culvert or 4-sided Box Culvert	(add removal, roadway over & t.c.)	SFT	$400.00 /SFT										
Other													
NEW SUPERSTRUCTURE													
Concrete	(includes remove exist super, new railing; add t.c. & approach)	SFT	$140.00 /SFT										
Steel	(as above)	SFT	$180.00 /SFT										
Over Water	(add to new superstructure cost)	SFT	$40.00 /SFT										
Other													
WIDENING													
Added portion only ______ ft of width	(add road approach transition)	SFT	$280.00 /SFT										
Other													
NEW DECK													
Includes remove exist deck & new railing	(add traffic control & approach)	SFT	$75.00 /SFT										
Other													
DEMOLITION													
Entire bridge, grade separation		SFT	$32.00 /SFT										
Entire bridge, over water		SFT	$42.00 /SFT					200,246.0	$8,410,332				
Other													
SUPERSTRUCTURE REPAIR													
Concrete Deck Patch	(includes hand chipping)	SFT	$38.00 /SFT	5,619.0	$213,522							6,010.0	$228,380
Full Depth Patch		SFT	$80.00 /SFT										
Sidewalk Patch	(includes hand chipping)	SFT	$38.00 /SFT	2,888.0	$109,744								
HMA Overlay with WP membrane	(add bridge rail if req'd)	SFT	$5.50 /SFT										
Removal of Concrete Wearing Course (latex) or HMA Overlay		SFT	$1.50 /SFT										
Healer Sealer		SYD	$22.00 /SYD							15,505.0	$341,110		
Epoxy Overlay	2269'x61.5'	SYD	$34.00 /SYD	15,505.0	$527,170							15,505.0	$527,170
Shallow Overlay	(includes joint repl & hydro; add bridge rail if req'd)	SFT	$30.00 /SFT			133,830.0	$4,014,900						
Deep Overlay	(includes joint repl & hydro; add bridge rail if req'd)	SFT	$32.00 /SFT										
High Load Hit Repair	(PCI Beam)	SFT	$260.00 /SFT										
PCI Beam End Repair	($2800-$5600 per beam end)	EA	$4,200.00 EA										
Repair Structural Steel	($4800 bolted, $6800 welded)	EA	$6,000.00 EA										
Paint Structural Steel	(includes clean & coat)	SFT	$12.00 /SFT										
Other: Epoxy Crack Injection	(2'x2x8 beams x 19 spans)	LFT	$32.00 LFT	608.0	$19,456								
Soffit Patching (shotcrete) 9781sft x 2		SFT	$80.00 /SFT	19,562.0	$1,564,960								
Other: Superstructure patching (9544sft x 2 x .33')		CFT	$350.00 /CFT	6,300.0	$2,205,000								
SUBSTRUCTURE REPAIR													
Pier repair	(measured x 2) Replace unit if spalled area > 30%	CFT	$310.00 /CFT										
Pier repair over water	(measured x 2) (2578sft x 2 x 0.33')	CFT	$350.00 /CFT	1,702.0	$595,700								
Pier replacement		CFT	$90.00 /CFT										
Abutment repair	(measured x 2) (75sft x 2 x 0.33')	CFT	$310.00 /CFT	50.0	$15,500								
Temporary Supports for Substructure Repair		EA	$1,800.00 EA										
Slope Protection repairs		SYD	$100.00 /SYD										
Other: Epoxy Crack Injection		FT	$32.00 /FT	441.0	$14,112								
MISCELLANEOUS													
Expansion or Construction Joints	(includes removal) (5 exp jts x 61.5') + all sdwk joints	FT	$560.00 /FT	840.0	$470,400							2,460.0	$1,377,600
Bridge Railing, remove and replace	($230 Type 4, $310 Aesthetic Parapet)	FT	$290.00 /FT										
Thrie Beam Railing retrofit		FT	$40.00 /FT										
Deck Drain Extensions (19 spans x 2 x 2)		EA	$500.00 EA	76.0	$38,000								
Articulating Concrete Block System (ACB)		SYD	$130.00 /SYD										
Other: Electrical hand hole repairs		LSUM	$10,000.00 LSUM	1.0	$10,000								
Other: Pedestrian Railing Repairs		LSUM	$20,000.00 LSUM	1.0	$20,000								
ROAD WORK													
Approach Pavement, 12" RC	(add C & G, GR, Slope, Shldr.) 40' ea. end	SFT	$16.00 /SFT	4,920.0	$78,720	4,920.0	$78,720	4,920.0	$78,720				
Approach Curb & Gutter	(18' ea. quad.)	FT	$55.00 /FT			144.0	$7,920	144.0	$7,920				
Guardrail Anchorage to Bridge	(<40')	quads	$1,600.00 /quad										
Guardrail, Type B or T	(beyond GR anchorage to bridge, <200')	FT	$23.00 /FT										
Guardrail Ending	(end section)	EA	$1,750.00 /EA										
Roadway Approach work	(beyond approach pavement)	LSUM	$100,000.00 LSUM	–		1.0	$100,000	1.0	$100,000				
Utilities: protection of sidewalk conduits for patching and joint replacement		LSUM	$10,000.00 LSUM	1.0	$10,000			1.0	$10,000				
Other													
TRAFFIC CONTROL	*(Unit Cost to be determined by Region or TSC Traffic & Safety)*												
Part Width Construction		LSUM	$100,000.00 LSUM	0.5	$50,000	1.0	$100,000			0.5	$50,000	1.0	$100,000
Crossovers		EA	$275,000.00 EA										
Temporary Traffic Signals		set	$22,000.00 /set										
RR Flagging		LSUM	LSUM										
Detour		LSUM	LSUM										
Other: Temporary Bridge (2x12' + 2x10') x (2270') = 99,880 sft		LSUM	$10,000,000.00 LSUM					1.0	$10,000,000				
CONTINGENCY	(10% - 20%) (use higher contingency for small projects)	%		20	$1,188,000	20	$860,000	10	$7,768,000	20	$78,000	20	$447,000
MOBILIZATION	(use 10%)	%		10	$713,000	10	$516,000	10	$8,545,000	10	$47,000	10	$268,000
(DOES NOT INCLUDE PE & CE)			CONSTRUCTION TOTAL		$7,843,000		$5,678,000		$93,993,000		$516,000		$2,948,000

Figure 3.26 - Example of project life cycle cost analysis (Michigan DOT)

Continuous Work

Several respondents interviewed in this task indicated that their agency has one or more big bridges that they plan to never replace. For these structures, an investment plan of recapitalization is necessary to ensure that the bridge can remain in service indefinitely, even if specific components are sometimes replaced. Several agencies also indicated that they have this goal for deck replacements as well, that they use protective elements and strict maintenance policies to try to keep deck structures in good condition so that deck replacement is rarely if ever needed. Agencies that have been following such a policy for a significant time report that they rarely replace bridge decks any more. Examples are Washington, which has significant use of deicing chemicals, and Florida, which experiences marine environments on many of its structures.

Some agencies having this type of policy use life cycle cost analysis to optimize preservation activities under an assumption that element replacement is feasible but bridge replacement is not. Others merely follow a policy of constant maintenance to keep protective systems in good condition, and might not have attempted to optimize the application rate of treatments. California is an example where both types of policies have been used. Exceptionally large bridges, such as the San Francisco-Oakland Bay Bridge, famously have full-time paint crews that never stop painting the structure. On other big bridges which are not quite as large, such as the San Diego Coronado bridge, the agency has used life cycle cost analysis to move from a continuous work scenario to one where a few years are allowed to elapse between painting cycles, to achieve a lower long-term cost.

3.4.4 Prioritization and Resource Allocation

Agencies often use their BMS to apply a set of statewide budget constraints, and to prioritize bridge projects within that constraint for each year of a program. Some agencies divide their networks into districts or other administrative units with separate budgets. Up until recently, it has been common practice to use federal funding allocations to establish the budget constraints.

For big bridges, it is becoming increasingly common to set aside a separate funding reserve and to establish separate, often more rigorous, performance objectives. The Michigan example, discussed earlier, is a case where the Department wishes to keep 100% of its big bridges in Fair or better condition, and will need to ensure that enough funding is set aside to accomplish this. It would be sensible to prioritize work within this program to minimize the risk of a bridge moving from Good to Fair or Fair to Poor.

Big bridges sometimes have a non-redundant role in the transportation network, or may have very long detour routes. Agencies that may prioritize work on most of their bridges based on condition or agency life cycle cost, may prioritize their big bridges differently, for example, considering traffic volume and risk of service disruption.

Virginia DOT, for example, has developed a risk-based scoring system for its 22 largest and most complex bridges, known as Special Structures. The plan uses a judgment-based score on a scale of 1 to 10 for the likelihood and consequences of problems, in categories of safety, traffic, and value of structure (Figure 3.27). The methodology does not specify the nature of problems and does not weight the separate categories. The value category could consider life cycle cost impacts, but this is not explicit. VDOT is considering a more objective means of quantifying life cycle cost and risk, possibly in conjunction with its implementation of AASHTOWare Bridge Management.

CATEGORY	STRUCTURE	Annual General Maintenance Need (thousands)	Projects			Risk$_a$ (likelihood of problem if work isn't done)			Risk$_b$ (potential consequences of problem if work isn't done)			Risk Score	10 Year Interval
			Cost (Millions)	Ideal Ad Year	Description of Work	Safety	Traffic	Value of Structure	Safety	Traffic	Value of Structure		
TUNNELS	Big Walker Mountain	$1,300	11	2020	Electrical and Mechanical Systems	6	4	4	7	7	5	5.50	1
TUNNELS	East River Mountain	$1,400	11	2020	Electrical and Mechanical Systems	6	4	4	7	7	5	5.50	1
TUNNELS	Hampton Roads Bridge Tunnels	$600	25	2020	Electrical, Mechanical Systems&Ceiling	6	4	4	7	8	5	5.67	1
			56	2020	Fire Detection, Suppr & Safety	7	4	4	9	8	7	6.50	1
			13	2020	Traffic Control Upgrades	4	7	3	6	8	3	5.17	1
			15	2020	Structural Repairs	6	8	6	6	5	6	6.17	1
			43	2030	Upgrades & Repairs	6	5	5	6	5	4	5.17	2
			118	2040	Upgrades & Repairs	6	5	5	6	6	4	5.33	3
TUNNELS	Monitor Merrimac Memorial Bridge Tunnel	$500	55	2020	Electrical and Mechanical Systems	6	5	4	7	6	4	5.33	1
			56	2020	Fire Detection, Suppr & Safety	7	4	4	8	7	7	6.17	1
			13	2020	Traffic Control Upgrades	4	7	3	6	8	3	5.17	1
			20	2020	Structural Repairs	5	7	6	6	4	4	5.33	1
			40	2030	Upgrades & Repairs	5	5	5	6	5	4	5.00	2
			100	2040	Upgrades & Repairs	5	5	5	6	5	4	5.00	3
TUNNELS	Downtown Tunnel	$0	0		Maintained by Others							N/A	
TUNNELS	Midtown Tunnel	$0	0		Maintained by Others							N/A	
TUNNELS	Rosslyn Tunnel	$450	0		None							N/A	
MOVABLE BRIDGES	Chincoteague	400	16	2040	Electrical and Mechanical Systems	6	5	4	7	6	4	5.33	3
MOVABLE BRIDGES	High Rise	200	23	2020	Trunion, Generator, Span Locks	4	7	3	3	8	3	4.67	1
			425	2030	REPLACE STRUCTURE							N/A	2
MOVABLE BRIDGES	Berkley	500	60	2025	Rehabilitate Structure	4	6	5	4	7	6	5.33	2
MOVABLE BRIDGES	Coleman	400	30	2030	Paint, Electrical, Drives, Sub, Cables	3	5	6	3	7	5	4.83	2
MOVABLE BRIDGES	James River	250	30	2020	Drives, Span Locks	3	7	8	4	8	5	5.83	1
MOVABLE BRIDGES	Benjamin Harrison	300	12	2017	Structural & Security Repairs	7	7	9	10	7	9	8.17	1
			27	2020	Electrical&Mech Systems	3	6	7	3	6	6	5.17	1
			10	2027	Vessel Impact Protection	2	3	2	10	4	9	5.00	2
MOVABLE BRIDGES	Eltham	300	9	2045	Electrical and Mechanical Systems	3	5	7	3	6	7	5.17	3
MOVABLE BRIDGES	Gwynn's Island	250	0		None							N/A	
COMPLEX STRUCTURES	Varina Enon	$30	$25	2021	Tendon and Cable Stay Repairs	5	5	9	7	5	8	6.50	1
			$15	2035	Concrete overlay	5	6	7	6	6	7	6.17	2
COMPLEX STRUCTURES	Norris bridge	$240	$17	2017	Paint Structural Steel	3	3	8	2	3	6	4.17	1
			$53	2025	Replace Deck & Repair Structural Steel	7	6	7	7	7	8	7.00	2
COMPLEX STRUCTURES	HRBT approaches	$200	$55	2017	Pile Jackets & Super Repairs	6	9	10	6	9	10	8.33	1
			$21	2018	Concrete Overlay	7	8	9	8	9	9	8.33	1
COMPLEX STRUCTURES	I-64 over Willoughby Bay	$50	$7	2018	Overlay & Joints	7	8	9	8	9	9	8.33	1
			$15	2018	Pile Jackets & Super Repairs	6	9	10	6	9	10	8.33	1
COMPLEX STRUCTURES	MMMBT approaches	$300	$25	2018	Waterproofing & Overlay	3	6	7	3	5	7	5.17	1
			$40	2025	Pile Jackets	4	6	7	7	7	8	6.50	2
			$13	2035	Overlay & Coating	3	6	7	3	5	7	5.17	2
			$8	2040	Fender	2	3	2	10	4	9	5.00	3
COMPLEX STRUCTURES	James River Bridge Approaches	$800	$41	2018	Overlay, Joints & Waterproofing	7	8	9	8	9	9	8.33	1
			$20	2025	Fender	2	3	2	10	4	9	5.00	2
			$40	2030	Pile Jackets	4	6	7	7	7	8	6.50	2
			$21	2040	Paint & Overlay	3	6	7	3	5	7	5.17	3
COMPLEX STRUCTURES	I-64 High Rise bridge approaches	$250			See Movable portion of High Rise								
				2030	REPLACE STRUCTURE*								2
COMPLEX STRUCTURES	Smart Road bridge	$40	None										
COMPLEX STRUCTURES	460 Connector	$50	None										
	Total	$8,810	$1,633										

Figure 3.27 - Example of Big Bridge prioritization (Virginia DOT)

Although Virginia has a prioritization system for its big bridges, it does not yet have a clear funding source for this program. A goal for this year is to implement a funding source specifically for big bridges. Virginia's representative commented that even for timeframes beyond the STIP, it is important on large structures to reserve funding from an identified source to give decision makers an accurate picture of future needs, because big bridge needs are lumpy, not uniform from year to year, and affect the size of the overall program. It is important for decision makers to understand why the required level of preservation funding for the agency as a whole is not constant year-to-year.

3.4.5 Investment Programming

Transportation Asset Management Plans and toll authority business plans all contain financial and investment plans, featuring forecasts of revenues and expenditures over a multi-year timeframe. State DOT TAM Plans almost invariably cover a period of 10 years, since that is the timeframe specified in MAP-21. Some State DOTs develop long-range capital programs separate from their TAM Plans, which may cover 10 years or longer. Toll authority investment plans for big bridges are found to cover a wide range of timeframes, from 5 years (Delaware River Port Authority, New York State Bridge Authority, Blue Water Bridge Authority) to 40 years (Sault Ste. Marie International Bridge Authority).

All State DOTs develop Statewide Transportation Improvement Programs (STIPs) and other programs of projects covering at least 5 years. It is nearly universal that agencies use current inspection data to scope these projects. For timeframes beyond 5 years, deterioration rates play a role in expenditure estimates, and these rates have considerable uncertainty.

Some of the investment plans attempt to list specific projects over very long time frames, and may even include capsule descriptions of long-range projects, which may be highly speculative. Governing bodies require long-range capital expenditure estimates in order to ensure a sustainable fiscal environment, but such estimates must reflect uncertainty, including the possibility of significant reinvestments whose probability within the timeframe of the projection is less than 50%. In the program of projects format of most big bridge investment plans, it can be difficult to create a meaningful list of specific projects with specific timeframes, and such listings may be misleading since they are likely to understate actual preservation needs.

Given these considerations, best practice is to use a BMS to develop estimates of total annual preservation needs for long-range planning purposes. Although a BMS develops these estimates at the bridge level, they are probabilistic. Only the annual totals should be reported in the long-range projection. Project-level cost estimates and descriptions in best practice are limited to the first five years, when there is more certainty in bridge element conditions.

3.4.6 Owners Manuals

As a part of the interviews conducted under this task, the research team asked each respondent to comment on the concept of a Bridge Owner's Manual, and to provide a good example if they knew of one. Most of the respondents had heard of this concept, but understood it as either a bridge-specific inspection manual, or a movable bridge operations manual. Several people commented that they had been attempting to get design or inspection consultants to write useful bridge-specific inspection manuals for unusual structures, but had had limited success.

Some of the respondents had thought of the concept as including a capital reinvestment plan and a maintenance plan, but expressed skepticism. California, for example, commented that usually the designer, builder, inspector, and preservation contractor are different entities. It is difficult to get them to agree on a life cycle approach. Also, the Department does not have a way of implementing a performance warranty. Virginia commented that bridge performance is a dynamic phenomenon, where future needs change constantly depending on outside events and the ability of the agency to keep up with preservation needs. Also, bridges are sufficiently long-lived that best-practice maintenance procedures and materials evolve. An Owners Manual that includes a maintenance or preservation plan would need to be updated regularly in order to stay relevant.

The most complete example of a Bridge Owner's Manual that was received in this task came from Michigan DOT. It describes the Zilwaukee Bridge in Saginaw, Michigan. Its outline is as follows:

1. Introduction
    - 1.1 Purpose of the manual
    - 1.2 Overview of structure, physical characteristics and special features
    - 1.3 Overview of inspection requirements
    - 1.4 Description of maintenance facilities for the bridge
2. History of design, construction, inspections, and maintenance
    - 2.1 Introduction
    - 2.2 History, design, and construction

   2.3 Initial monitoring and testing
   2.4 Previous inspection reports
   2.5 Post-construction repairs and replacements

3. Original maintenance manual from 1988, unchanged from original
   3.1 Project history
   3.2 Recommended maintenance and MDOT inspection procedures
   3.3 Recommended consultant inspection procedure
   3.4 Appendix – drawings related to design, inspection, and maintenance

4. Engineering inspection operations
   4.1 Introduction
   4.2 General procedures surrounding the inspection
   4.3 Engineering inspection scope of service
   4.4 Bearing inspection
   4.5 Existing concrete condition
   4.6 Progression of cracks and delaminations
   4.7 Deformation monitoring
   4.8 Inspection of unique repairs

5. Bridge maintenance
   5.1 Introduction
   5.2 Routine maintenance
   5.3 Periodic maintenance

6. Bridge documents
   6.1 Introduction
   6.2 Document storage
   6.3 Construction documents
   6.4 Post-construction documents
   6.5 Repairs/replacements
   6.6 Document log

The Owner's Manual is, in effect, a compilation of all the background information a designer, inspector, and bridge owner would need to know about the structure aside from specific changeable programming information.

3.4.7 How Big is Big?

The research uncovered multiple definitions of the concept of Big Bridge, which vary by agency and also by purpose:

- For the purposes of dividing up a bridge into separate projects, the general pattern found in the research is that agencies would need to have structures at least 8,000 to 12,000 feet long to routinely consider doing this. Respondents considered this size of bridge to be at a level where major rehabilitation would be difficult or impossible to fund within a single project.
- Agencies may assign specialized staff support for bridges significantly smaller than 5,000 feet if they have unusual management requirements, most commonly border bridges and movable bridges. This was observed in Indiana and Illinois.
- Agencies often grouped unusually large bridges with movable bridges, complex structures, and tunnels, for the purposes of developing a specialized program with separate funding and prioritization criteria, as is done in Virginia.
- New York State has a threshold deck area of 27,000 sq.ft for a specialized needs analysis. In Michigan, a corresponding process is triggered at 100,000 sq.ft.
- The unique operational requirements and fiscal environment of toll bridges would qualify them for the same management treatment as any big bridge, regardless of size.
- Pennsylvania considers a bridge with maximum span length of at least 500 feet to be a big bridge, but this does not have much practical effect on how they manage bridges. They do assume a 100 year service life when planning preservation and replacement work on big bridges, but they do not have a life cycle cost analysis at present so the effect of this longer lifespan on project priority is limited.

If there is any common pattern in these observations, it would be that all of these structures have characteristics that the agency considers inadequately handled within the routine operations of its bridge management system. All of the agencies that use BMS to support decision making include their big bridges with all the rest of the inventory for life cycle cost analysis, but often proceed to program work on those structures in a separate process.

3.4.8 Chapter Summary

The following points provide an overview of the current state of the art in the management of Big Bridges, focusing on applications of element level data:

- Big bridges often contain unusual elements and appurtenances that are separately noted in bridge inspections. Many agencies have created agency-defined elements for their bridge management systems to facilitate these inspections. Chapter 2 (Tasks 2 and 3) describes them.
- Three of the state DOTs inspect all of their bridges span-by-span, with separate element lists for each span. Many more agencies set up structure units, representing variations in structure type or configuration, to organize element inspection records. This granularity is used for bridge management purposes, mainly for project definition.
- Bridge management systems readily support the addition of new types of elements, and are able to model deterioration, costs, action effectiveness, and life cycle cost for the new elements in the same way that they do for AASHTO's standard elements.
- Bridge management systems readily support dividing up of bridges by span or structure unit for inspection purposes. However, none of the existing systems automatically develops project scopes that are limited to portions of bridges, or that automate the segmentation of bridges for separate projects. AASHTOWare Bridge Management does have a capability to manually divide up work candidates by bridge segment and assign those separate work candidates to separate projects and implementation years. BrM is also able to automate the division of work candidates by type of work, such as deck work vs painting.
- Most bridge management systems lack the database flexibility to store variations in bridge characteristics, such as multiple structure types and multiple roadways that are often found on big bridges.
- Bridge management systems focus on the biennial (or in a few states, annual) inspection process that corresponds to federal reporting requirements. Most do not have a means of recording the more frequent safety checks, nor specialized non-destructive evaluations, that are common on big bridges.
- While all bridge management systems have the ability to record defects as bridge elements, as in the AASHTO Manual for Bridge Element Inspection, few have the ability to record individual defects as separate objects with a location, severity, and extent that can be tracked over time. Thus, they do not have the ability to model the onset and progression of individual defects.
- Most bridge management systems have facilities to model life cycle costs based on element level data. These costs are very significant on big bridges. So far, no

agencies have been found that have customized their models of deterioration, action effectiveness, or unit cost to reflect the special characteristics of big bridges.

- AASHTOWare Bridge Management has a capability to model the likelihood and consequence of natural and man-made hazards, and the ability for inspectors to record bridge characteristics that affect risk. It is able to use this information in priority setting and other management analyses. NCHRP Project 20-07(378) is documenting models that can be implemented in this framework. One of the models relates element condition to the likelihood of service disruption. Risk models are especially important for big bridges because of the large number of road users exposed to risks at any given time.
- Section 3.3 describes many other aspects of BMS functionality that are relevant to all bridges, but that agencies may consider to be of significant importance to big bridges. This relative importance will vary from one agency to another.
- Under proposed federal rules, all state DOTs are required to prepare Transportation Asset Management Plans (TAM Plans), and nearly all big bridges are required to be included in these plans. Toll authorities all prepare business plans, whose content overlaps that of the federal TAM Plans. The business plan is more focused on big bridge needs but often lacks the analytical content, such as condition tracking, life cycle cost analysis, and risk management, that is found in TAM Plans.
- The operation of big bridges often includes functions, such as toll collection and customer assistance, that are less common on other structures. One implication is that the strategic goals that an agency might have for big bridges may include goals (e.g. revenue maximization, customer satisfaction) that are less relevant or interpreted differently for other bridges.
- Federally-mandated performance targets are weighted by deck area, giving disproportionate importance to big bridges. This is starting to affect the way in which agencies establish targets. At least one agency (Michigan DOT) has different targets for its big bridges than for other bridges.
- Long-range capital needs estimates (10-40 year timeframe) often found in toll authority business plans are performed by trying to identify specific projects, using “engineering judgment”. This approach does not adequately address potential needs which may arise from deterioration and various hazards, whose probability and timing are very uncertain. The overall effect may be to understate future capital needs.

- In addition, the use of judgment for long-range forecasting is of doubtful quality due to lack of standard methodologies and inability to validate each engineer's judgment. None of the toll authorities interviewed indicated that they are taking full advantage of state DOT tools (e.g. bridge management systems) and expertise for estimating long-range preservation needs.
- Citing fiscal limitations, agencies having bridges in the 8,000 to 12,000 foot range or larger in total length, tended to find it necessary to divide up big bridges into small projects phased over many years, for rehabilitation activities. Agencies with no bridges in this range generally avoided this strategy, usually citing the prolonged or repeated disruption to traffic flow. Agency approaches to work zone management and contract incentives may help to mitigate or exacerbate the traffic flow concerns.
- Bridge management systems were by far the most common means found in use by agencies to perform analysis of life cycle cost and risk using element level data on big bridges. It was common for the cost of future work to be re-estimated or scaled, separately from the BMS, to allow for higher big bridge unit costs (in terms of bridge element measurement units). No agencies relied directly on their BMS for big bridge project cost estimates without some sort of adjustment.
- Multiple examples were found of agencies developing separate capital programs for big bridges, having a separate allocation of funding and a separate means of prioritization. Since the preservation needs of big bridges are large and highly variable from year to year, this strategy may aid in helping decision makers to understand and accept the annual variation in total needs.
- A few examples were found of Big Bridge Owner's Manuals. Agencies generally preferred that the content of such manuals be limited to material that is stable in the long term, and that dynamic content such as investment plans be omitted.
- Typically the management strategies developed by agencies for their big bridges were also applied to smaller complex structures, movable bridges, and tunnels.

These findings were of considerable value in developing a recommended approach in Task 6 of the present study.

CHAPTER 4 - BIG BRIDGE INSPECTION METHODOLOGY USING ELEMENT LEVEL INSPECTION DATA

4.1 Introduction

Currently, big bridges are treated the same as small or standard complexity bridges within existing bridge management programs and software packages. Whether a bridge is a 3-span girder bridge or a 50+ span suspension bridge, both are viewed the same in terms of data collection, analysis and storage. In reality, the level of effort required to inspect, analyze, and maintain these bridges is usually much greater and more specialized. Furthermore, the content and format of data needed to effectively manage these large and complex structures is different than what is required for more typical structure types.

In the current system, the repair/preservation/replacement of specific bridge components is often determined by the amount or percentage of members in particular condition states for the whole bridge. Breaking a big bridge into smaller, more manageable units, would give greater prominence to defects within each unit that would likely have been overlooked when viewing the bridge as a whole. In this way, a problem does not need to be widespread to get necessary attention. One structure may consist of a combination of many bridge types (multi-beam, girder, truss, arch, suspension, etc.), each of which require different strategies for analysis, maintenance, inspection and repair, and may be better addressed as separate structures rather than one big bridge.

To make the best use of collected element inspection data for bridge management analysis, specific defects for each element need to be accurately located within the affected member and the condition of each defect needs to be tracked over time to determine its actual rate of deterioration. Current software packages and databases used by most owners do not have the capability to store this type of information, so this crucial information is often recorded in customized spreadsheets or databases.

AASHTO has established a large number of National Bridge Elements (NBE), Bridge Management Elements (BME) in the Manual for Bridge Element Inspection (MBEI) to represent the common bridge elements. The MBEI also includes Appendix A which provides agencies the means to create Agency-Defined Elements (ADE) to represent element which are not included in the defined element set. Such elements may include those that are entirely independent of the defined elements or sub-elements of existing NBEs and BMEs. Numerous ADEs have been created to represent the unique elements found on big bridges. While it is infeasible to define every possible element for each unique structure, many big bridges of similar type share some common elements that are not currently defined in the MBEI. The collection, organization and reporting of the Element Level Information is also much different due to the size of the structure, number of different elements, usual use of multi-person inspection teams, and the size or complexity of some of the components.

The guidelines presented in this chapter are aimed at assisting in the planning and performance of inspections with specific direction in regard to the accurate collection and use of element level data by the respective bridge management agencies. However, as big bridges are often complex bridge types with unique details and configurations, this study cannot prescribe specific solutions for all bridges. Principles behind the current bridge inspection standards and element level analysis are conveyed which support responsible inspection and condition reporting to provide meaningful data to bridge management agencies. Accurate information for analysis and prioritization by bridge managers results in economical appropriation of resources, maintaining the safe operation of the transportation network.

4.2 Modifications to MBEI Bridge Element Articles

As stated in the MBEI's introduction, "the goal of this manual is to completely capture the condition of bridges in a simple, effective way that can be standardized across the nation while providing the flexibility to be adapted to both large- and small-agency settings" (AASHTO, 2015). The MBEI is designed to be applicable to all bridges throughout the country, therefore generic NBEs and BMEs were developed to encompass most bridges in the National Bridge Inventory (NBI). Refer to Section 2.1.2 for descriptions of the current elements and categories in the MBEI.

For each element in the MBEI there is an article with description, commentary, and quantification information, as well as an associated table of possible defects that can be used for that element. These defects are categorized into four different condition states with descriptions for each state. The condition states are numbered one through four, representing good, fair, poor, or severe condition, respectively. For example, the article for Steel Truss (Element 120) as it currently exists in the MBEI is shown on the following page.

Element 120—Steel Truss

Description: All steel truss elements, including all tension and compression members for through and deck trusses. For all trusses regardless of protective system.
Classification: NBE
Units of Measurement: ft
Quantity Calculation: Sum of all of the lengths of each truss panel measured longitudinally along the travelway.

Condition State Definitions

	Condition States			
	1	2	3	4
Defects	**GOOD**	**FAIR**	**POOR**	**SEVERE**
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Cracking (1010)	None.	Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.	Identified crack that is not arrested but does not warrant structural review.	
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
Observed Distress in truss vertical or diagonal members shall be reported as the length projected along the length of the truss.

While FHWA reporting does not require submission of these defect types, they could potentially be used for deterioration modeling and other types of analysis. For this reason, it is recommended that all present defects and quantities be collected for each element type to improve analysis. This reasoning and implications behind this recommendation are further discussed in Section 4.4.2. The AASHTO Subcommittee on Bridges and Structures (SCOBS) recently approved a ballot item to make collection of multiple defects optional. This will change the current direction of the MBEI by eliminating the requirement to determine only the predominant, governing defect for a given unit of an element. Defect quantities will no longer have to add up to the respective totals for each condition state of the element which provides leeway to bridge managers to record all defect data within their bridge management systems (BMS) while complying with the federal requirements to compile the element condition state summaries.

The elements used throughout a bridge may be composed of similar materials, exhibiting to similar defects, deterioration processes and rates, and have the same units of measurement. However, function and unit cost are also important to consider in element analysis of the structure. For example, steel girder, stringer, and floorbeam elements may have identical defect types and units of measurement, but likely serve different functions, are subject to different loading cases, and have vastly different associated repair/replacement costs. The pervasiveness of floor system elements throughout complex bridge designs and the advantages incurred by distinguishing these elements for enhanced analysis necessitate their inclusion in the MBEI.

4.2.1 Limitations of the Manual for Bridge Element Inspection

While the current list of elements included in the MBEI covers the majority of element and material types, the manual is, understandably, not inclusive for big bridges and complex bridge types. Based on review of bridge inspection and management reports and nationwide survey results, there are a number of common elements that big bridge owner agencies have developed as ADEs to help track and manage the condition of their structures. In the following Sections 4.2.2 and 4.2.3, suggestions for new NBEs and BMEs to be included in the MBEI are presented. If applicable, big bridge owners are encouraged to create ADEs of these elements. Proposed description, quantity, commentary, defects, and condition state definitions similar to those for each element in the MBEI articles are presented for each suggested element in Appendix A of this final report.

Occasionally, the element or defect is not sufficiently defined either with respect to how the quantity is calculated or what bridge components are included in the element. This lack of clarity can lead inspectors to make judgment calls which can produce inconsistencies in the element level data collected. These problems are prevalent during the initial element total quantity calculation phase where assumptions used are not adequately relayed in the inspection documents. For example, painted surface area for a truss built-up box member may not have included the interior surface area during the calculation phase, but inspectors may count area of paint defects on both interior and exterior surfaces. For this reason, detailed notes of how the element quantities were calculated must be documented and included in the tabulation of bridge elements for reference. Because big bridges typically have more elements with much greater quantities and are often inspected by teams of inspectors, the effect of inconsistencies can be amplified; therefore, uniformity in the element level assessment and thorough understanding of the MBEI is essential to collect meaningful and accurate element level data. Suggestions for modifications to bridge element descriptions and quantification procedures are presented in Section 4.2.4.

4.2.2 Recommendations for New National Bridge Elements (NBEs)

Pier Tower

Element 237—Concrete Pier Tower
Description: All concrete pier towers regardless of protective or reinforcing system. **Units of Measurement**: ft **Quantity Calculation**: Sum of the heights of individual legs of concrete pier towers.

Element 238—Masonry Pier Tower
Description: All masonry pier towers regardless of protective system. **Units of Measurement**: ft **Quantity Calculation**: Sum of the heights of individual legs of masonry pier towers.

Figure 4.1 - Inspector rappelling a reinforced concrete pier tower.

While Steel Tower (Element 207) and Timber Trestle (Element 208) exist for the larger built-up substructure elements analogous to Steel and Timber Columns (Elements 202 and 206), no corresponding element exists for massive Masonry, Unreinforced, or Reinforced Concrete Columns (Element 205) that are frequently used in complex bridge designs such as cable-stayed bridges or very tall structures. The closest existing element is the Reinforced Concrete Pier Wall (Element 210), but its unit of measurement is length measured along the skew angle. This method of measurement does not accurately represent tall members with height to width ratios greater than 3:1. The quantification of this new element, similar to those for Steel Towers and Timber Trestles, should be length measured as height. For this reason it is recommended that new NBEs be created for Concrete and Masonry Pier Towers; see Appendix A for proposed element articles similar to those for existing elements in the MBEI.

Anchorage Chamber

Element 221—Concrete Anchorage Chamber	Element 223—Masonry Anchorage Chamber
Description: Exterior walls of concrete anchorage chambers regardless of protective or reinforcing system. **Units of Measurement**: ft **Quantity Calculation**: Sum of the lengths of the exterior walls (perimeter).	**Description**: Exterior walls of masonry anchorage chambers regardless of protective system. **Units of Measurement**: ft **Quantity Calculation**: Sum of the lengths of the exterior walls (perimeter).

Similar to the suggested Pier Tower elements, suspension bridge anchorage chambers are not adequately defined by the current elements available in the MBEI. These structures are usually much larger and more complex than the available Reinforced Concrete Pier Wall (Element 210), often containing numerous interior walls, floors and/or chambers. Because anchorage chambers also typically have a large footprint (significant longitudinal and transverse lengths), the measurement of length along the skew used for the Reinforced Concrete Pier Wall is also insufficient. It is proposed that Anchorage Chamber elements be established for Masonry and Concrete Anchorages that use the length of the chamber perimeter as a quantity with the typical concrete and masonry defects. Length should be used as the quantification unit to be consistent with the quantification of typical substructure units. Refer to Appendix A for the suggested MBEI element articles.

Figure 4.2 - Reinforced concrete anchorage chamber on the Mackinac Bridge.

Anchorage Chamber Interior Walls

Element 222—Concrete Anchorage Chamber Interior Walls	Element 224—Masonry Anchorage Chamber Interior Walls
Description: Primary load-path interior walls of concrete anchorage chambers regardless of protective or reinforcing system. **Units of Measurement**: ft **Quantity Calculation**: Sum of the lengths of all of the interior walls.	**Description**: Primary load-path interior walls of masonry anchorage chambers regardless of protective system. **Units of Measurement**: ft **Quantity Calculation**: Sum of the lengths of all of the interior walls.

As stated previously in the suggested Anchorage Chamber element, these structures often contain internal walls that serve to support components of the anchorage chamber. A sub-element should be created for these walls that is quantified as the sum of lengths for all interior walls. These interior walls may be considered a NBE as they may be within the primary load path for the anchorage roof, which may be considered a Reinforced Concrete Slab (Element 38) or other type of superstructure system in the case of the common suspension bridge configuration in which the anchorage comprises a portion of the roadway. Refer to Appendix A for suggested MBEI element articles.

Steel Main Cable Bands/Splay Castings

Element 163—Steel Main Cable Bands/Splay Castings
Description: Steel main cable bands and splay castings regardless of protective system. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual cable bands and splay castings.

Figure 4.3 - Steel main cable splay casting.

Currently, cable band defects are included as part of the Steel Main Cable (Element 147). Because the cable bands serve a much different purpose and have different associated defect types than the main cable, they should be defined as separate elements and be enumerated as "each." Because defects could occur at cable bands that would not directly affect the capacity of the overall main cable, the inclusion of this element could distinguish these less critical deficiencies from those on the main cable itself. Additionally, the element could include a defect for rotational misalignment which is a common deficiency noted at main suspension cable bands. Refer to Appendix A for a suggested MBEI element article.

Steel Main Cable Saddles

Element 164—Steel Main Cable Saddles
Description: Steel main cable saddles regardless of protective system. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual main cable saddles.

The main tower and deviation saddles distribute and transfer the main cable load and direct the cables to the anchorages. These are important components of a suspension bridge and should be included in the MBEI and quantified as "each". Because they serve as specialized bearings, they should share many of the moveable and fixed bearing defect types and descriptions. Refer to Appendix A for a suggested MBEI element article.

Figure 4.4 - Steel main cable tower saddle.

Steel Cable Anchorage Socket or Assembly

Element 165—Steel Cable Anchorage Socket or Assembly
Description: Steel cable anchorage sockets or assemblies for main or secondary cables regardless of protective system. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual main and secondary cable anchorage sockets or assemblies.

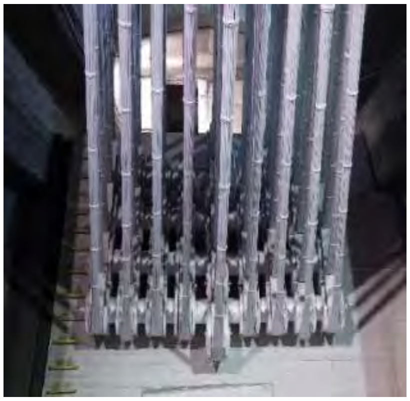


Figure 4.5 - Steel main cable strand anchorage assemblies.

This NBE should be created to define the various types of cable attachments to bridges. This element should include secondary cable attachments to the superstructure, cable-stayed bridge anchorage sockets at the tower head and attachment to superstructure, suspension bridge helical strand anchorages and the various components of parallel wire anchorage systems. The element should be quantified as "each" and should contain the defect types typically associated with steel components. Refer to Appendix A for a suggested MBEI element article.

Post-Tensioning Assembly

Element 166—Post-Tensioning Assembly
Description: Post-tensioning assemblies, including respective ducts and embedment materials, regardless of protective system. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual post-tensioning assemblies.

Figure 4.6 - Post-tensioning assembly on a reinforced concrete pier cap (Element 234).

Internal and external post-tensioning assemblies, which may be critical components of reinforced concrete or prestressed concrete superstructure members, decks, or substructure elements, are currently not represented in the MBEI. Defects which may be present at the post-tensioning components cannot be represented with the defects which are listed for the concrete elements that they are tensioning. Creation of a new element that could include the "steel" and "other" material possible defects which may be noted at these assemblies would greatly benefit element analysis of such structures. Refer to Appendix A for a suggested MBEI element article.

Curved Bridge/Primary Load Path Diaphragm or Bracing Assembly

Element 170—Steel Curved Bridge/Primary Load Path Diaphragm or Bracing Assembly
Description: Primary load-path or curved bridge steel diaphragms or bracing assemblies regardless of protective system. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual steel diaphragms/bracing assemblies.

Element 171—Concrete Curved Bridge/Primary Load Path Diaphragm
Description: Primary load-path or curved bridge concrete diaphragms regardless of protective system. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual concrete diaphragms.

Although not typically primary load carrying members, diaphragms and lateral bracing members may support primary loads, common at end diaphragms. These elements may also be considered primary structural components on curved structures as they resist live lateral loads. The MBEI currently lacks any definition for these types of elements. It is recommended that new NBEs be created and enumerated as "each" for each steel and reinforced concrete diaphragm or bracing assembly that serves as a primary load carrying member. Connection plates for steel diaphragms or lateral bracing assemblies would also be included as part of the element. It should be noted that a number of agencies whose management programs were reviewed as part of Task 2 have already developed

Figure 4.7 - Curved girder bridge

ADEs for "Secondary Members," "Cross Bracing," or "Diaphragms." Typically, these items are referring to secondary bracing members and not the primary load carrying members or those used on curved girder bridges. Refer to Appendix A for suggested MBEI element articles.

4.2.3 Recommendations for New Bridge Management Elements (BMEs)

Cable Protective System

Element 518—Cable Protective System
Description: Weatherproofing protective systems on main cables of suspension or cable-stayed structures. Does not include additional conventional paint coatings. **Units of Measurement**: ft² **Quantity Calculation**: Should include the entire outer surface area of the protective system on the cable element.

Figure 4.8 - Tear in Cable Protective System material, exposing wrapping wires.

A separate element for the main cable protective system for suspension and cable-stayed bridges should be created to accommodate additional defects which are not applicable to conventional Steel Protective Coatings (Element 515). Main cable wrappings are more complex, and can be comprised of weatherproof wrapping materials which can split or tear, or rigid steel or polyethylene sheaths filled with grout in the case of a cable-stayed bridge. Blast protection shielding on main and secondary cables at the roadway level and state-of-the-art suspension main cable dehumidification systems, likely to become more prevalent in the future, could also be included. The new element for Cable Protective system should be quantified similar to Element 515 but would not include defects in conventional paint coatings. This element would include defects associated with the 'Other Materials' present. Refer to Appendix A for a suggested MBEI element article.

Vibration Damper

Element 308—Vibration Damper
Description: For vibration damper systems of all types which may be present on main cables of cable-stayed bridges, secondary suspender ropes of suspension bridges, or truss members. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual damper assemblies.

Figure 4.9 - Stay Cable Vibration Dampener

These systems for reducing vibration and wind-induced oscillations are used on long structural members; often main cables of cable-stayed bridges or suspender ropes of suspension bridges, and may also be used on truss members. Dampening systems may consist of tuned weights, cross ties or mechanical shock absorbing systems. They are important components for the serviceability of the structure. Because their function and possible defects are often much different from those of the component to which they are attached, they should be classified as a unique BME. The dampeners should be quantified as "each" and use most of the movable bearing defect tables. Refer to Appendix A for a suggested MBEI element article.

Deck Drainage

Element 340—Deck Drainage
Description: All elements which facilitate drainage of runoff from the deck, including troughs beneath open joints, scuppers, and deck drainage basins and the connected drainage pipes. Collector pipes to which numerous drain pipes connect may be considered an additional separate drainage element. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual drainage devices or assemblies.

Drainage system elements such as deck drains, scuppers, and joint troughs remove water from the roadway surface and help protect superstructure and substructure elements located below. Their failure can greatly accelerate deterioration of NBE components; therefore, being able to correlate the condition of these systems with deterioration rates could be a benefit. The element should be quantified as "each" and use some of the "other materials" defects. Refer to Appendix A for a suggested MBEI element article.

Substructure Impact Protection

Element 350—Substructure Impact Protection
Description: All elements which protect substructure elements from direct collision and resulting damages, including placed riprap, crash walls, dolphins, and fenders of all material types, regardless of protective system. **Units of Measurement**: each **Quantity Calculation**: Sum of the number of individual crash protection devices.

Elements which protect substructure components from impact damage such as placed riprap, crash walls, fenders and dolphins are used on many big bridges over navigable waterways. These elements should be considered as a whole and their overall effectiveness be evaluated for its ability to protect. For this reason, the created element would use the quantification of "each" and use the defects associated with the "other materials" because their material makeup and design can vary greatly. Refer to Appendix A for a suggested MBEI element article.

Figure 4.10 - Numerous dolphins and placed riprap protecting the Sunshine Skyway Bridge.

4.2.4 Element Descriptions and Quantification Issues

Steel Main Cables Quantification

	Element 147—Steel Main Cables
Current	**Quantity Calculation**: Sum of all of the lengths of each main cable measured longitudinally along the travelway.
Revised	**Quantity Calculation**: For suspension bridges, sum of all of the lengths of each main cable measured longitudinally along the travelway. For cable-stayed bridges, sum of all of the actual lengths of each main cable from tower head to the roadway attachment.

Steel Main Cables (Element 147) are quantified as length along the travelway rather than actual length of cable. While a relatively minor point for suspension bridges, the difference in length is more apparent in the inspection of cable-stayed bridges which have steeply inclined main cables near the tower, greatly increasing the ratio of actual length of cable to horizontal length of cable along the longitudinal travel, thus making MBEI defect quantities difficult to quantify for an inspector in the field. For cable-stayed bridges, it is recommended that this element more accurately be quantified as actual length measured from tower head to roadway attachment. Determining the actual length of cable is required to compute the area of Steel Protective Coating (Element 515), nonetheless, and therefore revision of the quantity calculation would not require additional effort, would be conducive to defect quantification by inspectors, and would better represent the quantity of the element for analysis. Recommended revisions to the element article as it currently appears in the MBEI is shown above.

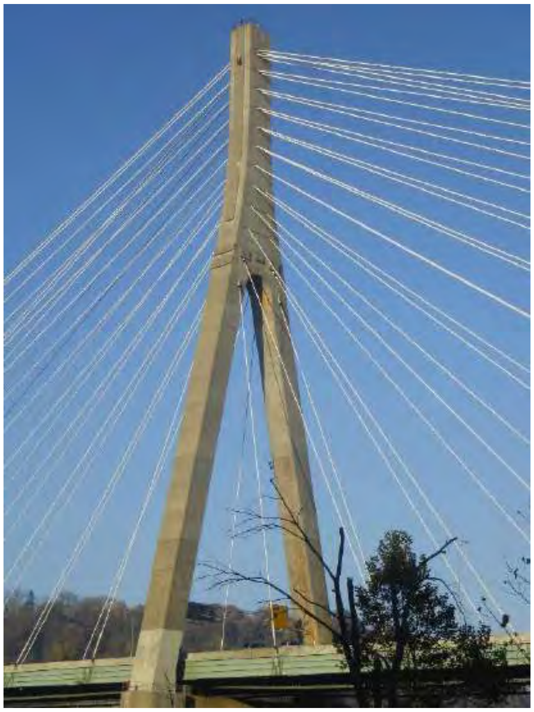


Figure 4.11 - Veterans Memorial Bridge, West Virginia.

Steel Pin and Pin & Hanger Assembly or Both

	Element 161—Steel Pin and Pin & Hanger Assembly or both
Current	**Description**: Steel pins and pin and hanger assemblies regardless of protective systems. **Quantity Calculation**: Sum of the number of pins, pin and hanger assemblies, or both.
Revised	**Description**: Primary load path steel pins and pin and hanger assemblies regardless of protective systems. **Quantity Calculation**: Sum of the number of individual pins or pin and hanger assemblies.

The description and quantity calculation direction in the MBEI for Steel Pin and Pin & Hanger Assembly or both (Element 161) is ambiguous and may lead to inclusion of pins which are not intended to be captured by this element. For example, pins which are part of a bearing assembly to permit rotation should be included in the condition assessment of the respective bearing element. Implicitly, pins located at wind tongues which transmit lateral loads and maintain span alignment should be excluded as well as these mechanisms are not transferring primary load, and therefore should not be considered an NBE.

Steel Truss and Steel Gusset Plate

	Element 120—Steel Truss
Current	**Quantity Calculation**: Sum of all of the lengths of each truss panel measured longitudinally along the travelway.
Revised	**Quantity Calculation**: Sum of all of the lengths of each truss line measured longitudinally along the travelway.

	Element 162—Steel Gusset Plate
Current	**Quantity Calculation**: Sum of the number of primary load path gusset plate assemblies. For multiple plate gusset connections at a single panel point, the quantity shall be one gusset plate regardless of the number of individual plates at the single connection point.
Revised	**Quantity Calculation**: Sum of the number of primary load path gusset plate assemblies. For multiple plate gusset connections at a single panel point of a truss line, the quantity shall be one gusset plate regardless of the number of individual plates at the single panel point.

Quantity calculation directions for Steel Truss (Element 120) and Steel Gusset Plate (Element 162) are unclear on whether the quantity should include only one or multiple truss lines. The information for these elements should be revised as shown above to clarify that each truss line should be quantified individually to prevent all being resolved to a single length for two or more separate longitudinal truss lines which would greatly reduce accuracy of condition representation and capabilities for analysis.

Stringer Bearings

	Element 310—Elastomeric Bearing
Current	**Commentary**: None.
Revised	**Commentary**: This element should include all elastomeric bearings which transfer primary load and permit expansion and/or rotation, including stringer bearings.

	Element 311—Movable Bearing
Current	**Commentary**: None.
Revised	**Commentary**: This element should include all movable bearings which transfer primary load and permit expansion and/or rotation, including stringer bearings.

Stringer bearings, commonly found in truss-floorbeam-stringer type superstructures are not addressed in the description or commentary for any of the bearing elements which may be applicable to stringer bearings, such as Elastomeric Bearing (Element 310), Movable Bearing

(Element 311), Fixed Bearing (Element 313), etc. It is not clear whether to include stringer bearings in the element analysis and may lead to inclusion of only the truss or girder bearings for each span. As stringer bearings are transferring primary load, and therefore may be considered NBEs, they should be included in the element analysis as the appropriate bearing element; proposed commentary as shown in the above tables could be added to all bearing elements.

Steel Tower Quantification

	Element 207—Steel Towers
Current	**Quantity Calculation**: Sum of the heights of built up or framed tower supports.
Revised	**Quantity Calculation**: Sum of the heights of individual legs of built-up or framed tower supports.

Steel Towers (Element 207) are quantified as the "sum of the heights of built up or framed tower supports," which may be taken to mean that the element quantity for a steel tower must be reduced to a single height. Due to the significant size of the suspension tower supports, this can greatly oversimplify the results with many overlapping defects from the numerous, separate interior cells. As each cell is accessed as part of the inspection, the element would benefit from a revised quantity calculation which defines the element as the height of each tower leg which would effectively double the quantity in the case of common two-legged towers and will result in a more detailed and meaningful element assessment. The quantity could alternatively be the total height of individual cells, however, this could complicate the element summary with overlapping connection defects at interior walls and is not warranted due to the inherent safety and seemingly overdesigned condition of conventional steel towers.

Reinforced Concrete Deck Crack Quantities

	Element 12—Reinforced Concrete Deck
Current	**Commentary**: [No pertinent information.]
Revised	**Commentary**: For calculation of crack area defect quantities, a 12" affected deck width should be assumed. Therefore, each linear foot of crack equates to one square foot of deck area which is included in the defect quantity.

The method of calculation for areas of cracking for deck elements is not defined in the MBEI. As only length, crack width, and spacing of cracks are typically noted, quantification of the cracks in area units is ambiguous. There must be a constant width of affected deck area along the crack to be included in the quantity; otherwise, the only applicable measurement would be the crack width which is infinitesimally small in comparison. It is widely understood that the affected width should be 12”, therefore, each linear foot of a crack corresponds to one square foot of affected deck area in the element summary (Figure 4.12). However, this issue is not discussed in the element commentaries for the respective elements nor is it shown in examples in Appendix B of the MBEI, which could lead to wide variability in the concerned quantities which may be one of the driving factors behind prioritization for deck rehabilitation or replacement. Commentary for all deck elements should be revised to include a statement which explicitly defines the method for calculation of crack defect area quantities, similar to what is shown for Reinforced Concrete Deck (Element 12) above.

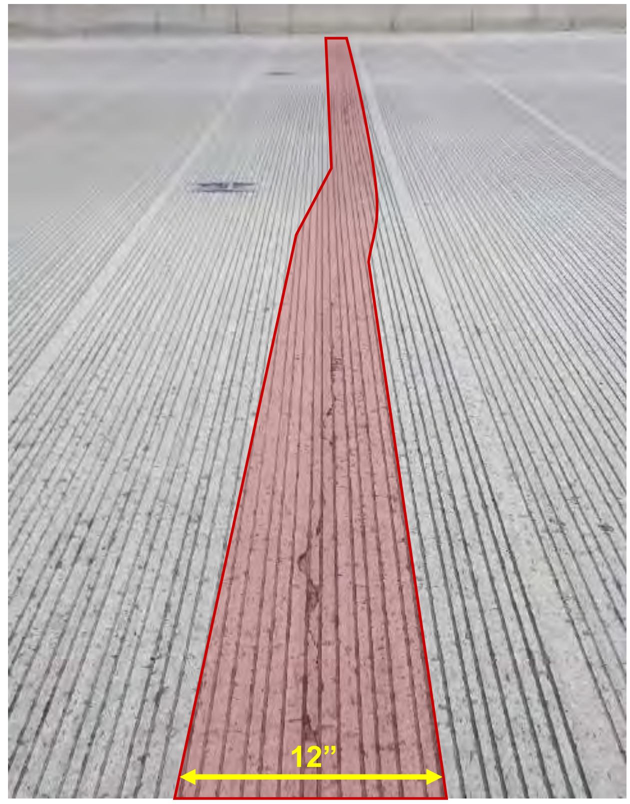


Figure 4.12 - Typical transverse crack in a reinforced concrete deck with 12” wide affected area illustrated.

Steel Protective Coating

	Element 515—Steel Protective Coating
Current	**Quantity Calculation**: Should include the entire protected surface of the steel element.
Revised	**Quantity Calculation**: Should include the entire protected interior and exteriors surfaces of the steel element which are visible or accessible for inspection using typical methods.

Total quantity calculations for Steel Protective Coating (Element 515) are unclear and often lead to uncertainty when deciding whether to include interior surfaces of elements which are sealed or otherwise not subjected to the same environmental conditions as the exterior faces. Quantity calculation guidance should be revised to assert that all protected interior faces of elements which are visible or accessible for inspection should be included in the total quantity. Interior surfaces which can be remotely inspected using a scope should be included in the total quantity only if such methods are employed on a regular basis and not performed as part of a special inspection.

4.2.5 Defect Type Omissions

Wear

Steel elements do not have a defect for wear and associated fretting corrosion, which is a common deficiency at elements accommodating expansion movements. Common elements and locations which exhibit wear with lack of lubrication are Steel Truss (Element 120) at pin connections and expansion devices such as wind tongues and false chords, Steel Pin and Pin & Hanger Assembly or both (Element 161), and Movable Bearings (Element 311) of the sliding plate variety. Wear and fretting corrosion may also be noted at connections or locations on steel members where unwanted relative movement or vibrations occur which reduces fatigue strength and may be a precursor to fatigue crack formation. Although the analysis of wear may be similar to section loss caused by corrosion, the cause and associated maintenance/repair may be significantly different. For these reasons a new defect is recommended and proposed condition state definitions are shown in the following table.

Figure 4.13 - Wear and fretting corrosion occurring at a sliding plate stringer bearing.

Defect	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Wear (Steel) (XXXX)	None.	Minor wear or fretting corrosion.	Moderate to significant section loss due to wear is evident and fretting corrosion is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.

Misalignment

The Alignment (2220) defect exists for bearings and other materials and specifically describes inconsistent bearing alignments for temperature conditions. No applicable defect exists for other various member misalignments which may be encountered, such as misaligned pin and hanger assemblies or main cable bands. Such instances may cause unintended contact between elements or loss of capacity in some members. Addition of a new defect is recommended and proposed condition state definitions are shown below. Alternatively, the suggested general condition state language could be added to the existing Alignment (2220) defect which is currently only applicable to bearings to include all alignment deficiencies which may be noted.

	Condition States			
	1	2	3	4
Defect	GOOD	FAIR	POOR	SEVERE
Misalignment (XXXX)	None.	Tolerable misalignment.	Significant misalignment but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.

4.3 Organization

4.3.1 Sub-Unit Organization

As was discussed in Chapter 2, division of a big bridge into smaller sub-units based on span configuration or material type is the most common first tier organization for big bridges. Treating these smaller sub-units as independent structures can help improve the management, analysis, maintenance, inspection, and reporting by dividing the various efforts into more manageable portions.

Figure 4.14 - Suspension and cantilever truss sub-units of Westbound Chesapeake Bay Bridge.

Typically, big bridges are comprised of a larger more complex main span (arch, suspended, cable-stayed, or a continuous or cantilever truss) with numerous shorter approach spans that may consist of simpler beam or girder spans, or more complex simple, continuous or cantilever truss spans, or any combination, thereof. Transitions between the various structure types provide inherent division points to separate the structure into sub-units which can then be viewed, essentially, as a series of distinct, adjoined bridges. Depending on the BMS system being used by a particular agency, the sub-units may or may not be able to be assigned unique Bridge Identification Numbers (BINs). Within the sub-units for a big bridge, a second tier of organization is provided, typically by sequentially numbered spans; then as a third tier, each panel of a truss or between floor beams. The third tier subdivision may also take the form of identifying, within the span, where the element or portion of the element is located such as interior/exterior members, end or middle portion of members, or even individual members, and is discussed further in Section 4.4.2. This method of subdivision is especially beneficial for analyses that are affected by the level of exposure the member may be subjected. An inspector will use this organization and coordinate system to locate and describe specific locations.

When dividing a bridge into sub-units, it is important to clearly define the boundaries between adjacent sub-units to ensure that all portions of elements are accounted for during inspection efforts. For example, a reinforced concrete pier may provide support for two separate steel towers at the ends of the associated sub-units, or finger joints present between adjacent spans. In most of these instances, the shared elements can be assigned to the preceding sub-unit in accordance with the second tier span numbering convention; however, special consideration may be needed for certain, more complex elements like suspension bridge anchorage chambers. These substructure elements should be assigned to the suspension bridge sub-unit instead of the preceding sub-unit as may be the convention adopted. Appropriation of such unique elements must be explicitly defined to ensure that all portions are inspected, especially when the adjacent units are being inspected by independent contractors or on divergent inspection cycles.

Figure 4.15 - Sault Ste. Marie International Bridge connecting the US and Canada in Michigan's Upper Peninsula.

Care must be taken to ensure that the element is only counted once in the element condition state summary; therefore, the most effective solution may be to attribute the entire element to one sub-unit in regards to the element level inspection. This would be conducive to the proper inspection of the element in accordance with the MBEI by considering all the present defects.

From an analysis standpoint, dividing bridges into sub-units by structure type and materials makes sense because different structural configurations and materials behave differently, have different deterioration modes and rates, different life-cycle cost factors and different vulnerabilities to risk.

By using smaller bridge units, bridge performance measures can more accurately represent the actual condition of each of the sub-units, allowing bridge owner to more precisely pinpoint areas of need.

Finally, another method for subdivision of big bridges is to use county, state, international or other geographical or political borders. This can significantly complicate inspection of such bridges as the structure is typically split into parts and requires the respective governing bodies to coordinate inspections and maintenance. These separations do not always occur at structurally intuitive points with respect to management or analysis (e.g. the international boundary at mid-span of the Blue Water Bridges). For many interstate and international structures, specific bridge management agencies are often created to handle the specific intricacies of the adjacent governmental regulations and legislative requirements. Division of big bridges which cross borders typically can follow the same conventions which are used to divide those which do not cross borders, being established at changes in span types, configurations, construction materials, at the centerline of the main span, or at actual border lines when no apparent locations are present. Sometimes, management or maintenance of the structure may be entirely attributed to one agency which is affiliated with one side of the structure, or any other complex arrangements. One example which was discussed in Chapter 2 is the Sault Ste. Marie International Bridge, maintained entirely by the International Bridge Administration, an entity within the Michigan Department of Transportation (MDOT). However, operational and policy direction is led by the Sault Ste. Marie Bridge Authority, a partnership between Canada's Federal Bridge Corporation Ltd. and the MDOT.

Figure 4.16 - Blue Water Bridges between the USA (Port Huron, MI) and Canada (Sarnia, ON).

4.3.2 Organization of Element Data

An important consideration in planning the element level inspection of a big bridge, for both the owner and inspector, is what specific defect information will be collected and how it will be organized. While bridges on the NHS require only an element summary for the entire bridge with no specific defect information to be submitted to the FHWA for the NBI, this simple summary is extremely limited in its representation of the condition of a big bridge especially if the data may be used for any meaningful analysis. Retaining the specific element defect information for all elements span-by-span or panel-by-panel permits significantly more detailed data analysis capabilities, enabling the bridge owner to distinguish areas of advanced deterioration and prioritize maintenance efforts appropriately.

As was noted in previous tasks, New York, Pennsylvania, and Texas DOTs and the Maryland Transportation Authority (MDTA) often retain separate element quantities for each span or panel. This practice has a unique implication as it applies to big bridges because the relative cost for inspection of such bridges is much greater than for the multitude of small highway bridges due to difficult access for inspection, traffic disruptions, complexity of the structure and number of elements included; therefore supporting span-by-span or panel-by-panel retention of element data has greater organizational and economic significance. MDTA accomplishes this through the use of their own proprietary, web-based program in which inspectors enter or modify description and location information for specific defects with prioritization codes and recommendations for repair for all of their structures. Element condition state summaries are manually entered and stored separately for each span or panel of the structure, and summations for spans, sub-units, and the entire structure are computed automatically. In lieu of such proprietary systems, customized spreadsheets can be used to achieve the same results, although these can be slightly more labor-intensive and susceptible to errors due to their individual development.

4.4 Inspection

Consistency is vital for the effective condition inspection of any structure; even more so for big bridges, with greater quantities and variety of elements involved in these structures. The MBEI itself ensures objectivity and consistency in element evaluation to a high degree to yield meaningful element data for deterioration analysis and forecasting. The possible defect types are listed within the MBEI and specific condition states (CS) are qualitatively or quantitatively described, except for the case of differentiating between CS 3 (poor condition) and CS 4 (severe condition), which requires engineering judgement to determine whether the element warrants a structural review. Element inspection of big bridges presents additional challenges, such as undefined sub-elements and large or complex elements for which the accurate quantities can be difficult to compile consistently. Recommended additions and modifications to the MBEI to result in more useful and consistent evaluations of big bridges are provided in Section 4.2.

4.4.1 Preparing for Element Inspection

Careful review of the bridge file prior to on-site inspection activities is essential to a successful and thorough inspection. All available bridge plans, as-built plans, and rehabilitation plans should be examined to accurately determine the current configuration of the bridge and any specialized access needs that may be required to perform the inspection. Previously collected element level data should be reviewed and compared to the current bridge plans to ensure accuracy, especially if a major rehabilitation was recently performed. If discrepancies are found, the owner should be consulted which may result in the elements and/or quantities being re-calculated or re-identified. Any additional reports and special studies beyond typical inspection reports that were performed in previous years should also be reviewed to make inspectors aware of possible findings. For example, if a detailed fatigue investigation was recently performed, the results may inform inspectors to expect fatigue cracks in certain locations.

All inspection team members should be familiarized with the MBEI prior to the element level inspection of a bridge as it has become a significant portion of the National Highway Institute's (NHI) two-week "Safety Inspection of In-Service Bridges" course. An inspector's understanding of the involved elements and defects and how they are quantified is crucial to ensuring completeness and consistency in the result and subsequently provides accurate data for meaningful analysis, prioritization, and development of performance measures by the bridge manager. During the establishment of the elements and quantity calculations, it is important to record detailed notes of specifically how the element quantities were calculated, so inspectors can correlate their findings with the presented elements. For example, if stringer bearing bolsters are counted as part of the bearing or part of the stringer itself, or details on how much of the approach roadway is counted as part of the approach slab. These details can help the inspector appropriately assess conditions and assign appropriate condition state quantities in the field without the need to reevaluate and modify notes.

A common practice used by bridge inspectors to aid the field collection of data is use of an inspection packet. This document is based on the previous inspection report and includes all the significant findings organized in a manner so an inspector can easily reference and append it with new findings. The inspection packet is usually organized by specific location (span, panel point, pier number, etc.); however, on more complex inspection projects that may involve many types of access equipment, it may be more efficient to organize the information based on the access method (e.g., separate packets for areas of the bridge accessed by manlift, underbridge inspection unit, maintenance walkways, sidewalks, etc.). If the information in a report is largely tabular, this process is fairly straightforward but will require significant processing if the information is more narrative. The inspection packet should also include all general plan and elevation drawings, typical cross-sections, fracture critical member identification drawings, important/critical defect sketches, expansion joint and bearing monitoring tables and details of the bridge location referencing system. Pre-generated, blank sketch sheets can also be of particular usefulness to an inspector to record location-specific defect information. This is especially true for the larger substructure units and decks, or complex connection details.

Specific information which is useful to inspectors for an element level inspection may include previous data tables for verifying or noting changes in quantities, or pre-prepared sketch sheets that can substantially simplify the inspection of larger elements by eliminating cumbersome narrative location notes detailing the location, size, and orientation of the defect. Sketches that detail specific defect locations can greatly help the effort to visualize and aid defect quantification. This circumstance is frequently encountered on big bridges for massive concrete substructure units which are currently usually quantified by their horizontal length, such as a pier wall, or for the various deck types. These types of elements are not easily assessed from one vantage point and all sides may not actually be evaluated by the same inspector. For this reason, sketches detailing specific locations of defects are important.

Use of Mobile Devices

In lieu of paper, an inspection team may utilize mobile tablets which must provide reliable access to all the necessary resources and software applications needed for the task. Tablets can be purchased as rugged units more likely to survive challenging field conditions, or they can be made more ruggedized by addition of protective cases. Useful software might include customized spreadsheet or database applications, a word processor preloaded with the previous inspection report materials, a sketching application, or specific bridge inspection software. Dedicated data service or tethering with mobile hotspots to provide internet access enables the use of collaborative applications which allow inspectors to see changes made by other inspectors, instantaneously; this is an advantageous feature in the inspection of sizable elements which require several passes or viewing from multiple vantage points to fully evaluate, such as the deck and wearing surface, trusses, steel towers, and substructure elements. Investment in these devices for big bridge inspectors is recommended to facilitate collaborative recording and organization of inspection information. Use of these methods also reduces time required for condition report preparation by eliminating labor-intensive needs to manually organize and enter notes recorded on paper.

Additional new technologies are in development that may also aid field inspection efforts. These include the use of augmented or mixed reality headsets (e.g., Microsoft HoloLens, Google Glass, etc.) that could, in real-time, overlay data onto the inspector’s view of the structure either in the form of text or graphics. This information could include previous inspection notes, ratings, photographs, sketches, etc.

4.4.2 Element Data Collection

Currently, awareness of the units and quantity calculations for elements, as well as the proper recognition of the governing defect, are all crucial to create an accurate representation in accordance with the MBEI. For common big bridge elements quantified by length such as trusses or towers, there may be many deficiencies at a given unit of the element which requires

Figure 4.17 - Inspectors in an underbridge inspection unit (UBIU) inspecting a deck truss.

comparison and engineering judgement in cases when deficiencies result in the same CS rating. With the common methods used for inspection of big bridges, often consisting of disparate notes on paper or in electronic files, in conjunction with multiple inspections of large elements from different access methods by various inspectors, this can require considerable effort post-inspection to interpret, sort, and compare the data to produce the element level condition state summary. With recent changes to the MBEI, inspectors are now allowed to record all defects for a given location not just the most severe; however, these additional less severe and overlapping defects will not be included in the condition state summary for the element. Determination of the governing defect for each given unit of an element or noting specific locations of each defect is necessary to produce the element condition state summary.

Defect data from the inspection of a big bridge has greater economic significance due to the cost and difficulty of access; therefore, it is recommended that big bridge owners retain separate element defect data sets for each panel or span to facilitate more detailed analysis. Pre-made tables with element defect data from the previous inspection are an important resource which permit the inspector to verify quantities and note changes which further contributes to the accuracy of the data.

Accommodating More Detailed Defect Data

Depending on management needs, agencies may find it cost-effective to gather more detailed data for ongoing deterioration processes. The benefits of having this information are:

- Maintenance crews can more quickly and reliably locate damaged areas noted by the inspector for repair;
- Specific instances of damage can be followed over time by inspectors on repeated visits to the structure to note condition, extent and progression;
- Cost estimation can be more precise;
- Project treatment selection can be more reliable;
- The timing of significant needs can be forecasted more accurately; and
- Engineers can gain a better understanding of the causes of ongoing problems.

In addition to the creation of specialized elements and sub-elements as discussed in previous sections, another common way to increase the level of detail is to divide the large bridge into smaller areas, recording conditions on these smaller areas separately. Considering all of the engineering and management requirements of BMS, two basic approaches can be used in existing systems to enhance the collection and management of the detailed data:

- Subdivided units – the structure is permanently sectioned into spans, panels, and other physically-defined areas, which in every inspection are treated as though they were separate structures.
- Enumerated damages – the structure may be divided into structure units and/or spans, but each inspection further divides the structure into damaged areas, which can change in size from one inspection to the next due to deterioration and preservation work.

Figure 4.18 contrasts these two approaches. In both cases, a big bridge is divided into one or more structure units, and for each inspection is further divided into element inspections. In both cases, the listing of elements and their quantities is intended to represent the total substance of the structure for bridge preservation management. Both approaches permit, but do not require, the division of a bridge into spans that are inspected separately. Within a bridge, the structure units may differ in the elements they contain due to the use of different structure configurations and materials. Over time, the element lists may change if the bridge is modified or if new types of defects are observed in inspections.

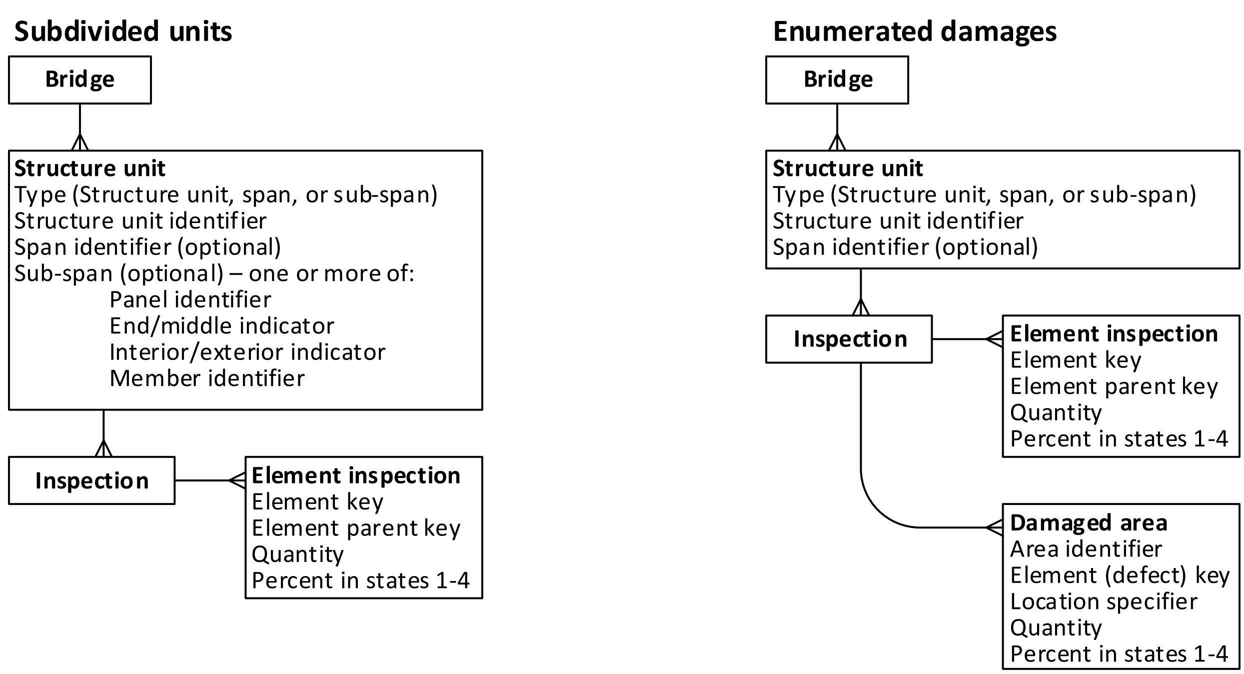


Figure 4.18 - Two approaches for more detailed defect data.

For the purposes of this discussion, defects and protective systems will be considered as specialized types of elements, identified using an element key in the same manner as ordinary elements (NBEs, BMEs, and ADEs). This corresponds to the way these objects are stored in the AASHTOWare Bridge Management database. For protective elements (such as coatings), the parent key indicates which element is protected. For defects, the parent key indicates which element is experiencing the distress.

Currently, the MBEI recommendation for recording defect information is to record only the most severe, governing defect for a given unit of an element. While this greatly simplifies the resulting element summaries and reduces the amount of data which must be ultimately collected, it is not conducive to further enhanced analysis beyond that which even span-by-span or panel-by-panel retention of data in accordance with the MBEI permits. Defect data are not useful for network level bridge management purposes unless all defects are consistently recorded. As mentioned previously, the recently approved SCOBS ballot item will help alleviate this issue by permitting bridge management agencies to include all the present defect quantities in the element analysis, not only those which are the governing defect. Both approaches to manage element defect data assume that an agency will record every defect not in condition state 1 to permit analysis of the data.

In the 'Subdivided Units' approach, structure units are further divided to the span or sub-span level. A sub-span identifier may indicate portions of a span such as truss or floor system panels, ends or middles of beams, interior or exterior members, or even individual members (such as separate bearings). Each piece of the subdivided structure is given a permanent identifier according to a standardized labeling system for which all inspectors are trained. Each sub-span has its own listing of one or more elements, and its own separate listing of defects. Defects are inspected and recorded in accordance with the MBEI.

Ideally the BMS would support the labeling scheme within its database, using a graphical presentation if possible. AASHTOWare has relatively limited support for subdivided units, but only a few of the states are using it. The Ontario and Quebec BMS are examples where this model is more fully supported, and is used on large and small structures.

In the 'Enumerated Damages' approach, the structure may still be permanently divided, but typically into larger units. Instances of observed damage are recorded in a separate listing of damaged areas. Each damaged area has an element key identifying the type of defect, a location specified in a standardized three-dimensional manner within the structure, and a quantity. The quantity would typically be smaller than the quantity recorded for the entire parent element since it represents just the size of the damaged area.

Unlike the ‘Subdivided Units’ approach, ‘Enumerated Damages’ allow multiple instances of the same defect on the same element, at different locations. Damaged areas of the same or different types can overlap. From one inspection to the next, the listing of damages can change substantially.

The following case study illustrates the differences in the defect information resulting from each approach. The ‘Enumerated Damages’ approach lists the defects for the Stringers (Element 113) of a single truss panel in a table. The ‘Subdivided Units’ approach summarizes the same deficiencies in the typical “Element Quantity and Condition State Summaries” following the MBEI format for each three subdivided units of the element; the stringer ends (2’-0” long portions of each stringer), the fascia stringers (includes Stringers 1 and 7), and the remaining interior portions of the stringers.

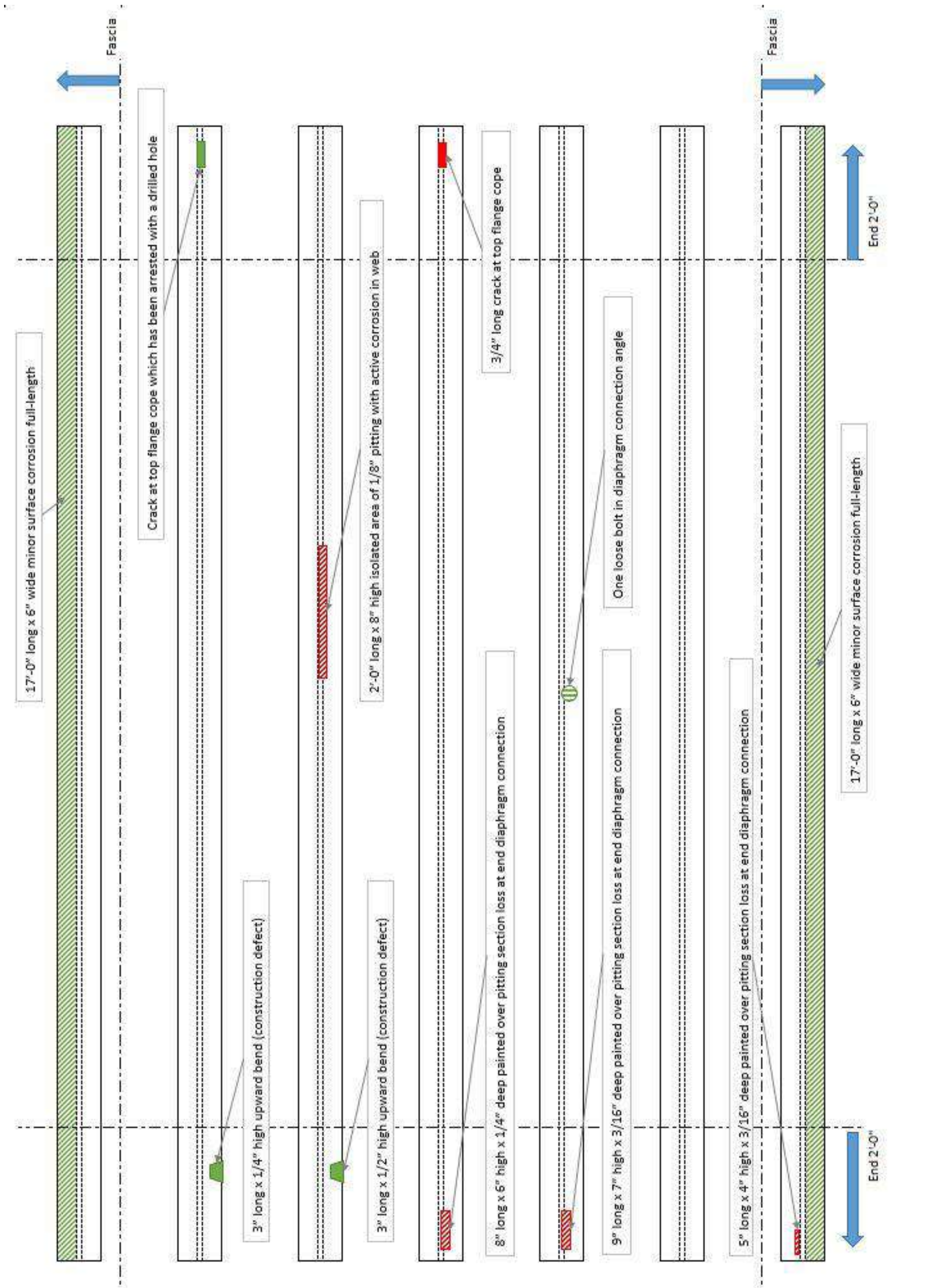


Figure 4.19 - Case Study – Sketch of stringer deficiencies.

'Enumerated Damages' Approach

Steel Stringers (Element 113), Panel 7

Stringer Number	Relative Component	Relative Location	Description	CS	Quant. (LF)	Defect(s)
1	West bottom flange	0'-0" from north end	17'-0" long x 6" wide minor surface corrosion full-length	2	17	Corrosion (1000)
2	Web	0'-4" from north end	Crack at top flange cope which has been arrested with a drilled hole	2	1	Cracking (1010)
2	East bottom flange	1'-3" from south end	3" long x 1/4" high upward bend (construction defect)	2	1	Distortion (1900)
3	West web	6'-3" from north end	2'-0" long x 8" high isolated area of 1/8" pitting with active corrosion in web	3	2	Corrosion (1000)
3	East bottom flange	1'-3" from south end	3" long x 1/2" high upward bend (construction defect)	2	1	Distortion (1900)
4	East web	0'-2" from south end	8" long x 6" high x 1/4" deep painted over pitting section loss at end diaphragm connection	3	1	Corrosion (1000)
4	Web	0'-4" from north end	3/4" long crack at top flange cope	3	1	Cracking (1010)
5	Connection to east diaphragm	8'-6" from north end	One loose bolt in diaphragm connection angle	2	1	Connection (1020)
5	East web	0'-2" from south end	9" long x 7" high x 3/16" deep painted over pitting section loss at end diaphragm connection	3	1	Corrosion (1000)
7	East bottom flange	0'-0" from north end	17'-0" long x 6" wide minor surface corrosion full-length	2	17	Corrosion (1000)
7	West web	0'-3" from south end	5" long x 4" high x 3/16" deep painted over pitting section loss at end diaphragm connection	3	1	Corrosion (1000)

Panel 7, Element 113 Summary

Element Number	Element Description	Unit of Measure	Total Quantity	CS 1	CS 2	CS 3	CS 4
113	Steel Stringer	ft	119	76	37	6	0
1000	*Corrosion*	*ft*	*38*	*0*	*33*	*5*	*0*
1010	*Cracking*	*ft*	*2*	*0*	*1*	*1*	*0*
1020	*Connection*	*ft*	*1*	*0*	*1*	*0*	*0*
1900	*Distortion*	*ft*	*2*	*0*	*2*	*0*	*0*

‘Subdivided Units’ Approach

Panel 7, Stringer Ends (2’-0”)

Element Number	Element Description	Unit of Measure	Total Quantity	CS 1	CS 2	CS 3	CS 4
113	Steel Stringer	ft	28	16	10	4	0
1000	*Corrosion*	*ft*	*10*	*0*	*7*	*3*	*0*
1010	*Cracking*	*ft*	*2*	*0*	*1*	*1*	*0*
1900	*Distortion*	*ft*	*2*	*0*	*2*	*0*	*0*

Panel 7, Fascia Stringers (excluding end 2’-0”)

Element Number	Element Description	Unit of Measure	Total Quantity	CS 1	CS 2	CS 3	CS 4
113	Steel Stringer	ft	26	0	26	0	0
1000	*Corrosion*	*ft*	*26*	*0*	*26*	*0*	*0*

Panel 7, Interior Stringers (excluding end 2’-0”)

Element Number	Element Description	Unit of Measure	Total Quantity	CS 1	CS 2	CS 3	CS 4
113	Steel Stringer	ft	65	62	1	2	0
1000	*Corrosion*	*ft*	*2*	*0*	*0*	*2*	*0*
1020	*Connection*	*ft*	*1*	*0*	*1*	*0*	*0*

Panel 7, Element 113 Summary

Element Number	Element Description	Unit of Measure	Total Quantity	CS 1	CS 2	CS 3	CS 4
113	Steel Stringer	ft	119	76	37	6	0
1000	*Corrosion*	*ft*	*38*	*0*	*33*	*5*	*0*
1010	*Cracking*	*ft*	*2*	*0*	*1*	*1*	*0*
1020	*Connection*	*ft*	*1*	*0*	*1*	*0*	*0*
1900	*Distortion*	*ft*	*2*	*0*	*2*	*0*	*0*

Because very large, complex bridges are composed of so many elements of such vast quantities, the time and expense needed to implement either the ‘Subdivided Units’, ‘Enumerated Damage’ or even the current requirements of the MBEI would be proportionally significant.

Although the ‘Subdivided Units’ approach can be accommodated in BrM as it currently exists, the approach may become complicated for big bridges due to the greater number of elements and variety of configurations. Boundaries such as those between interior and exterior or end and middle portions of elements must be decided prior to the inspection and then strictly adhered to by inspectors when recording findings in the field. For example, the inspector must know that the girder end element would apply only to the portions of a continuous girder adjacent to the unit’s ends and not at interior support piers, and making sure that the end of an exterior girder only gets counted for once.

The 'Enumerated Damages' approach would require significant modifications to BrM to be incorporated into that software. To implement this approach at the present time would require development of separate database tables to store and analyze the collected damage information. Most big bridge owners already maintain specialized spreadsheets for the management and analysis of their bridge(s), so the level of effort needed to apply this approach would depend highly on their existing analysis tools. With this approach, the collection, organization and presentation of damage information very closely matches the reporting methods currently used by most inspectors for big bridges, so its implementation, from an inspection standpoint, would be more intuitive. This method also provides more valuable information for bridge maintenance operations, and can more closely track changes in specific damages over time.

Both methods presented could benefit greatly from future 3D bridge software capable of modeling bridges overlaid with the condition data for inspection or analysis. The BMS used in Finland and Switzerland, as well as BMS currently in development in the United States by IBM and MIDAS, have demonstrated 3D functionality.

It is important to note that life cycle cost analysis, and especially the forecasting of future needs, make it necessary to have an element inspection table, regardless of whether a damaged area table is also provided. The entire quantity of each element is subject to deterioration and may potentially need preservation work at some point in the future. Ideally, if a BMS has a capability for 'Enumerated Damages' it would also need a capability to summarize the damages at the element level, including the reasonable handling of overlapping damages.

If deterioration modeling is performed at the level of damaged areas, it is necessary that the analytical process be able to forecast the onset of future damaged areas not observed in the current inspection. This means the deterioration modeling approach would be substantially different from what is currently found in most BMS. For these reasons, even if the 'Enumerated Damages' approach is used for inspections, agencies may prefer to limit the analysis of life cycle cost and preservation needs to the element level.

The reliable coding of damaged location and quantity may be a difficult skill for inspectors to become proficient. The continued development of 3D bridge inspection software would greatly improve this method of data collection and organization. At this time, the collection of damaged location and quantities might be a worthwhile goal for automated inspection software. For the current state of the art, and probably for the foreseeable future, the capabilities of automated systems are much stronger and more mature for certain elements (such as decks) than for other elements. Also, many of the more innovative techniques may be more cost effective for big bridges than for small ones.

Statewide needs analysis and other management functions require uniform statewide coverage of all elements and all significant structures, which is readily feasible for the subdivided units approach but not for the enumerated damages approach. On the other hand, the need for innovation in data collection might be best served by the flexibility of the enumerated damages approach. Considering all these factors together, the subdivided units approach might be viewed as highly desirable for near-term full support in all BMS used by big bridge owners. In contrast, the enumerated damages approach might be developed and implemented more incrementally based on research progress and the needs of specific agencies for project level analysis and design.

Element Level Inspection Difficulties

While consistency and accuracy are essential to producing element data sets that can be used for deterioration tracking and forecasting, perfect accuracy for elements which are quantified based on area such as the deck, wearing surface, and concrete or steel protective coatings, is not typically feasible for standard inspection rates when employing traditional inspection methods. Estimations are often used when evaluating the very large areas inherent for these elements of big bridges, resulting in potential widespread inaccuracies. As a result, performance tracking and deterioration forecasting for such elements is unsubstantiated in most cases. Advanced remote sensing NDE methods presented in the upcoming Section 5.2 may provide methods to conduct repeatable, precise assessments for meaningful analysis.

Figure 4.20 - Large area of paint failures on a suspension bridge steel tower strut.

Estimation is further complicated for deck elements which may have deficiencies in the top and bottom faces with areas of overlap, making the defect quantities impossible to determine without the use of scaled drawings, measurements and location notes which are seldom within the scope of the condition and element inspection; especially in the case of a big bridge which may have hundreds of thousands of square feet of deck area. This problem may be overcome through the use of advanced 3D bridge model inspection programs discussed further in Section 4.4.3.

Difficulties accessing elements on big bridges further exacerbate inaccuracies; typically, the top of the deck must be inspected from single outside lane closures that may inhibit close-up inspection and measurement of defects near the centerline. To assess protective coating areas, members must be viewed from multiple angles and from the interior, when applicable, to see all faces; this is a challenging task for an inspector to accomplish with precision when inspecting from a slow-moving underbridge inspection unit (UBIU) with limited range of movement.

Figure 4.21 - UBIU being used to inspect the Walt Whitman Bridge deck truss approach spans.

Duplicate Defect Information

Traditionally for big bridge inspections, all notable defects and their specific locations are recorded and presented in the narrative inspection report. This treatment of inspection information is generally more detailed than the requirements of the MBEI which mandates that only the most severe defect for each given location is represented in the overall condition state summary for the element. Less severe defects which overlap the same given unit may be represented in the individual defect quantities for the element, but the overlapping defects must be compared to determine the governing defect for the overall condition state summary for the element. This poses a dilemma for many inspectors who recognize that detailed defect data can render the element data redundant. This may lead to the inspector forgoing the more generalized MBEI element defect quantity calculations during the inspection, instead concentrating their effort on compiling detailed description and location notes for the deficiencies that will be included in the inspection report. With the detailed defect notes, the inspector assumes it will be possible to formulate the element defect and condition state data, post-inspection.

While compiling the element summaries post-inspection has merits in minimizing note-taking and field inspection time, instances of minor or typical widespread defects which are only generally noted in the inspection report may be overlooked. Greater care must be taken by inspectors to ensure that the determination of governing and/or overlapping defects will be possible, either with sketches or by recording adequately detailed location notes. Inspectors should be well-familiarized with the MBEI and its intricacies prior to conducting an element level inspection in this fashion. For instance, while sound concrete repair patches are not typically noted in narrative inspection reports unless the patch is deteriorated or failed, sound repairs designate at least a CS 2 rating for the respective quantity of the element. Without this knowledge, sound concrete repair patches may not be noted by the inspector and would be erroneously omitted from the element condition state summary.

4.4.3 Advanced Inspection Software

Several existing software packages designed for the inventory and management of bridges were explored as part of Task 4 of this study; however, none were found to have the capabilities to become an all-encompassing tool for big bridge inspection and management. For instance, most lack the ability to store variation in bridge characteristics between spans which is common on big bridges. The ability to record and track individual defects over time is also absent. For these reasons, many big bridge inspectors and owners have developed customized spreadsheets and management systems to suit their specific needs. Unfortunately, this often results in either bespoke solutions consisting of disparate and disconnected data sets, or development of proprietary software or systems at a substantial cost to the bridge owner.

Defect Database Software

Rather than employment of labor-intensive methods which rely on the inspector's abilities and knowledge of the MBEI and require intensive handling of redundant information (refer to the first two topics in Section .4.2), inspection software on a mobile device could assist inspectors in detailed defect description and location note taking and organize the information in a database. Such software could also automate conversion of defects to their element defect quantities as defined in the MBEI in addition to any other conceivable methods for analysis of the deficiency data. As noted in Section 4.4.2 under "Element Level Inspection Difficulties", the issue of redundant data sets such as those which are maintained by the MDTA for each span or panel of their structures could be alleviated by organizing the detailed defect description and location data into separate fields to enable automatic conversion to MBEI defect quantities, eliminating a significant amount of time consuming and error-prone manual data entry.

The implementation of such software will be a significant step by streamlining the flow of defect information which encompasses all aspects of bridge management; inspection, condition reporting, load rating, and action prioritization through life-cycle cost analysis, considering deterioration forecasts and potential risks. In addition to the detailed defect data, the software would benefit from the flexibility to store any possible historic NDE results for analysis, as advanced non-destructive evaluation (NDE) methods utilizing remote sensing technology (described in upcoming Section 4.5.2) are likely to become more prevalent in the future.

3D Inspection Software

Ergonomic 3D inspection software which displays a full scale model of the structure being inspected could significantly increase the accuracy and rate of inspection by providing to the inspector a visual representation of noted defects on the element. This would allow for a quick comparison with the current condition, eliminating the need to otherwise mentally visualize and verify cumbersome defect descriptions and location information. General location information could be automatically populated using a mobile device with sufficiently accurate GPS capabilities. Verifying, modifying, or recording defects would be easier with the assistance of user prompts and well-designed graphical controls. Built-in validation checks could assist inspectors by preventing easily recognizable errors and ensuring that all necessary data is collected.

While the use of 3D models in mobile inspection software could transform the inspection process by streamlining the way inspection data is viewed and stored, its implementation may entail significant effort in the initial preparation of the 3D models. Facilitating the desired simple and systematic generation of the bridge models necessitates the development of additional software. While the use of full 3D models is very effective for smaller and simple bridge types, the models may be inadequate in their representation of the unique details and configurations of big bridges without extensively detailed customization options.

Short of software which displays a complete 3D model for inspection and analysis, a more feasible version which models selected elements individually could afford the same advantages; allowing the inspector to visually compare the previously noted deficiencies with the current condition. Such software would be more manageable with mobile device controls and hardware and could artificially solidify the objectives of bridge element inspection by focusing the inspector on individual elements. Optimally, software capable of displaying either a full 3D bridge model, individual spans or panels, or individual elements would offer flexibility in the inspection of a variety of structure sizes and add the necessary functionality to enable its application to big bridges.

Under a Michigan DOT (MDOT) funded project (Brooks et al. 2017b), a 3D bridge inspection application has been created with many of the aforementioned capabilities. The app is a mobile software tool that was designed to make recording of bridge element information easier for inspectors through incorporating element-level data into a 3D environment where data could be uploaded and downloaded through cellular networks. The software is able to create an interactive 3D model of the bridge. The inspector is then able to markup the bridge model in the 3D environment with defect information, which is recorded and visualized in the tablet-based application (Figures 4.22 and 4.23). Additionally, the inspector can record photos of the defects and other bridge features and tie them to specific locations within the 3D model.

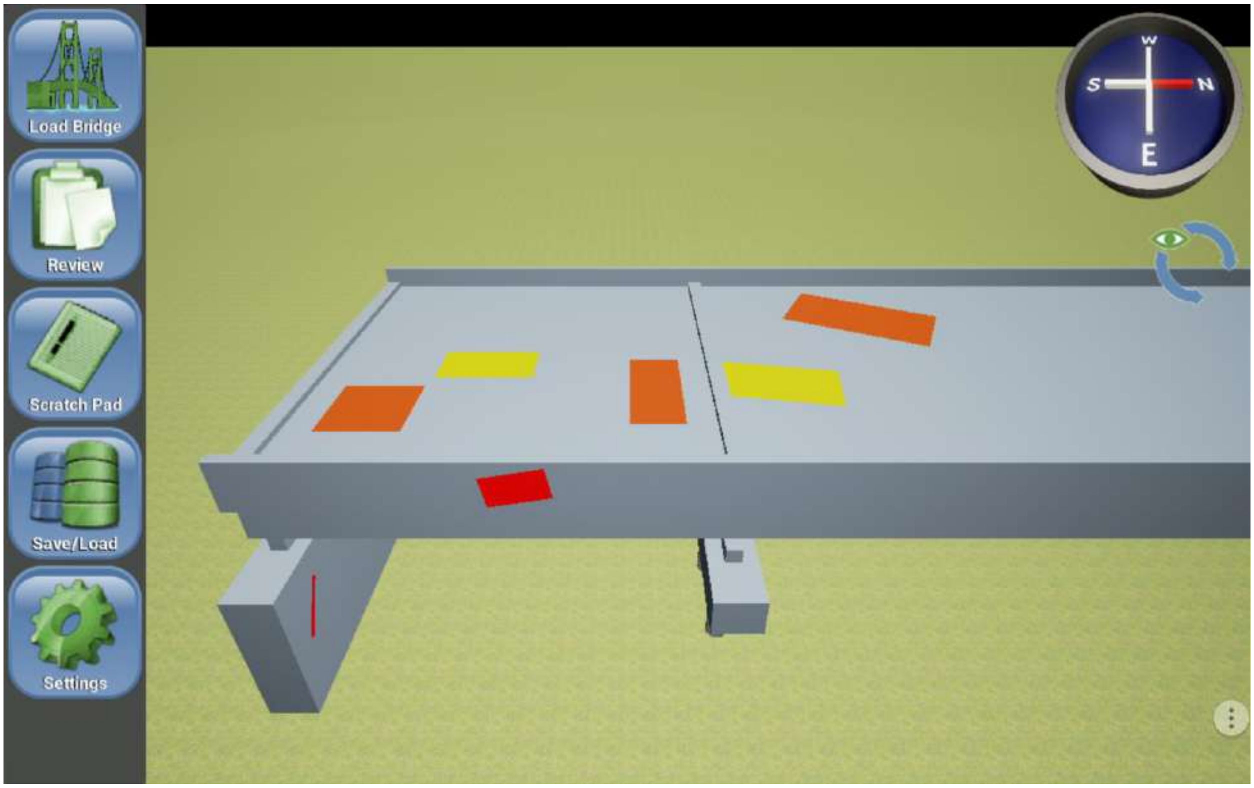


Figure 4.22 - Defects are added and manipulated at specific locations by the inspector within the 3D BRIDGE application.

Figure 4.23 - Element condition state summary within the 3D BRIDGE application corresponding to the defects shown in Figure 4.22.

The application uses a local 3D coordinate system to record defect information as well as load previously recorded defect information. The bridge model is constructed within this local 3D coordinate system based on the structure data and dimension values recorded in MDOT's bridge management database (Figure 4.24). Users are provided the capability to modify generic assumptions and automatically retrieved bridge information to help create a better model of the structure.

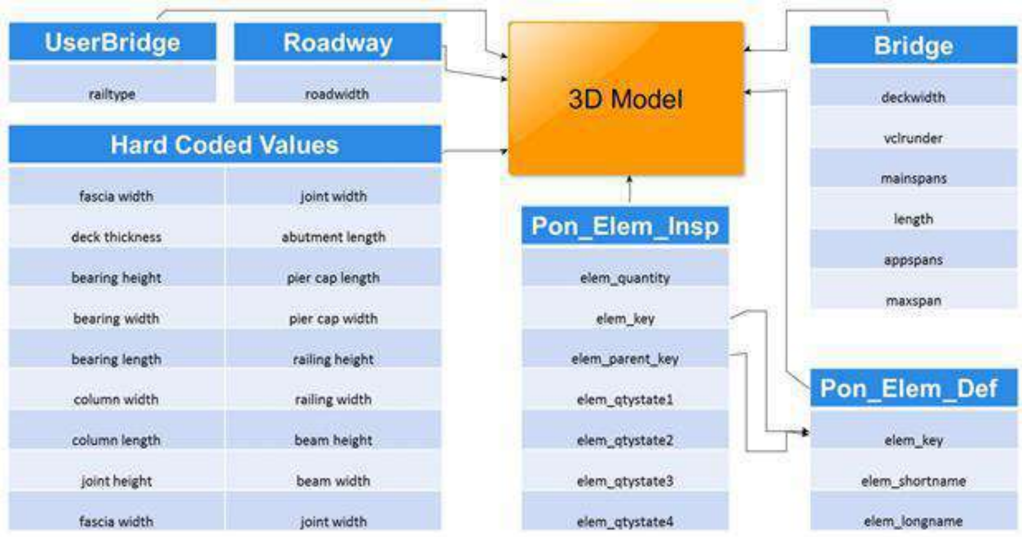


Figure 4.24 - Flowchart of the database back-end containing the data necessary to create the 3D model.

While the application is currently providing MDOT inspectors with a new method of collecting, storing, and reviewing important bridge data for typical highway bridges, the application still has limitations such as lacking models for many complex bridge types used in big bridges. Although complex bridges were not a priority for the current project, future development of the application could address this limitation.

4.5 Non-destructive Evaluation (NDE) Methods

4.5.1 Current NDE Methods

There are numerous non-destructive evaluation (NDE) methods which are commonly used to further investigate specific deficiencies or detect latent deficiencies in elements. Refer to Table 4.1 for descriptions and applicable defects, elements, and material types for the methods which are prevalent in bridge inspection.

Table 4.1 - Descriptions of Common NDE Methods and Suitable Applications for Bridge Elements

Method	Description	Applicable Elements/Defects
Dye penetrant	Low surface tension fluid infiltrates surface-breaking discontinuities and developer is applied to draw out penetrant and produce a visible indication.	Surface discontinuities in steel and other non-porous materials
Ultrasonic	Ultrasonic waves are transmitted into material and arrival time and intensity of reflected waves are displayed on a diagnostic machine which can be used to determine thickness of characterize sub-surface discontinuities.	Sub-surface discontinuities in steel and other metallic elements
Magnetic particle	Electric current is passed through the element establishing a magnetic field. Ferrous particles are applied which are attracted to areas of flux leakage which occur at discontinuities in the material to indicate the location and size of the defect.	Surface and slightly sub-surface discontinuities in steel and other ferromagnetic materials
Magnetic flux leakage	Magnetizes the element being tested and the magnetic field leakage is detected allowing identification of areas of section loss or other discontinuities.	Surface and subsurface discontinuities in steel and other ferromagnetic materials
Magnetostriction	Detects loss of section or broken wires at the interior and exterior of suspender ropes by generating a guided acoustic pulse which travels up and down the ropes. A portion of the pulse is reflected back to the source at discontinuities which can be measured to determine the size and location of the defect.	Wire ropes
Eddy-current	Electromagnetic method which induces and measures changes in current in the specimen to detect and characterize surface and sub-surface defects.	Surface and slightly sub-surface (<3/16” deep) defects in steel and other conductive materials

Table 4.1 - Descriptions of Common NDE Methods and Suitable Applications for Bridge Elements (Cont.)		
Method	**Description**	**Applicable Elements/Defects**
Acoustic emissions	Monitoring of acoustic (elastic) waves in solids which are emitted when a material undergoes irreversible changes in its internal structure such as crack formation or plastic deformation.	Steel and other metallic elements
Radiography	Electromagnetic radiation is passed through the test subject and an image of the radiation which passes through can be viewed to detect internal voids and flaws.	Internal discontinuities in steel and other metallic elements
Impact echo	An impactor device is used to propagate stress waves into the element and a transducer detects the reflected waves which can then be used to characterize internal discontinuities.	Sub-surface discontinuities in concrete elements
Ground-penetrating radar	Electromagnetic waves are transmitted through the element and reflected signals are received which can be interpreted by the inspector.	Sub-surface discontinuities in concrete elements

4.5.2 Advanced Remote Sensing (NDE) Methods

The NDE methods listed in Section 4.5.1 must be manually conducted on individual or selected areas of elements, therefore, most are typically used for investigation of specific defects or to perform in-depth inspections. However, advanced NDE methods with remote sensing capabilities exist which could potentially replace traditional inspection techniques. These methods, in conjunction with use of unmanned aerial vehicles (UAVs), for which consumer and commercial markets have grown rapidly in recent years, could significantly reduce inspection times and access costs while improving safety of inspections. Such methods could greatly improve assessment accuracy for numerous elements, particularly larger elements with high surface area such as decks, steel towers, concrete substructure units, and concrete or steel protective coatings. Human error in estimating defect quantities could be reduced or eliminated by consistently producing precise results for meaningful analysis. However, required training for operators and initial investments in hardware for these methods may hinder widespread implementation and use by conventional bridge engineering and inspection companies. This may result in growth of specialized inspection sectors and more prevalent use of special inspection contracts, particularly on big bridges where the practices are more easily justified and funded.

This section overviews four different NDE remote sensing technologies that have previously been applied to bridge inspections, including 3D Optical Sensing, Thermography, Light Detection and Ranging (LiDAR), and At-Speed Ground-Penetrating Radar (GPR). This section is meant to provide a description of how each technology can be applied to big bridges while Chapter 5 provides specific performance ratings measuring the accuracy of each NDE remote sensing technology in detecting and quantifying the condition of various elements. Table 4.2 summarizes the compatible applications which have been found for each sensing technology and typical and complex bridge elements.

Table 4.2 - Applicable Remote Sensing Technologies for Typical Elements and Materials.

Element	3D Optical	Thermography	LiDAR	At-speed GPR
Concrete Deck	X	X		X
Concrete Substructure	X	X	X	
Steel Substructure	X		X	
Concrete Superstructure	X	X	X	
Steel Superstructure	X		X	
Protective Coatings	X			
Steel Element (obscured by Protective Coating)		X		

Preparing for Element Inspection

3D optical remote sensing can include the use of vehicle- or aerial-based platforms equipped with high-resolution cameras, which collect imagery used to build 3D models, including 3D models of bridge decks. This idea is based on the principles of photogrammetry, which is "the science or art of deducing the physical dimensions of objects from measurements on photographs of the objects" (Henriksen 1994). To construct 3D models from the imagery, 60% overlap between images must be achieved, ensuring that each object on the ground is represented in at least two photos (McGlone et al. 2004). This allows for an object's height (or depth) information to be extracted from the imagery; a vital piece of information when studying various bridge elements and the respective condition states. Identifying and quantifying distress features is feasible through processing the collected imagery into a point cloud and a digital elevation model (DEM) to determine where changes in depth, indicative of element distress, occur.

Figure 4.25 - Example 3D orthophoto of a truss bridge foundation (Zink and Lovelace, 2015).

Current 3D optical remote sensing capabilities are practical for evaluating and quantifying defects in concrete decks, superstructure, and substructure elements (Figure 25). Each of these elements can experience defects such as cracking, spalling, and scaling, all of which have successfully been detected by previous 3D remote sensing platforms and software and could have quantities reported by such a system. Additionally, steel pitting and section loss in steel elements may also be able to be quantified with 3D optical sensing with appropriate measurement sensitivity.

Optical sensing is also able to detect defects that do not have a measurable depth quantity, but instead, where values such as overall area is desired. This is especially useful in evaluation of concrete and steel elements and protective coatings by detecting and quantifying areas of corrosion, efflorescence, patched areas, and coating deterioration such as chalking or peeling/curling.

Advantages of 3D optical sensing are realized in its ability to create 3D models of difficult to access elements, such as large Reinforced Concrete Arches (Element 144), effectively eliminating needs for costly access equipment, traffic disruptions, or other complex methods to gain physical access for close-up inspection. Short of complex photogrammetry processing to create 3D models of elements, images retrieved by optical sensors mounted to UAVs (further discussed in Section 4.5.3) could economically be used to visually inspect difficult to reach elements, albeit with less accurate measurement and depth sensing capabilities.

Thermography

Applications of thermal remote sensing of bridges is aimed at detecting thermal anomalies, which are associated with delaminations and other similar structural distresses (Maser and Roddis 1990; Washer et al. 2009; ASTM 2007; and ACI 2001). Active (using artificial heat sources) and passive (using natural heating patterns) thermography can be used to detect differences in temperature between sound and unsound elements due to environmental conditions, diurnal temperature, and insolation changes. Sound and distressed areas are impacted differently by changes in temperature, resulting in radiant differences that can be detected by thermal sensors and remote sensing methods. Through successful and timely detection of such defects, inspectors are able to identify damaged areas which are not easily observed with the naked eye before defects progress towards higher condition states, such as a delamination turning into a spall for concrete bridge decks (Washer et al., 2016, Ahlborn et al.

2012, Washer et al., 2009), cable surface anomalies (Mehrabi, 2006), and steel coating corrosion (Washer et al., 2016).

Applying thermography remote sensing methods could assist greatly in the assessment of concrete decks, superstructure, and substructure elements. Testing conducted by Ahlborn and Brooks (2015) indicated that active infrared (IR) thermography can be applied to Element 210 (Reinforced Concrete Pier Wall) to detect and identify delaminations. After manual delamination testing was conducted by trained inspectors using hammer sounding methods, a heat lamp was used to heat the area marked off as being delaminated. The FLIR SC640 and a FLIR Tau 2 thermal cameras were positioned approximately 6 feet away from the surface of the pier cap and collected continuous imagery for the length of the tests to study how the delamination appeared during heating and cooling periods (Figure 4.26). Testing indicated that a heating period of 15 minutes was suitable for detecting and quantifying delaminations.

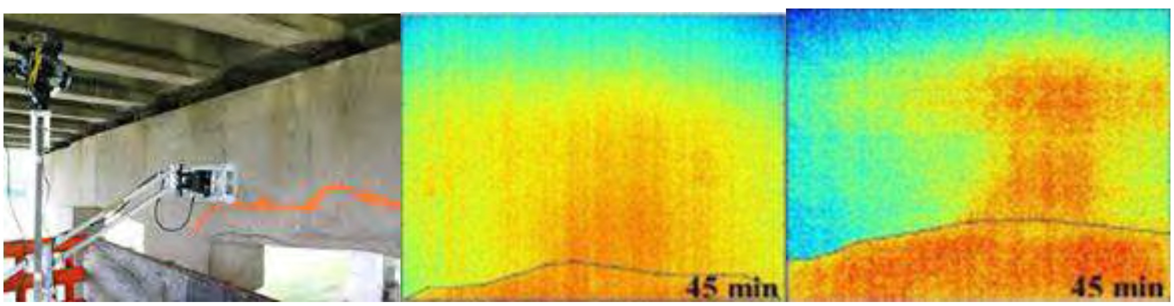


Figure 4.26 - Active IR thermography set up at a concrete bridge pier (left), and thermal delamination detection using the FLIR SC640 (middle) and FLIR Tau 2 (right) (Ahlborn and Brooks, 2015).

Washer et al. (2009) used thermal gradient and signatures at a prestressed box girder bridge in New York. The internal box girders appeared in the thermal imagery due to the thermal gradients through different depths in the concrete (Figure 4.27). This testing also confirmed suitable heating and cooling periods for the detection of sub-surface defects.

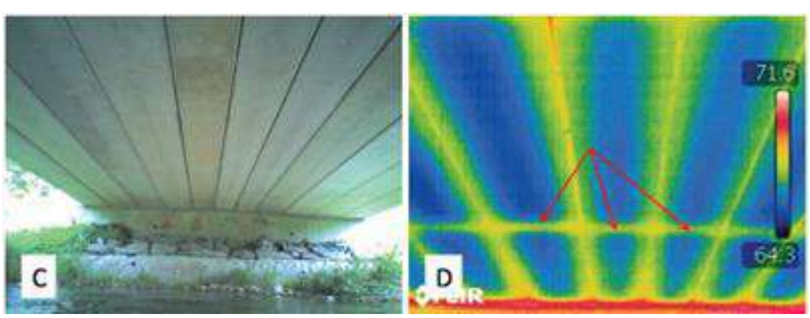


Figure 4.27 - Optical (left) and thermal (imagery) were used to determine if any delaminations existed on the underside of the bridge (Washer et al., 2009).

As demonstrated by Mehrabi (2006), thermography can be used on cable-stayed bridges by detecting anomalies near the surface of cables by measuring how heat flow is impacted by distress features. For this study, inflicted splits in polyethylene pipes were either filled with epoxy or left unfilled. Thermal imagery was collected 3 to 6 feet from the pipes after removing the pipes from a controlled environment. Testing indicated that only unfilled splits that were exposed to heat were able to be identified, but repaired (epoxied) splits were not thermally visible (Figure 28). Additionally, Washer et al. (2016) used infrared coating inspection system technology to detect corrosion areas that are not visually observable under steel coating. This system consists of a handheld thermal sensor that collects a thermal image at high rates (30 to 60 samples per second) to assist in the observation of heat distribution during heating and cooling periods. The difference in heating and cooling patterns between sound and distressed sections of steel indicate where corrosion is occurring (Figure 4.28).

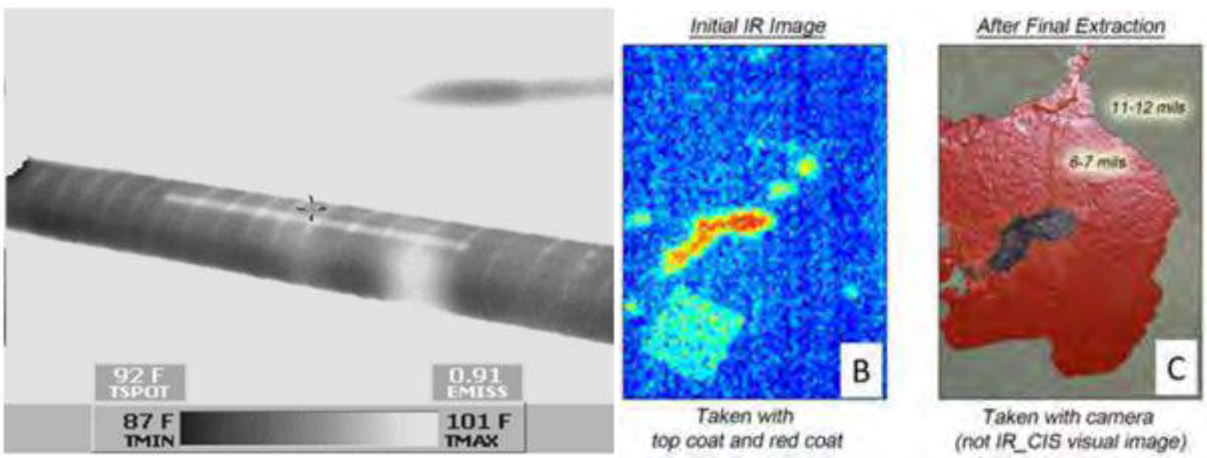


Figure 4.28 - Infrared image of an unfilled split (right, Mehrabi, 2006) and corrosion detection (right, Washer et al., 2016).

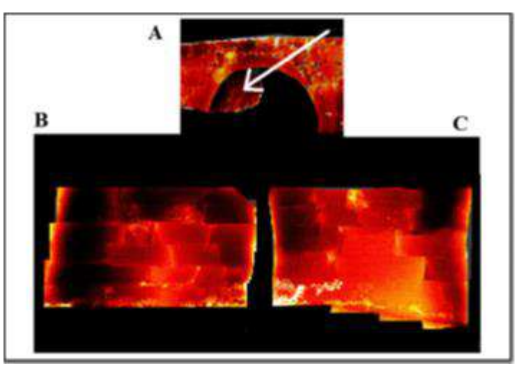


Figure 4.29 - 3D model of thermal data indicating where high areas of moisture were detected (arrow) in an arch bridge (Solla et al., 2013).

Thermography has had limited use for Reinforced Concrete Arch (Element 144) bridges. Solla et al. (2013) incorporated passive thermography to assess moisture content within a historic arch bridge in Spain. Using a distance of 5 meters between the walls of the bridge, thermal imagery was collected and processed into a 3D model. Results indicated that moisture areas within the bridge were cooler than drier areas and mainly existed in two specific arches and along the upper part of the walls, where the walls and border of the road met. As for the inner arch, which was identified as being the most vulnerable part of the bridge, thermography indicated that water existed at the edge of the vault (Figure 4.29).

Washer and Schmidt (2014) used thermography for quality control and inspection techniques during the construction of hybrid composite beams (HCBs). HCBs were an experimental technology being used by the Missouri Department of Transportation and consist of an arch beam enclosed in fiberglass reinforced polymer. Tests indicated that thermography was applicable in detecting the quality of the arch and for the detection of delaminations within the composite shell (Figure 4.30).

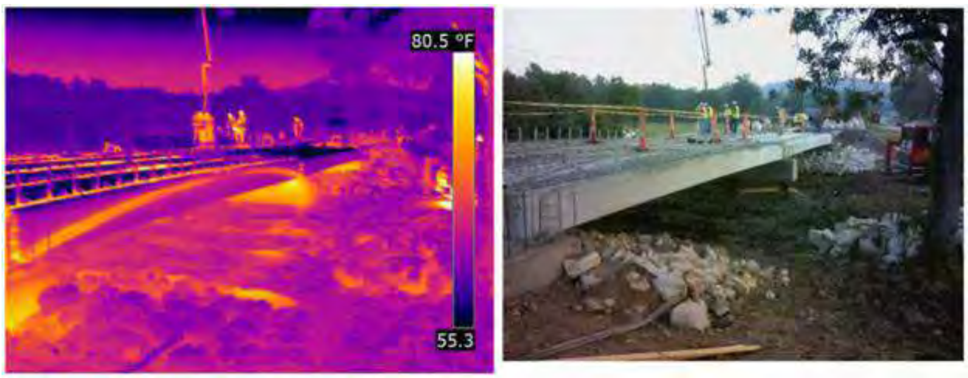


Figure 4.30 - Thermal imagery (left) detected the arch within the HCB bridge, which is not possible using optical imagery (right) (Washer and Schmidt, 2014).

Light Detection and Ranging (LiDAR)

LiDAR has been used to assess both pre-existing and new bridges, with applications being focused on detecting damage, clearance measurements, and static deflection movements (Liu and Chen, 2013, Dai et al, 2011). This technology is especially useful when traditional measurements cannot produce the accuracy needed during inspections or when the bridge is not easy to access (Liu and Chen, 2013). With the development of automated algorithms that can detect and quantify material mass loss (such as LiDAR-based bridge evaluation, LiBE), assessment of such features can be conducted more quickly using LiDAR technology as compared to traditional manual measurements (Liu et al, 2010). Numerous studies and assessments utilizing LiDAR have been conducted on a variety of bridge types which follow, including several of the complex bridge types which are the subject of this study.

Use of LiDAR on Suspension Bridges

The California Department of Transportation (Caltrans) used LiDAR data to obtain quantitative information pertaining to a new 10,000 ft. span of the San Francisco - Oakland Bay Bridge (SFOBB) (Speed, 2015). Data collection was conducted to obtain as-built measurement records, which were previously missing after the 1989 Loma Prieta earthquake. During the earthquake, sections of the SFOBB collapsed and, due to the missing measurement records, reconstruction of the original east span truss section was not possible. Under the Caltrans study, the bridge was closed during Labor Day week, providing ideal, traffic-free conditions, to collect LiDAR data, which consisted of a manned aerial flight and three ground-based scanners (results shown in Figures 4.31 and 4.32). After processing the data, Caltrans determined that LiDAR can provide details of the suspension bridge that conventional methods cannot in five days, with data showing details of bolts and rivets. Additionally, using LiDAR to obtain measurement records improved safety and efficiency as compared to other current methods.

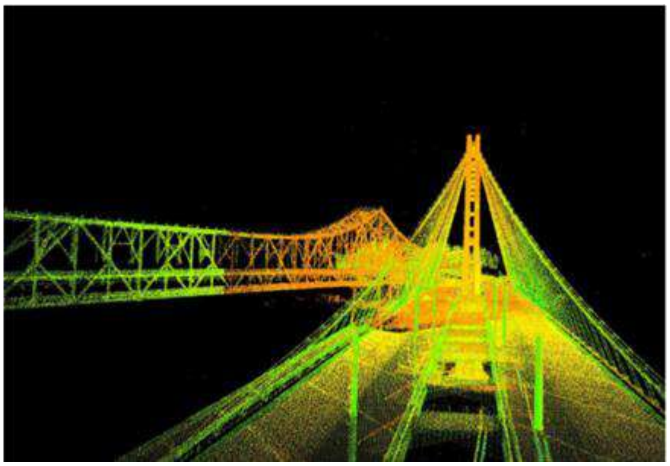


Figure 4.31 - Point cloud of the San Francisco-Oakland Bay Bridge (Speed, 2015)

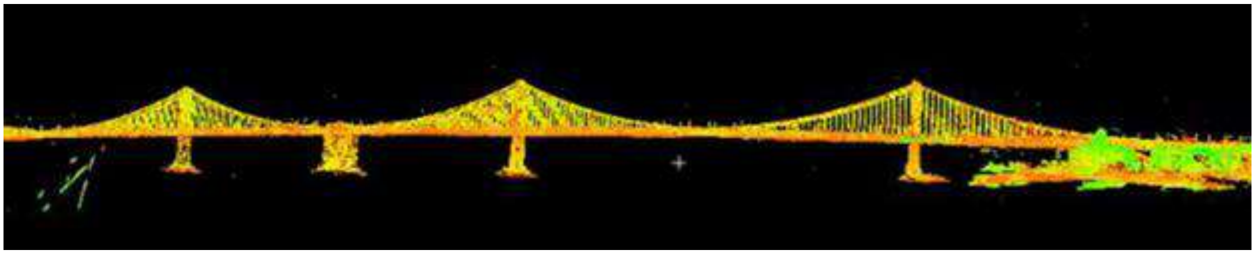


Figure 4.32 - Point cloud of the San Francisco-Oakland Bay Bridge’s profile (Speed, 2015)

Use of LiDAR on Cable-Stayed Bridges

LiDAR technology can help assess conditions of Steel Main Cables (Element 147), such that a load capacity analysis can be conducted. LiDAR technology was used by Berenyi and Lovas (2009) to measure the displacement of bridge cables. Assessing the Megyeri Bridge in Hungary, two RIEGL LiDAR units collected data from a nearby riverbank, with the collected high-density 3D point clouds being used to measure the displacement of the cables as vehicles drove across. Through analysis of the data, it was determined that the greatest displacement occurred along the longest cables.

Use of LiDAR on Truss Bridges

Multiple studies have been conducted to assess the use of LiDAR for inspection and measurements of truss bridges. For example, the Oregon Department of Transportation used LiDAR to measure the overall geometry of the Bridge of the Gods, which connects Oregon and Washington. Using the Leica ScanStation C10 (with an approximate cost of $150,000), with an accuracy of ¼ inch at 150 feet, the bridge was scanned and data reconstructed into a point cloud and CAD model (Figure 4.33). The models allowed bridge inspectors to extract information pertaining to truss geometry and measure lengths of secondary members for a dead load analysis (Rooper, 2013).

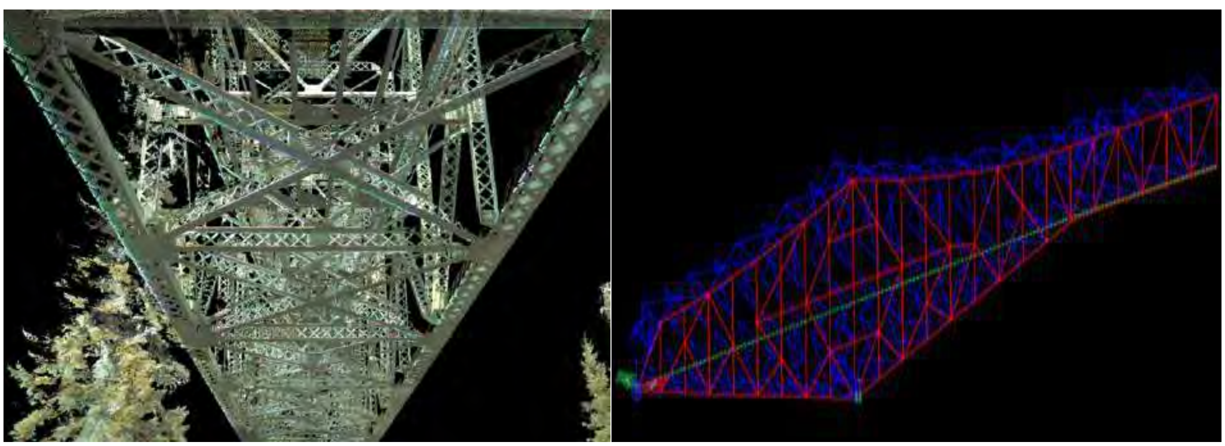


Figure 4.33 - 3D point clouds of the truss bridge (left) and the CAD model built from the LiDAR data (right) (Rooper, 2013).

Use of LiDAR on Arch Bridges

LiDAR technologies were used to assess a masonry arch bridge using a fully automated point cloud segmentation technique (Riveiro et al 2016). The segmentation was used to differentiate between vertical walls and main structural elements (Figure 4.34). Results indicated that the algorithm was able to indicate the number of arches and presence of piers. The algorithm did not assess the condition of any of the elements listed above. However, the results presented in Riveiro et al (2016) could extract condition data about features, potentially allowing for the assessment of such elements.

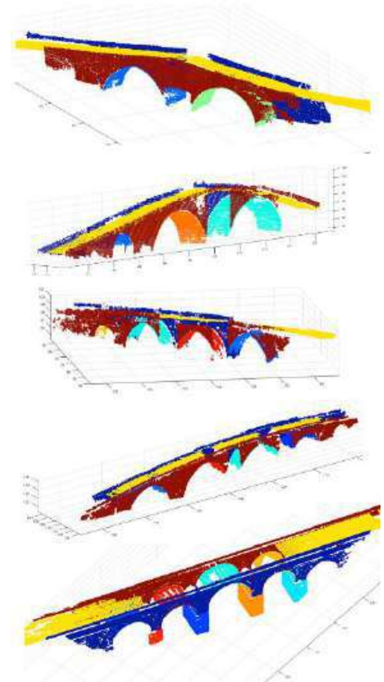


Figure 4.34 - LiDAR segmentation of bridge components (Riveiro et al, 2016).

Use of LiDAR on Girder/Beam Bridges

Various testing has been conducted to show the applicability of using LiDAR to detect girder/beam bridge deflections and locations of distress. Dai et al. (2011) used LiDAR to measure bridge deflection based on truck loads and concentrated on steel bridge girders and concrete parapets, among other components. Using loaded tandem dump trucks, girder deflection measurements were effectively collected by the LiDAR sensor, and showed girder bottom flange deformation under the various stress loads.

At-Speed Ground Penetrating Radar (GPR)

Like traditional radar, ground-penetrating radar (GPR) uses a transmitter and receiver to send and receive pulses of electromagnetic energy. Differences in the electrical permittivity of layers or features, such as steel, concrete, asphalt, or air gaps, affect the time and strength of the returned signal and can be used to create underground continuous cross sections. Frequencies can be chosen depending on the purpose, with high frequencies used for higher resolution at shorter depths, and lower frequencies used to map deeper layers with less resolution. However, moisture ingress is capable of distorting the results of GPR (Kilic 2014).

GPR has been an established evaluation method for assessing the condition of bridge decks for several decades (Wright 2011; Parrillo and Roberts 2006). GPR can either be coupled to the ground, increasing transmission at the sake of speed, or air coupled. At-speed GPR uses an air coupled system that allows for bridge decks to be assessed at traffic speeds, as fast as 30 to 45 mph (Geovision). The penetration depth allowed by the frequencies used for at-speed GPR allows for the detection of level of rebar corrosion and resulting delaminations (Barnes and Trottier 2000). Other bridge deck applications of GPR include determining deck thickness, concrete cover and rebar configuration, concrete deterioration, and properties of concrete (Gucunski et al. 2011). At-speed GPR systems are typically attached to a vehicle and, therefore, most applicable as NDE technology to evaluate bridge decks.

At-speed GPR is very useful in evaluating the condition of a large number of decks in a short span of time. Though the specific type of bridges evaluated was not mentioned, Maser (2009) used at-speed GPR and thermography to examine 87 bridge decks in two summers. A New Jersey study used at-speed GPR on local, state, and interstate highways to cover nearly 600 lane-miles in a two month span (Gucunski and Shokouhi 2004). The studies exemplify the potential of at-speed GPR to cover a large area of bridge decks in a time efficient manner.

In preparation for a large rehabilitation project, Fisher Associates used at-speed GPR to test and report on the deck condition of an aged and locally iconic arch bridge in Corning, NY (Logan 2014) (results shown in Figure 4.35 and Figure 4.36).

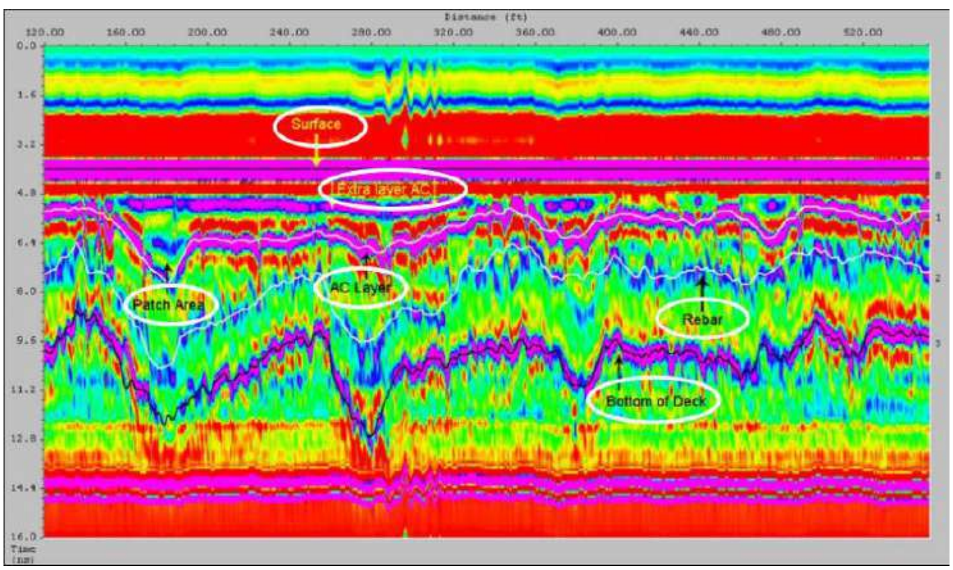


Figure 4.35 - Longitudinal deck section from GPR of the Centerway Bridge in Corning, NY (Logan 2014).

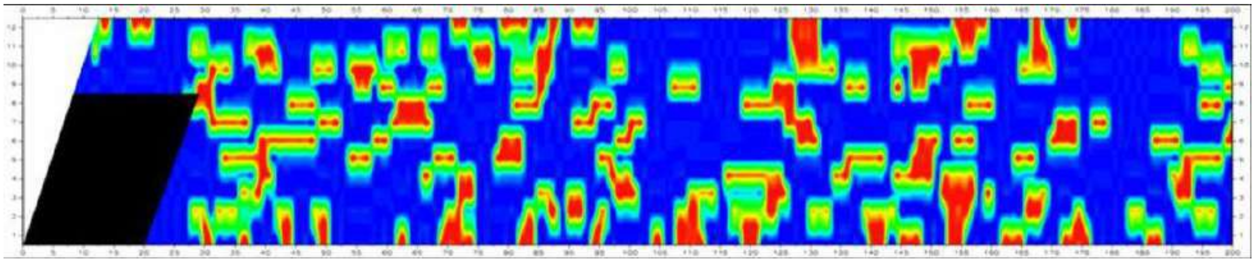


Figure 4.36 - Detection of voids or delaminations on Centerway Bridge deck (Logan 2104).

4.5.3 Unmanned Aerial Vehicle (UAV) - Enabled Remote Sensing

With the availability and accessibility of multicopter UAVs becoming more widespread and economical, recent research studies have assessed placing remote sensors onboard of UAVs to aid in the assessment of bridge element condition. Remote sensing technologies that have been successfully implemented on board of an UAV include optical, thermal, and LiDAR sensors. The incorporation of these types of technologies have the potential to make bridge inspections safer for both the inspectors and general public by removing inspection personnel from the roadway, and by reducing the amount of time and bridge closures needed to conduct the inspections.

Depending on which type of remote sensing technologies are being implement on the UAV platform and the resolution of the sensor, many elements and associated defects have the potential to be evaluated and detected. For instance, UAVs with high-resolution digital cameras would assist cable-stayed bridge inspectors in minimizing the use of complex rope access methods and access equipment currently used to inspect these elements. The UAV can fly along the cables at a safe distance, taking digital photos of the cables that can then be reviewed for presence of defects. Similarly, UAVs could be used to inspect large concrete arches which are very difficult to access for close-up inspection. With implementation of 3D optical sensing or LiDAR data collection, depth and/or area of spalls, patched areas, efflorescence/rust staining, and exposed rebar could be assessed. Areas of apparent distress and delaminations could be identified and allow for planning of further actions.

Before implementing UAV use for any bridge inspection, inspectors must be aware of and follow all federal UAV guidelines and restrictions imposed by the FAA, which may include restricted area spaces or requirements to fly within line of sight. The use of UAVs may also be limited by weather conditions (i.e. rain or wind) or small areas which may require access. Newer UAVs with built-in sense and collision avoidance sensors can help collect needed data in space-restricted areas. Smaller sized UAVs should be used when inspection between beams, girders, and deck floor system members is desired (Figure 4.37). Additionally, it should be noted that the use of the global position system (GPS) signal to keep the UAV steady is minimized due to the UAV being located underneath the bridge deck. Therefore, manual flights (without the use of GPS) will often need to be conducted when inspecting closely underneath bridge decks.

Figure 4.37 - DJI Phantom Vision 2 collected imagery of damage and exposed rebar (left) and girders/beams (right) (Brooks et al. 2015).

Brooks et al. (2017a) summarized examples of using UAVs to provide bridge condition data for the Michigan DOT on six bridges, including automated detection of spalls and delaminations through 3D optical and thermal data. During this analysis, two girder bridges that were part of the I-96 Fix construction project had bridge decks assessed using the UAVs with attached optical and thermal sensors. The reconstructed imagery showed the presence of spalls on the bridge deck and delaminations within the deck (Figure 4.38). A recent article describes the capabilities of UAV-enabled thermal and optical sensing to detect delaminations in concrete bridge decks, which can help with assessment of large bridge decks (Escobar-Wolf et al. 2017). The Minnesota Department of Transportation (MnDOT) has also been investigating the use of UAVs for bridge inspection with an overall goal of studying the impact and use of this new technology to increase bridge inspection safety (Zink and Lovelace, 2015).

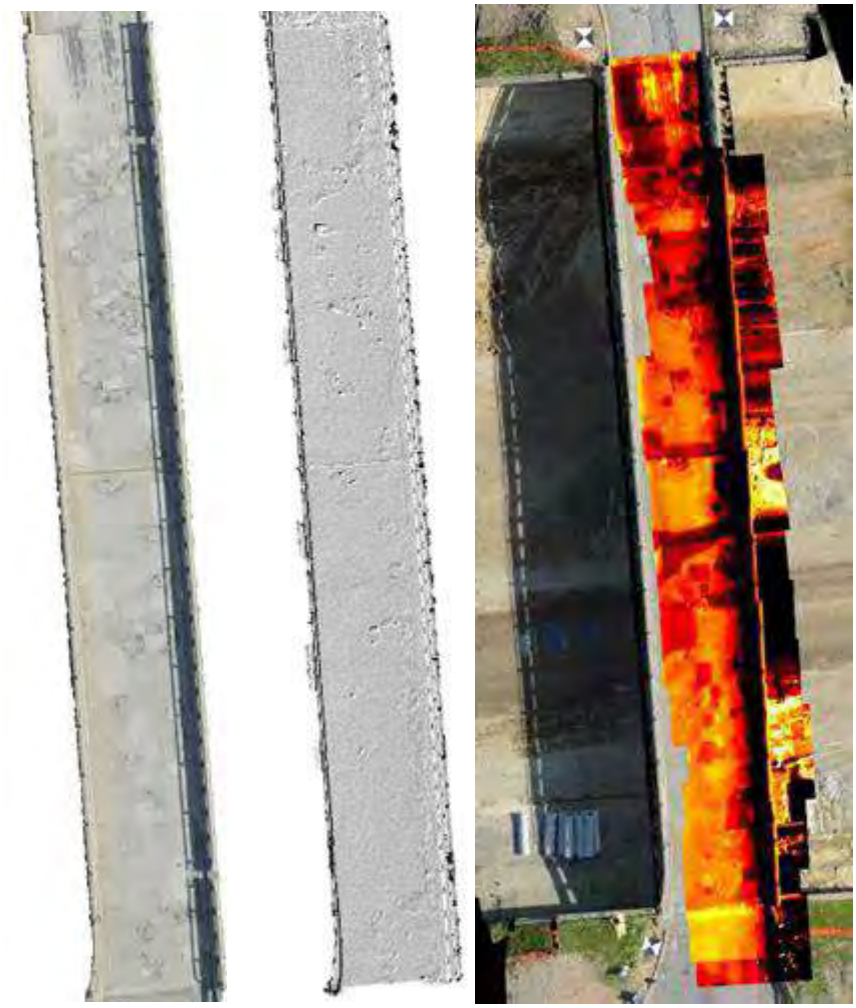


Figure 4.38 - Optical (left), hillshade (middle), and thermal (right) UAV-collected data show the presence of bridge deck distress features.

An additional study conducted by Brooks et al. (2015) tested a LiDAR unit attached to a UAV. Flights were conducted over two bridges whose decks were about to be replaced under a major reconstruction project (MDOT's I-96 Fix project). Traffic was closed off to each bridge during the data collection. Results indicated that UAV-mounted LiDAR units can produce high-quality models of beam bridges, showing details such as the guard rail, curbs, embankments, and the ground elevation surrounding the bridge (Figure 4.39).

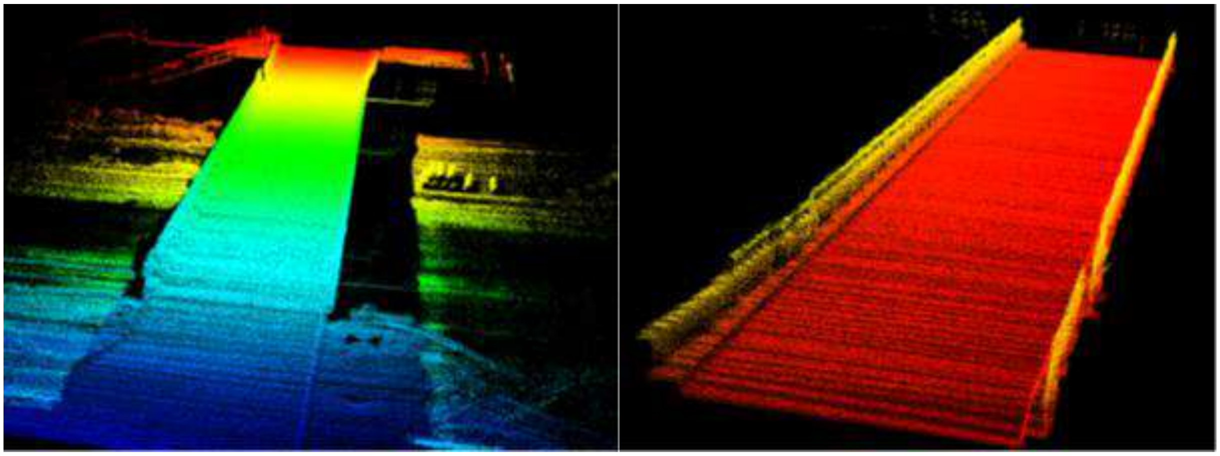


Figure 4.39 - 3D LiDAR point clouds of two beam bridges in Michigan (Brooks et al, 2015).

4.6 Reporting

Narrative inspection reports are a key component of the big bridge inspection. They provide the owner with both an overall condition of the bridge and detailed descriptions of deficiencies. In general, the narrative report should, at a minimum, identify the scope of the inspection, means of access to various locations on the bridge, the numbering convention referenced, a brief history including major rehabilitation efforts, identify any fracture critical members or fatigue sensitive details found, and provide descriptions of general and specific conditions of all components. Additionally, inventory information may also be provided that details key geometric properties, vertical and lateral clearances, and load capacities.

For a big bridge, organization of this information becomes a significant challenge. This organization usually follows the format of the bridge subdivision as presented in Section 4.3. The condition of each sub-unit is then described in detail grouped by the three major bridge components (substructure, superstructure and deck). Depending on the bridge configuration, these major components are further divided by specific elements. For example, there may be a south approach deck truss span section that has a superstructure section divided into sub-sections for trusses, floorbeams, stringers, bearings, etc.

The importance of location-specific information and tracking of defects over time cannot be understated. Because a large amount of information must be collected for each defect to efficiently and accurately analyze, it is recommended that tabulations of defects be recorded within either spreadsheets or databases. Depending on their intended use, different tables can be created or organized based on material type, component type, location, etc. The defect number can be used to store the date when the defect was first identified and changes over time can be indicated with bold text as in Table 4.3 below for Steel Stringers (Element 113):

Table 4.3 - Stringer Deficiencies (Element 113)

Item No.	Global Location			Deficient Component	Relative Component	Relative Location	Description	CS	Quant. (LF)	Defect(s)
	Span	PP (Start)	PP (End)							
0012-2014	13	4	5	Stringer S3	West web	6'-3" from south end	2'-6" long x 0'-8" high area of **1/8" pitting** with active corrosion in web (increased from 1/16" since 2014)	3	2.5	Corrosion (1000)
0013-2016	13	6	7	Stringer S5	Conn. to East Diaphragm	8'-7" from south end	One loose bolt in diaphragm connection angle	2	1	Connection (1020)

Note: text in **bold** has been modified since the previous inspection

Just as it was used as an important resource during the planning stage and throughout the inspection, the previous inspection report forms the basis for the next report. Typically, copies of the previous report files are modified to reflect the current condition of the structure and become the current inspection report. Often, formatting and text describing unchanged defects and conditions between reports is largely unaffected, often desired by bridge managers who wish to easily compare reports and determine where and how conditions have changed on the structure. Sometimes changes will be highlighted or noted in bold type to bring the changes to prominence.

4.6.1 Element Summary Reporting

Element level information is typically presented in the "Element Quantity and Condition State Summary" format which is shown in examples in the MBEI, one of which is shown in the following Table 4.4.

Table 4.4 - Resulting “Element Quantity and Condition State Summary” for the prestressed concrete girder bridge inspection example in the “Manual for Bridge Element Inspection” (AASHTO, 2015).

Element Number	Element Description	Unit of Measure	Total Quantity	CS 1	CS 2	CS 3	CS 4
12	Reinforced Concrete Deck	ft²	11,880	11,628	0	252	0
1080	*Delamination/Spall/Patched Area*	*ft²*	*252*	*0*	*0*	*252*	*0*
301	Pourable Joint Seal	ft	88	88	0	0	0
302	Compression Joint Seal	ft	132	92	0	0	0
2360	*Adjacent Deck or Header*	*ft*	*40*	*0*	*0*	*0*	*40*
330	Metal Bridge Railing	ft	540	540	0	0	0
515	Steel Protective Coating	ft²	1,726	1,726	0	0	0
331	Reinforced Concrete Bridge Railing	ft	540	540	0	0	0
109	Prestressed Concrete Girder/Beam	ft	2,144	2,144	0	0	0
310	Elastomeric Bearing	each	64	64	0	0	0
215	Reinforced Concrete Abutment	ft	88	88	0	0	0
205	Reinforced Concrete Column	each	9	8	0	1	0
1130	*Cracking (RC and Other)*	*each*	*1*	*0*	*0*	*1*	*0*
234	Reinforced Concrete Pier Cap	ft	132	114	0	18	0
1090	*Exposed Rebar*	*ft*	*12*	*0*	*0*	*12*	*0*
1120	*Efflorescence/Rust Staining*	*ft*	*6*	*0*	*0*	*6*	*0*

The level of detail in the MBEI element data to be presented is typically predetermined prior to the inspection, as was noted in Section 4.4.1. While preparing the element condition state summaries for each individual span or panel entails a significant effort, the practice affords opportunities for detailed analysis which may be considered indispensable in the case of big bridges. The enhanced analysis capabilities could identify areas of atypical deficiencies and accelerated deterioration rates which may warrant urgent maintenance. The intrinsic economic significance of inspection efforts for big bridges, due to higher costs for access and potential traffic disruptions, also supports retaining separated element quantity and condition state summaries for each panel or span. Numerous “Element Quantity and Condition State Summary” tables are required and are typically included as an appendix in the formal inspection report. Customized spreadsheets with formulas to automate many of the calculations and built-in error checks should be used to organize and present the information.

As mentioned in Section 4.4.2, all the element level data corresponds and could be obtained from comprehensive defect description and location notes which are typically presented in formal inspection reports. Therefore, inspectors may choose to compile element quantity and condition state summaries post-inspection, adding an additional step to the inspection and reporting process which can become tedious and time consuming for elements in stages of advanced deterioration.

Inclusion of Underwater Inspection Results

Inspection of submerged substructure elements is required every five years for all NBI bridges. Underwater inspection reports prepared by diving inspectors describe the general condition and specific deficiencies noted at submerged portions of elements. As underwater inspection reports do not entail an element level summary, it is the duty of those responsible for preparing the general condition report and element summary for the structure to view the latest underwater report and ascertain the condition of the submerged portions of substructure units. Scour is included as a defect category for all substructure elements and is typically only observable through underwater inspections. Defects in both the above and below water portions of the element must be incorporated into the quantities for the “Element Quantity and Condition State Summary.”

4.6.2 Future Inspection/Reporting Techniques

Improved inspection and management software could automate many aspects of the reporting process. Much of the formal inspection report consists of detailed defect descriptions which are typically presented in tabular form; capabilities to sort and generate tabular data instantaneously from a comprehensive inspection database could streamline the reporting process. Furthermore, direct delivery of the raw inspection data in the integrated inspection and management software could empower the bridge manager to view, sort, and analyze the information in tabular form or on 3D scale models of the structure or elements. Built-in functions facilitating analysis by bridge managers or the ability to export data for alternative or experimental analysis in customized spreadsheets could offer unparalleled flexibility and assistance in decision-making processes.

Automated Element Summaries

The creation of desired MBEI element quantity and condition state summaries for specific sub-units, spans, panels, or combinations thereof, could be automated with a database containing the detailed defect description and location notes. In fact, the use of such software could alleviate focus on the intricacies of the MBEI calculations in the NHI Safety Inspection of In-Service Bridges course as only awareness of the specific quantitative procedures may be warranted for inspectors. Instead, the NHI course could include more instruction and hands-on exercises to ensure inspectors are able to perform consistent qualitative evaluations by determining appropriate condition states for all materials and their respective defects, crucial to produce assessments for meaningful analysis.

In other words, the minutia involved in determining governing defects and calculating MBEI element defect quantities would no longer be required and inspectors could instead concentrate their efforts on accurately documenting the conditions, investigating areas of apparent distress or accelerated deterioration, and discovering hidden or latent defects. Theoretically, as the element data is intended to be strategic, exclusively supporting management processes for maintenance or repair prioritization such as life-cycle cost analysis, risk analysis, resource allocation and performance target setting, there could be limited to no involvement in the formulation of this data by inspectors. It is envisioned that future developments in 3D bridge inspection applications, combined with advancements in artificial intelligence could greatly aid automation efforts; reducing reporting and analysis times. The use of such software would likely be first applied to the vast number of smaller, less complex bridges in the NBI and eventually be applied to Big Bridges. With enough sophistication, this software could potentially perform structural analysis in the field as soon as data is entered, allowing inspectors to make more informed decisions about the significance of findings immediately.

Importance of Narrative Reporting

Although bridge inspection and management software could automate much of the straightforward and tangible defect description information that comprises a significant portion of formal inspection reports for big bridges, narratives within the report will always be necessary to describe unique and complicated defects not represented in element summaries and to describe general conditions of the structure in a format which is easily digestible by the bridge management staff. In the case of big bridges, such issues may include complicated interactions at complex details or between separate sub-units which may otherwise be omitted in the element level analysis but that require mitigation action or further attention.

4.7 Chapter Conclusions and Summary of Guidelines

Element level inspections, as guided by the MBEI, have introduced a high level of consistency in inspection by standardizing bridge condition assessment. The resulting element data provides owners with quantitative results which can be used to prioritize improvement and conservation efforts to maintain our deteriorated bridges. Unfortunately, prevalent bridge inspection and reporting practices are tedious, often requiring intensive manipulation of disparate inspection notes and measurements stored in various media in an effort to produce an organized, comprehensive inspection report. In the case of big bridges, this problem is compounded due to the complex and greater amounts of elements involved. Currently, minimal efforts are typically being exerted in the production and use of data for analysis by a majority of big bridge management agencies, sentiments revealed by the targeted surveys and interviews that were administered as part of this study. Several big bridge inspection reports were reviewed as part of Task 2; in many cases, only the “Element Quantity and Condition State Summary” was completed for the entire structure to comply with federal requirements for NHS bridges. While such summaries are valuable in prioritization for multitudes of small and simple bridges, applications for complex big bridges are limited without much consideration and enactment of customized approaches which may involve significantly more complicated element data retention by span or panel to permit detailed analysis.

The following list summarizes the guidelines and suggestions which have been presented:

- Divide big bridges into sub-units at transitions between differing structure types to promote more manageable analysis and projects of smaller scope. Ensure elements such as substructure units located at boundaries which support two sub-units are attributed to one sub-unit to ease preparation of the element condition summary by inspectors, considering all present defects.
- Create ADEs for additional complex bridge elements and other typical elements not defined in the MBEI as outlined in Sections 4.2.2 and 4.2.3 to more accurately monitor condition of these elements and enable analysis.
- Revise MBEI element articles as outlined in Section 4.2.4 to more accurately define and quantify existing elements for consistent results.
- Create additional element defects as outlined in Section 4.2.5 to include common element deficiencies which are absent in the MBEI articles.

- Present “Element Quantity and Condition State Summaries” by span or panel to reveal deterioration at specific areas of the structure.
- Record all detailed defect description and location information in tabular form for load rating and enhanced analysis capabilities.
- Ensure inspectors’ understanding of quantification methods for consistent element level analysis and preparation of “Element Quantity and Condition State Summaries” for unique or complex elements.
- Consider investing in mobile tablets and applicable inspection software which can be used offline or in conjunction with WiFi hotspots to enable internet access and use of collaborative applications by inspection teams, reducing inspection and condition reporting costs.
- Consider adoption of defect database and 3D inspection software when available to automate and streamline inspection, reporting, management, and analysis processes.
- Consider investing in multirotor Unmanned Aerial Vehicles (UAVs) with high-resolution cameras or 3D photogrammetry capabilities to allow prompt, close-up inspection of elements which are difficult to access, promoting safety of inspections and minimizing traffic disruptions.
- Consider the use of UAVs with attached optical and thermal sensors for analysis of concrete bridge decks which can reveal areas of unsound and delaminated concrete more efficiently and safely than traditional inspection methods.
- Consider the use of thermography for advanced inspection of concrete superstructure or substructure elements to reveal areas of unsound and delaminated concrete.
- Consider the use of thermography for inspection of steel elements obscured by protective coatings such as main cables and other steel superstructure or substructure members to detect hidden areas of corrosion or distress.
- Consider the use of Light Detection and Ranging (LiDAR) to accurately monitor deflections in bridge elements or quickly obtain detailed measurements of a structure for use in advanced studies, load ratings, or inventory.
- Consider utilizing At-speed Ground-Penetrating Radar (GPR) for swift and repeatable concrete bridge deck assessments which can reveal areas of unsound and delaminated concrete.

Implementation of 3D inspection and management software with a centralized defect database that can consolidate and automate many of the inspection and reporting processes could represent a turning point to those agencies considering adoption of such tools, replacing traditional paper and pencil practices. Future bridge management software is expected to optimize inspection, reporting, load rating, and analysis for prioritization and management of big bridges. Such software has the potential to revitalize these processes for bridges of all sizes at a cost which will be significantly outweighed by that required to employ conventional, labor-intensive methods.

An additional advantage may be to empower inspectors, who might feel hindered by current practices, by providing them access to state-of-the-art inspection methods, easing and improving the evaluation process, thus promoting vigilant inspection and resulting in more accurate inspection data for meaningful analysis. Chances that latent defects are found, recorded, and addressed before propagation or critical stages are reached, which could result in structural failures or costly repairs, also increase. Continued support to the software by the developers ensure that it is updated to reflect the bridge inspection standards and practices of the future, although establishing dependencies which may instill hesitation in potential users.

The goal of Task 6, to be presented in the following Chapter 5, was to elaborate on the relevant existing and emerging analytical tools and processes for analysis and management of big bridges. Such tools could provide significant advantages to bridge managers by providing the means for analysis to prioritize judicious and economical fund appropriations, principally important for those acting as stewards of the public interest. Management software with enhanced prioritization and robust risk analysis capabilities could potentially avoid future bridge emergencies which have historically become the impetuses for continued development and refinement of the bridge inspection standards we have today.

Figure 4.40 - Sault Ste. Marie International Bridge.

CHAPTER 5 - RECOMMEND ANALYTICAL TOOLS AND PROCESSES FOR BIG BRIDGE MANAGEMENT

5.1 Introduction

Transportation asset management is a strategic and systematic process that uses data and analysis to support infrastructure investment decisions that maximize transportation system performance, minimize costs, and manage risks. It adopts a stakeholder perspective on performance, where the ultimate stakeholder is the public. From the public perspective, optimal performance can be framed as the ability to travel from origin to destination safely, quickly, reliably, and sustainably, with minimal cost. These expectations tend not to change appreciably with the type, size, or ownership of infrastructure assets the traveler may encounter between origin and destination. However, because big bridges are so frequently traveled as key links in the transportation network, they are often subject to greater public expectations.

Some big bridge owners are state Departments of Transportation, which own large portions of the network; other owners are smaller agencies, some funded entirely by tolls, which might own just one big bridge and its approaches. Some are municipal governments or private entities. The institutional structure does not change stakeholder expectations, but only changes the means by which these expectations are met.

This chapter adopts the larger context of asset management, showing how big bridges fit within that context, and highlighting unique requirements and tools that can be especially useful for managers of big bridges to support the achievement of transportation network performance objectives. For agencies that are new to asset management, the chapter will also introduce the most relevant concepts, addressing the following questions:

- What goals and objectives drive the need for management analysis for Big Bridges as a part of the larger infrastructure network?
- What business processes contribute to the achievement of those goals?
- What information is needed in order to inform these processes?
- What data and analysis techniques can provide this information?

Throughout the discussion, an emphasis will be placed on describing the many ways that big bridge management may differ from smaller bridges. However, the document is meant to stand on its own and serve the needs of a diverse set of agencies, so each agency will want to evaluate the material in the context of its own management needs in deciding which parts to implement.

5.1.1 Asset Management Goals and Objectives

Quantifying transportation system performance is a matter of developing a clear description of what customers and stakeholders want and value. Fortunately, a great many big bridge owners already have this. These strategic values are stated in guiding documents such as MAP-21, the Moving Ahead for Progress in the 21st Century Act (P.L. 112-141), which was signed into law on July 6, 2012. This legislation sets national goals in 23 USC 150(b) as:

(1) SAFETY.—To achieve a significant reduction in traffic fatalities and serious injuries on all public roads.

(2) INFRASTRUCTURE CONDITION.—To maintain the highway infrastructure asset system in a state of good repair.

(3) CONGESTION REDUCTION.—To achieve a significant reduction in congestion on the National Highway System.

(4) SYSTEM RELIABILITY.—To improve the efficiency of the surface transportation system.

(5) FREIGHT MOVEMENT AND ECONOMIC VITALITY.—To improve the national freight network, strengthen the ability of rural communities to access national and international trade markets, and support regional economic development.

(6) ENVIRONMENTAL SUSTAINABILITY.—To enhance the performance of the transportation system while protecting and enhancing the natural environment.

(7) REDUCED PROJECT DELIVERY DELAYS.—To reduce project costs, promote jobs and the economy, and expedite the movement of people and goods by accelerating project completion through eliminating delays in the project development and delivery process, including reducing regulatory burdens and improving agencies' work practices.

Individual agencies often list their goals in legislation or strategic plans. For one example among many reviewed, the Revised Code of Washington (State) lists the following policy goals for public investments in the state's transportation system (RCW 47.04.280):

(a) Economic vitality: To promote and develop transportation systems that stimulate, support, and enhance the movement of people and goods to ensure a prosperous economy;

(b) Preservation: To maintain, preserve, and extend the life and utility of prior investments in transportation systems and services;

(c) Safety: To provide for and improve the safety and security of transportation customers and the transportation system;

(d) Mobility: To improve the predictable movement of goods and people throughout Washington state, including congestion relief and improved freight mobility;

(e) Environment: To enhance Washington's quality of life through transportation investments that promote energy conservation, enhance healthy communities, and protect the environment; and

(f) Stewardship: To continuously improve the quality, effectiveness, and efficiency of the transportation system.

These listings of goals do not distinguish bridges separately from other asset classes, nor big bridges separately from other structures. Significant commonality exists in goals across agencies:

- All of them list safety and/or security as a goal.
- Most call for preservation of the existing transportation system or make other references to asset condition, and often call for minimization of the long-term costs.
- Most list various aspects of mobility, including accessibility, travel time, congestion reduction, and reliability. Some of the documents emphasize both passenger and freight movement, general economic vitality, and intermodal connectivity.
- Most of these documents call for environmental sustainability.
- Many strategic documents reference statewide and metropolitan transportation plans.

All of these national and state goals are commonly found in toll authority business plans as well. Additionally, toll authority business plans typically include goals of revenue maximization (and/or cost minimization) and customer satisfaction. When customer satisfaction is listed as an agency goal, it is sometimes used as a catch-all category for all aspects of performance affecting road users, including safety and mobility. Other times, it refers to services distinct from safety and mobility of general traffic. The Mackinac Bridge Authority, for example, lists the following customer services in its business plan:

- Escorting over width trucks
- Escorting heavy trucks
- Escorting trucks hauling hazardous materials
- Escorting wind susceptible vehicles during strong winds
- Providing drivers to motorists who wish not to drive themselves
- Transporting passengers
- Transporting bicycles
- Transporting snowmobiles
- Providing support to community sponsored events at the Mackinac Bridge Authority (i.e. bicycle, jogging, car parades, and truck parades)
- Coordinating special events and functions (i.e. Annual Bridge Walk)
- Patrolling the bridge and properties
- Weighing trucks
- Assisting stranded motorists
- Assisting law enforcement agencies
- Providing bridge information to motorists and other interested parties

These services are most relevant to big bridges and are less common on other parts of the transportation network. They suggest that certain big bridges owners may have goals associated with revenue maximization and customer service in addition to the national and state goals common in state transportation agencies. Another perspective might be that the customer service aspects are a matter of safety and mobility, and the revenue objectives are a part of economic sustainability.

5.1.2 Statewide and Metropolitan Plans

Statewide and metropolitan transportation plans often place a spotlight on localized or subarea problems that might not be fully reflected in the general agency goals, such as community aspirations, growth management, economic development initiatives, equity issues, operational strategies, intermodal coordination, inter-agency cooperation, and fulfillment of earlier commitments. These are more complex to evaluate in a resource allocation or priority setting analysis because by definition they do not treat every part of the network in a uniform way.

Many agencies explicitly omit capacity as a performance criterion in transportation asset management (TAM), but this is not universal. TAM practices in other countries often include the analysis of demand and its potential effect on congestion (Gordon et al. 2011). The federal rules for system performance, freight movement, and congestion in 23 CFR 490 strongly suggest a role for capacity and demand management alternatives as a part of TAM decision making.

A related issue is the high level of interest recently shown for strategies that substitute technology for capacity, or that use technology to manage demand. A few agencies, such as Nevada, have already deployed enough Intelligent Transportation System assets to justify their inclusion within the TAM Plan. The performance characteristics of these systems are clearly very different from traditional highway facilities, and are not always well understood. Big bridges are increasingly instrumented with significant investments in electronic traffic management equipment, often intended to maximize the utilization of available capacity.

5.1.3 Transportation Asset Management Plans and Business Plans

"The term 'asset management' means a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life-cycle of the assets at minimum practicable cost.'' (23 USC 101(a)(2))

MAP-21 calls on state Departments of Transportation to prepare risk-based Transportation Asset Management Plans for the National Highway System (NHS) to "*improve or preserve the condition of the assets and the performance of the system*". The legislation mandates the establishment of condition and performance targets for at least pavements and bridges, and requires the TAM Plan "*to include strategies leading to a program of projects that* *would make progress toward achievement of the targets.*" Although only NHS pavements and bridges are mandatory in the TAM Plans, states are encouraged "*to include all infrastructure assets within the right-of-way corridor in such plan*." (23 USC 119(e))

Federal rules in 23 CFR Section 515.9 specify that the TAM Plan shall cover at least a 10-year period, shall be made easily accessible to the public, and shall establish a set of investment strategies that improve or preserve condition and performance in support of the national goals in 23 USC 150(b).

The regulation explicitly links the TAM Plan to the Statewide Transportation Improvement Program (STIP), which is the primary vehicle for programming of transportation projects. Section 515.9(h) indicates "A State DOT shall integrate its asset management plan into its transportation planning processes that lead to the STIP, to support its efforts to achieve the goals" of the TAM Plan. Section 515.9(d) lists the minimum content of the TAM Plan:

1. TAM objectives, aligned with agency mission;
2. Performance measures and targets;
3. Summary of asset inventory and condition;
4. Performance gap identification;
5. Life-cycle planning;
6. Risk management analysis;
7. Financial plan;
8. Investment strategies."

Many state DOTs use pavement and bridge management systems to develop much of the preservation component of the STIP. If the TAM Plan is to drive major parts of the STIP, then it must also feed back into the management systems to ensure a consistent linkage.

Almost all big bridges in the USA are on the National Highway System and are therefore required to be included within the TAM Plan and within state performance targets, according to the federal rules. In the Task 4 interviews (Chapter 3) it was determined that most rehabilitation and replacement work on big bridges is included in STIPs, with the exception of a few toll agencies that do not receive federal funds.

Many big bridges are owned and/or operated by independent or semi-independent authorities, many of which are wholly or partly toll-funded. Many of these agencies have published business plans, which contain many of the same ingredients required in TAM Plans. In the business plans that were reviewed in the present study, the following ingredients were typically found:

- Description and history of the agency and/or facilities
- Description of the organizational structure and governance
- Statements of mission, vision, and values
- Listing of strategic goals, often with listings of strategies or management initiatives related to each goal. Some of the business plans also include performance measures relating to each goal.
- Competitive analysis and business partnerships
- Historical traffic, revenue, and toll rates
- Historical capital and operating expenditures
- History and status of debt financing
- Forecast of revenue over 5 to 30 years in the future
- Forecast of operating expenses over a time period ranging from 5 to 30 years
- Program of projects for capital expenditures, including preservation and service improvement, over a period ranging from 5 years to 40 years. Some of the business plans include capsule descriptions of each project, from 1/3 page to a full page for each project.
- Vehicle and equipment replacement schedule

TAM Plans and business plans commonly contain forward-looking statements that are developed using analytical processes. Capital investments, operational budgets, and many other management decisions rely on these forecasts. Governing bodies often impose constraints on agency decisions, such as resource allocations, toll caps, debt service obligations, and operational regulations, relying on the accuracy of the forecasts. Revenues, subsidies, traffic flows, physical conditions, safety, travel time, delays, and other performance concerns can be the subjects of these forecasts. The ability to produce forecasts of sufficient quality is increasingly regarded as a professional discipline not unlike the professional expectations of bridge designers to accurately forecast the performance and longevity of their designs.

5.1.4 Business Processes

Information from a variety of sources, including forecasts, feeds into multiple business processes within a transportation agency. Rarely are these processes specific to big bridges, but most of them are affected in distinctive ways by the size of big bridge projects. The recommended framework starts with the basic objectives and management concerns common to practically all highway agencies, using these as the foundation for a common set of methodologies to support decision making in all of the fundamental business processes of TAM (Figure 5.1). The framework is developed from two perspectives:

Strategic (top of Figure 5.1):

- Statements of performance objectives, such as those listed in 23 USC 150(b) and further developed in 23 CFR 490, define the scope of a fully-implemented asset management process. These include goal areas such as condition, safety, mobility, and environmental sustainability.
- Statewide and metropolitan service plans establish development patterns, corridor emphases, and service priorities covering the same time frame as TAM Plans.

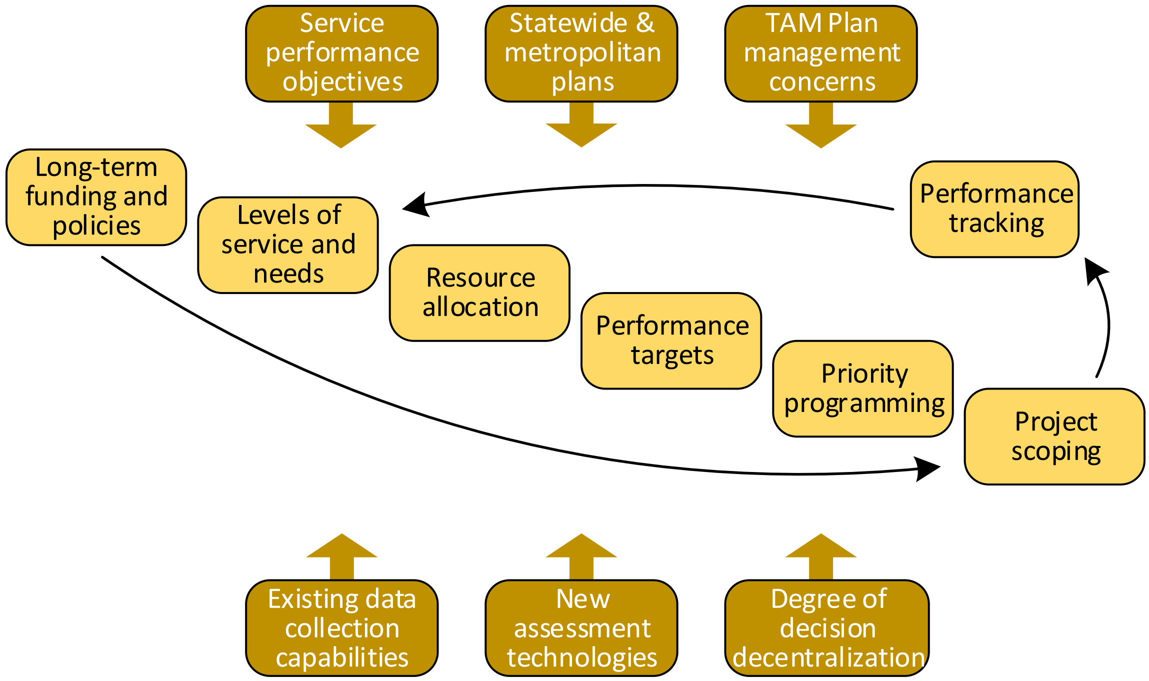


Figure 5.1 - Business processes addressed in the framework of Big Bridge management.

- Essential ingredients of a TAM Plan describe strategic management concerns common to all asset classes, including long-term cost minimization, risk management, and fiscally-constrained investment planning.

Tactical (bottom of Figure 5.1):

- Transportation agencies have a wide variety of existing data collection capabilities to monitor the condition and performance of their assets and of the collective network. This includes the entire bridge inspection process, although the emphasis here is on elements and defects.
- Considering the next 10-20 years, technological innovation in data collection will likely improve the range of typical agency data collection capabilities, improving agency knowledge of bridge performance. It is likely that big bridges will be the first to benefit.
- Agencies vary in the level of centralization or decentralization of asset management decision making. Most agencies assign aspects of big bridge planning discretion at a localized level where decision makers are most familiar with the facility. However, larger agencies, especially state DOTs, may make critical decisions at a distant level,

where a high bandwidth of high-quality communication is essential for coordinated planning.

The strategic and tactical perspectives have to be reconciled in order to establish a fully implementable framework (center of Figure 5.1). How this is done can vary among agencies, but typically incorporates a set of business processes such as:

- Negotiation of long-term funding mechanisms, and development of strategic directions, policies, and standard operating procedures;
- Development of level-of-service standards and corresponding needs;
- Allocation of anticipated resources, including funding and staffing;
- Establishment of performance targets, constrained by fiscal scenarios;
- Priority programming and the STIP process;
- Conceptual planning of projects; and
- Reporting and tracking of network performance, which provides metrics and expectations to drive future cycles of these processes.

Only raw condition data collection and some aspects of project planning are necessarily and consistently specific to bridges; the strategic constraints and business processes are often or completely asset-generic. Performance tracking and target-setting are for the bridge inventory in general under the proposed federal rules for condition, but can be generic in state practice (e.g., condition indexes) and for performance concerns other than condition (e.g., safety, mobility). Priority programming using benefit/cost analysis can be generic, even though many agencies retain the legacy practice of programming within asset-class silos. The selection of appropriate treatments is often specific to bridges or to an individual bridge, but agencies often create corridor-level projects that include all of the asset classes along a corridor, which may be prioritized together. An essential feature of bridge management is that much of it is done within a wider context.

5.1.5 Bridge Management Systems

While the preceding sections describe the qualitative structure and motivations for big bridge decision making, Figure 5.1 shows a set of business processes that are essentially quantitative; they rely on data and analysis. Most state transportation agencies use bridge management systems to support the implementation of their TAM Plans, including big bridges. These systems ideally have at least the following functions:

- Store, manage, and report on an inventory of assets. The data in this inventory typically include description, classification, location, jurisdiction, geometry, and historic data.
- Store, manage, and report on current and past condition; based on the inspection process. The management systems also typically include functionality for scheduling and managing the updating process for inventory and condition.
- Identify capital and maintenance needs on a given asset based on a set of standards or warrants, and based on current conditions and performance.
- Estimate costs and effectiveness of proposed work. Effectiveness is expressed at least in terms of condition, but may address other performance concerns as well.
- Predict conditions and future demand; using this information to project needs and their cost and effectiveness. One result is an estimate of long-term cost.
- Analyze the risk of service disruption caused by asset characteristics and hazards.
- Generate multiple scoping and timing alternatives for the identified needs. Apply a set of business rules which constrain the range of alternatives to be considered.
- Compute a priority indicator which may address one or more aspects of performance. Report and manipulate a priority list of needed work in a given year.
- Apply budget constraints, identify the set of investments which maximize desired outcomes in a given year when the constraint is applied, and forecast future network level outcomes for condition and performance based on the selected investments.
- Assist in the development of fiscally-constrained performance targets.
- Support the allocation of resources among parts of the inventory; forecasting likely scope and timing of projects, and forecasting of future performance as affected by the resource allocation.
- Support development of preservation and risk management strategies.
- Support negotiation of funding levels and development of new funding sources.
- Assist in organizing capital and maintenance needs into projects, tracking the status of projects, and maintaining a history of completed work.

All big bridges need these functions, although in certain contexts the issues of prioritization and resource allocation might be among components within one structure instead of (or in addition to) prioritization among assets.

Not all management systems have all these functions, although AASHTOWare Bridge Management attempts to address most of them. Even when the capabilities exist, not all agencies use them all, and some are better suited to bridges of ordinary size and less suited to big bridges. A barrier to implementation of the decision support capabilities is the siloed approach where, for example, bridge needs cannot be prioritized in the same list as pavement needs. Bridge management systems encapsulate scientific aspects of data collection, deterioration, risk, and cost modeling that are truly specific to bridges, as well as more generic capabilities, such as priority setting and resource allocation applying to all types of assets.

BMS planning support features provide a robust set of functionality to make use of the data, but many agencies find that the approach to programming and resource allocation does not fit their business needs, either because the methods don't fit non-bridge assets, or because specific big bridges are very different from other assets. Therefore, it may be necessary to develop separate analytical tools oriented toward particular decision makers and processes to accommodate big bridge issues. This is discussed at various points later in this chapter.

5.1.6 Multi-Objective Analysis

NCHRP 590 (Patidar et al. 2007) developed a framework and example tool for multi-objective optimization for bridge management, subsequently implemented within AASHTOWare Bridge Management. This framework treated risk as one type of performance. Subsequent work in developing tools based on Report 590 have treated risk as more all-encompassing, as potentially affecting all other aspects of performance including condition, long-term cost, safety, mobility, even environmental sustainability. In fact, recent risk models quantify the performance impacts of natural and man-made hazards in a manner similar to bridge functional deficiencies, as a statistical expected value of excess user costs (Thompson et al. 2017).

With their typically high traffic volumes and long detour lengths, Big Bridges have disproportionate influence on all of the objectives of the transportation network. Moreover, deteriorated element condition, which affects the risk of service disruption on any bridge, has much greater consequences on Big Bridges. This fact increases the motivation for knowing the locations of defects within a bridge, and having the ability, eventually, to model risk as a function of defects. The ability for bridge condition data to support risk management is one motivation for considering location-aware condition data, a theme that will be expanded upon throughout this chapter. As an example where this has already been put into practice, AASHTO's bridge load rating software has functionality to specify the location of section loss or cracking defects and to use this in order to refine the determination of the bridge rating factor, which is directly related to the likelihood of service disruption.

5.2 Use Case Analysis

Gaining a “big picture” view of bridge management analytical requirements can be difficult because, in most agencies, no one person is involved in all facets of it. Nonetheless, the database and analytical process behind effective bridge management needs to link the various parts together through a set of consistent assumptions and methods, so all participants are working, as much as possible, from the same data and assumptions. If this can be accomplished, and if decision makers can agree on goals and objectives, then it becomes more likely that asset management decisions at all levels of the agency will be consistent and have the desired outcomes.

Achieving this goal of an internally-consistent bridge management process starts with a complete survey of all the routine business processes and decisions that bridge management is intended to facilitate. The following sections address each process in a roughly top-down order. Some of the processes may seem much alike and in fact might be executed by the same unit or the same person. Even in those cases they often are not executed at the same time, so the facts on the ground and the desires of stakeholders can change. To be credible, the bridge management system and process should react to such changes in a predictable way.

Although most transportation agencies have these use cases, significant differences exist among agencies based on their revenue sources, governance, size, centralization, and other variables. The following discussion attempts to cover these cases as much as possible. Examples of reports potentially relevant to big bridges are shown, emphasizing graphics. Most of these are drawn from existing best practice, but in a few cases some new report formats are suggested in mock-up form in order to better accommodate big bridge needs. The means of computing these reports is discussed later in the document.

5.2.1 Determination of Funding and Policy (Network Level)

As the US vehicle fleet becomes more fuel-efficient, every state is experiencing a decline in fuel tax revenue yield in relation to traffic demand. Even in agencies that do not rely on fuel tax, as is the case for certain big bridge owners, costs increase and the buying power of tolls declines over time. For these reasons, it periodically becomes necessary to make adjustments in revenue sources. Because preservation is a significant ongoing expenditure, it is valuable to know what conditions can be purchased for various alternative investment levels.

Agencies that have been successful in negotiating higher fuel taxes or other revenue enhancements have determined that the ability to quantify the revenue vs. performance tradeoff is very helpful. Figure 5.2, for example, shows a graphic used by Utah DOT in its recent successful negotiations. This type of information can also be expressed using the federal performance indicators, percent of deck area on bridges in Good condition or Poor condition. An example is given later in this Chapter. For agencies having a small number of big bridges, however, the use of the bridge health index as in Figure 5.2 provides finer resolution and a more direct linkage to element level condition data (Shepard and Johnson 2001).

Similar to funding decisions, agency policy decisions can have a system-wide impact on achievable levels of condition or performance. For example, alternative approaches to paint system selection and maintenance, and lead paint containment and abatement, can have different effects on long-term costs. On toll bridges, if any preservation work zones or activity affect traffic flow, then revenue may be affected as well. This is also a case where bridge element data on paint systems and paint condition influence the ability to compare alternative policies and find the one with the best long-term outcome for the agency and stakeholders.

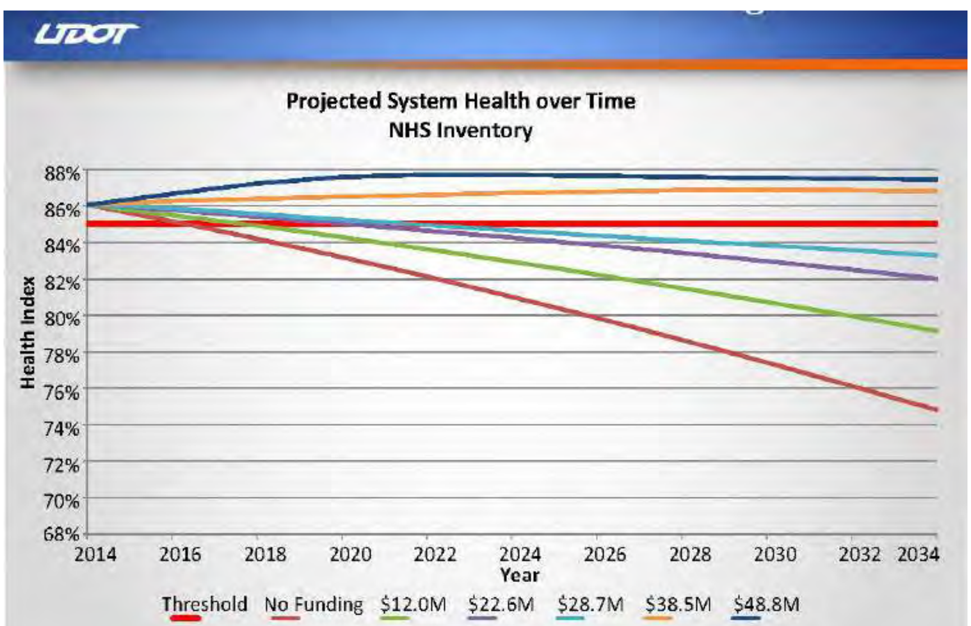


Figure 5.2 - Tradeoff of preservation expenditure vs performance in terms of bridge health index (Utah DOT).

5.2.2 Need Criteria or Warrants (Network and Project Level)

Transportation agencies typically maintain a set of thresholds, often known as minimum tolerable conditions or level of service standards, which determine whether the performance of an individual facility is acceptable or unacceptable. If unacceptable, the implication would be that the agency would plan work to remedy the deficiency. These thresholds can be defined in terms of any measurable aspect of performance, such as condition, traffic flow, or emissions.

Thresholds are defined at the network level to represent desired system-wide minimum levels of performance. They are applied, however, at the facility level to evaluate each asset individually. In large agencies, the networks are divided into functional classes with different sets of thresholds. Big bridges, because of their cost and utilization, tend to be subject to the most demanding standards.

When an asset fails to satisfy its thresholds, the work necessary to correct the deficiency is considered to be a "need," which may be developed into (or as part of) a candidate project with costs and benefits. Typically the total cost of all needs across an inventory is much more than the resource capacity of the agency to correct the problems. Hence, it becomes necessary to allocate resources and set priorities as discussed in later sections of this Chapter.

With element-level data the concept of "threshold" can be broadened to something more akin to need criteria or warrants. For example:

- The existence of certain elements in certain situations may trigger a need, as was the case when Washington State DOT identified single-column bents in specified configurations to develop an estimate of seismic retrofit needs.
- Under the 2013 AASHTO Element Inspection Manual, certain defects (e.g., scour, cracking, or deck spalling) in condition states 3 and 4 may trigger risk mitigation actions because of the potential for disruption to the desired level of safety or mobility of bridge users or surroundings.
- Many elements in condition state 4 by definition trigger a need for structural review, which may in turn trigger a need for remedial action. (2013 AASHTO Element Inspection Manual)
- Elements having cost-effective preservation treatments may trigger preservation needs in condition states other than state 4. When an agency states a management preference against "worst-first" decision making, this is often what they mean.

Increasingly, big bridge owners carefully manage bridge elements to ensure that state 4 either does not occur or at least does not create a structural problem. This is done by giving priority to the other condition states where preservation is especially cost-effective.

Table 5.1 shows an example of a big bridge element inspection summary, with application of treatment criteria. The information in the table may be sufficient to estimate the type and direct cost of needed work. More information, especially the location of the defects, may be necessary for a structural review and to estimate the work zone traffic planning requirements and associated indirect costs. This matter is addressed in more detail later in this Chapter.

Table 5.1 - Example Concrete Column Element Inspection Showing Implied Preservation Needs

Condition state	Quantity (each)	Need (cost-effective treatment)
1. Good	155	None
2. Fair	66	Clean exposed rebar, patch spalls
3. Poor	12	Clean exposed rebar, patch spalls, seal cracks
4. Severe	2	Clean exposed rebar, patch spalls, seal cracks. Perform structural review and consider wraps or other mitigation if needed

On big bridges it may be especially appropriate to develop action criteria for each bridge individually since life-cycle costs and structural considerations can differ significantly among bridges and even within a bridge. Agencies may differ in their inspector qualifications and expectations to make treatment recommendations. Such differences may affect the level of detail of agency documents prescribing need criteria and warrants: an agency with less rigorous inspector certification requirements might invest more in the creation of a detailed preservation manual with treatment criteria.

5.2.3 Resource Allocation (Network Level)

All bridge owners have limitations on available resources, and attempt to allocate resources in a way that optimizes the achievement of agency objectives. All of the objectives in strategic plans or enabling legislation are potentially at stake, including safety, mobility, environmental sustainability, and long-term cost.

Many of the agency strategies of interest to bridge management have indirect or long-term effects on these objectives: for example, actions to improve condition may affect costs by postponing the future time when reconstruction might become necessary; actions to increase safety or increase resilience to adverse events may reduce the likelihood or consequences of future hazards. The use of forecasting models is therefore an essential part of the quantitative evaluation of possible long-term outcomes of near-term actions.

The key concept in resource allocation is tradeoff analysis, a matter of deciding the relative priorities among multiple objectives, and attempting to maximize the total value that can be achieved under realistic fiscal scenarios. For example:

- Allocation of resources to preservation work today may delay the need for much more expensive reconstruction later. On big bridges, the investment in coatings, wearing surfaces, and joint seals are of special concern, because of both their cost and their long-term effectiveness. The management question is how much money to allocate to each activity.
- Investments in safety equipment may help to reduce the frequency and/or severity of vehicular accidents. While these investments are valuable they reduce the money available for other valuable investments, such as driver information for congestion reduction. This illustrates a tradeoff among competing objectives.

Figure 5.3 shows the fiscal tradeoff familiar to most bridge owners, that more frequent preservation leads to better conditions, and thus a longer time until reconstruction might be required. However, more frequent preservation also leads to higher preservation costs. For this reason, there is an optimal level of preservation investment, the “happy medium” where the total of near-term and long-term costs is minimized. An ability to quantify these curves is very useful for management purposes and is one of the main objectives of having a bridge management system with network-level analysis capability.

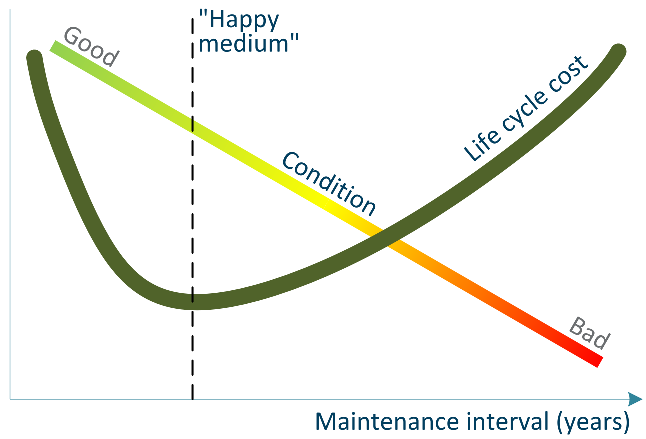


Figure 5.3. - Tradeoff of preservation frequency vs condition and long-term cost.

Later section of this Chapter discuss methods for measuring these tradeoffs. Because of the granularity of projects and significance of indirect project costs, it is common practice to combine resource allocation with priority setting, using the mechanism of prioritization to find the mix of projects that achieves the best combination of program objectives under likely fiscal scenarios.

5.2.4 Performance Targets (Network Level)

A significant new requirement faced by bridge owners after MAP-21 is the need to establish bridge condition targets, as the percent of network deck area on bridges in in Good or Poor condition. Targets are required for timeframes of 2 years, 4 years, and 10 years under different parts of the federal rules. All of these targets are meant to be fiscally-constrained, to reflect realistic revenue scenarios. The ten-year targets must also consider the changes in condition that occur because of deterioration. The required targets are statewide conditions and include all bridges on the National Highway System regardless of ownership. They are also considered best practice even for agencies that otherwise might not be concerned with the federal transportation asset management requirements.

For an inventory of bridges, condition targets have two significant management purposes:

- If derived from an optimization process such as what is suggested in Figure 5.3 above, they represent the ideal condition of the inventory where long-term costs are minimized;

- If derived from an analysis of deterioration and treatment effectiveness, even if not optimized, they describe realistic expectations for condition and a rationale for preservation investment.

Figure 5.4 shows an example, from Montana's Geotechnical Asset Management Plan, where the percent Good, percent Poor, and condition index (similar to bridge health index) after 10 years are affected by the level of preservation investment. In this analysis the cost to maintain the current level of condition index (labeled "desired") on the state's unstable rock slopes is at the high end of the fiscal scenarios it considered realistic; most of the scenarios produced declining conditions.

Big bridges raise some unique issues associated with condition targets. Their large deck areas imply big shifts in network performance if even one of these bridges makes a transition from Good to Fair or Fair to Poor. Given the penalties for failure to meet targets, the effect of individual big bridges may create an undesirable and unintended set of incentives on project level decision making for agencies responsible for numerous bridges and especially those managing both small and big bridges.

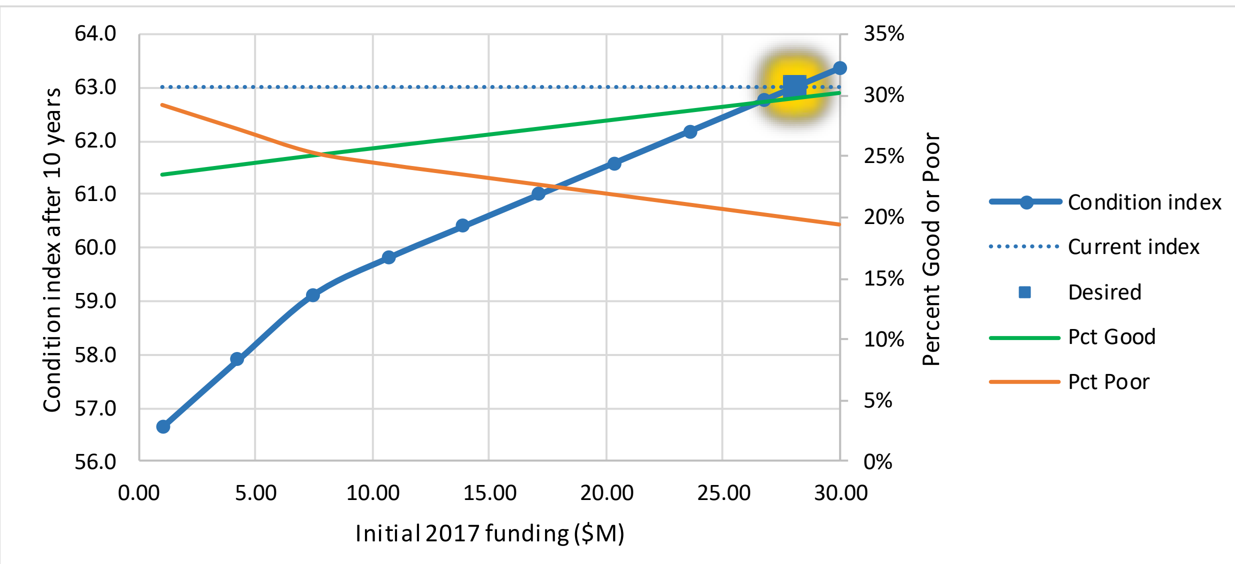


Figure 5.4 - Condition vs. investment level.

For internal management purposes, element-level data are more useful than Good-Fair-Poor for decision making, but may be too detailed for communication with non-technical audiences. Many agencies use the health index as an intermediate level of detail suitable for communication of trends, forecasts, and targets (Shepard and Johnson 2001). The health index is a weighted average of bridge element conditions, considering all of the possible condition states of each element. Figure 5.5 shows an example of a hypothetical condition trend on a big bridge. The graph communicates that conditions have improved due to agency preservation work, but more improvement is needed (and planned) in order to reach the target condition level for the structure.

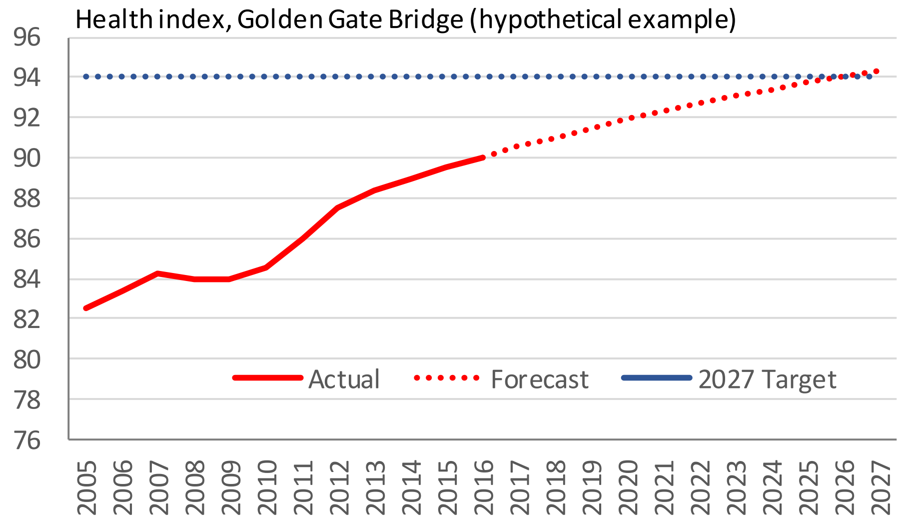


Figure 5.5 - Condition trend, forecast, and target using health index.

In contrast to Figure 5.5, Figure 5.6 shows the same bridge using NBI condition ratings. That graph shows that the bridge reached its target already in 2011, suggesting to a lay audience that no additional work is necessary. While it may be perfectly accurate, it fails to communicate the agency's preservation strategy.

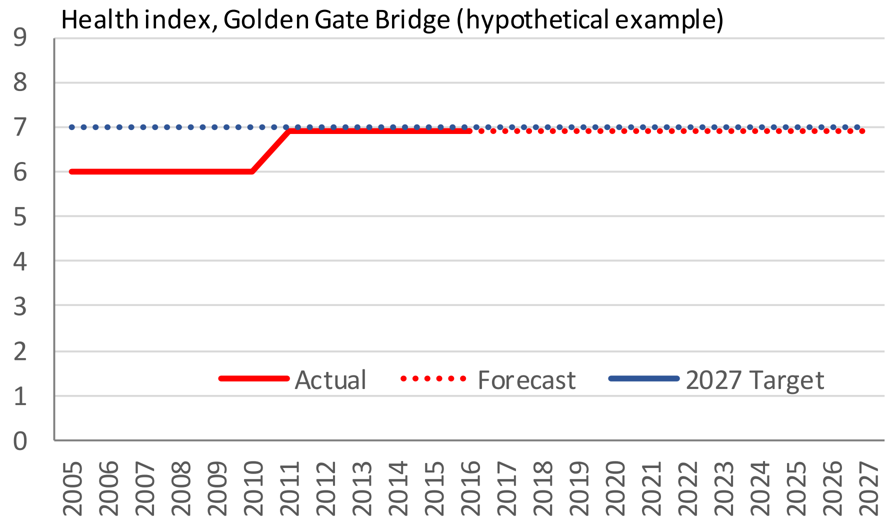


Figure 5.6 - Condition trend, forecast, and target using NBI rating.

Appendix E shows the procedure for computing the bridge health index as implemented in AASHTOWare Bridge Management and similar systems.

5.2.5 Forecasts of Future Performance

What many of the decision support use-cases have in common is their reliance on forecasts of future performance. There are different types of forecasts for different purposes:

- Long-term condition forecasts, over periods as long as 200 years, are used in evaluating the generic ability of preservation work to delay more expensive reconstruction on various element types or classes of structures.
- Near-term condition forecasts, over 10 years, are used in program planning of specific projects on specific bridges, especially for estimating the scope and timing of work.
- Traffic growth forecasts project future capacity requirements and the exposure of the public to safety and mobility risk caused by natural and man-made hazards.
- Extreme event likelihood forecasts focus on the probability that particular unfavorable events, such as floods or earthquakes, might occur.
- Action effectiveness forecasts predict the changes in condition and risk that can be expected after completion of a preservation or risk mitigation action.

All of these forecasts have a bearing on the planning of future needs within a ten-year time frame. Near-term condition forecasts are the basis for estimates of new needs that may arise, which have not yet been detected in bridge inspections. The other forecasts all relate to project benefits, the future costs that can be avoided if appropriate work is performed in a timely manner. Project benefit forecasts are meant to provide a consistent way of balancing multiple objectives across a diverse inventory of bridges.

Within the 10-year timeframe, the ability to forecast new needs is essential for a complete picture of fiscal requirements. There are two levels of these forecasts with differing data requirements:

- Network level needs forecasting. The main objectives here are to understand the likelihood of meeting targets for the inventory as a whole, and the funding requirements for each element category or type of work in order to meet targets.
- Bridge and element-level forecasting. The ability to anticipate on each bridge the types of work that will be needed within 10 years, and general location within the bridge, as a means of planning for traffic flows and work sequencing.

The first of these has been a capability of Pontis and other bridge management systems using element level data and deterioration models. Figure 5.7 shows a type of life cycle activity profile that can be produced from these models, using the health index to represent condition. This is a useful graph for understanding the alternative futures for a typical bridge element in a generic presentation, but with current element data it may be misleadingly precise for any specific bridge at a specific time. Each sharp line in the graph would be more accurately presented as a cloud of possibilities with significant uncertainty for a specific bridge.

AASHTO has added a number of features to BrM, most based on need criteria as discussed above, to identify specific bridges likely to need work, attempting to overcome some of the uncertainty. For further enhancement, it may be necessary to have more information about the location of defects within a bridge, especially on big bridges. Innovations such as 3D bridge inspection may soon lead to practical capabilities.

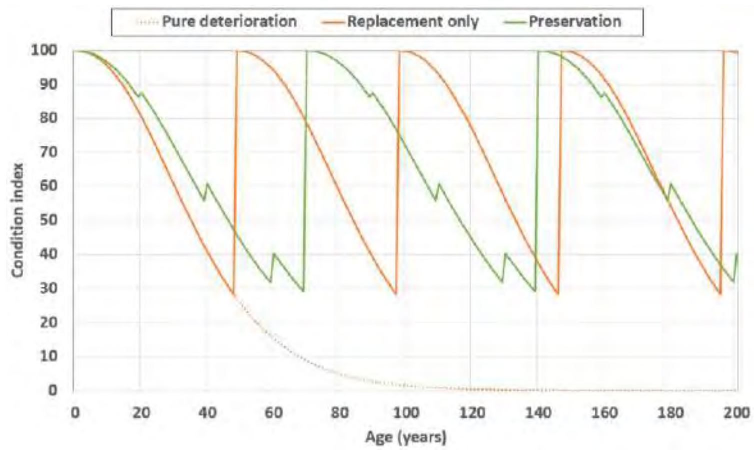


Figure 5.7 - Life cycle activity profiles, comparing two long-range strategies.

5.2.6 Project Development (Project Level)

A basic capability of an element level bridge management system today is the ability to report on current preservation needs at the level of detail of elements and condition states. Table 5.2 shows a partial example, adapted from a Florida DOT project level analysis report. On a big bridge, the full report can be quite long, especially if the bridge is divided into spans or structure units.

Because of the significant cost of preservation work and the challenges of access for maintenance crews, a more detailed presentation of needs can be of great value. The inspector may need to use specialized methods such as snoopers, ropes, or unmanned aerial vehicles to gain access for inspections. It is desirable that this activity capture all of the information needed for work planning and for directing subsequent maintenance crews to the correct location.

When planning work that might not be funded for several years, a report of current conditions may under-estimate preservation costs, because further deterioration is likely. As noted previously, element deterioration models at the current state of the practice are imprecise. Precision can be improved if the inspection process records the locations of defects, in any of the following ways:

- Recording elements span by span, as is already done routinely on many bridges in New York and all bridges in Texas.
- Recording exterior girders separately from interior girders, and assigning more aggressive deterioration models to exterior girders if exposed to moisture, especially salt spray.

- Recording girder ends separately, if located under expansion joints that may leak. This is a routine part of element inspection in Ontario and Quebec, where girder ends are subject to a more aggressive deterioration model. Similar handling may be given to piers, bearings, and other bridge elements potentially exposed under joints.
- Employing a full 3D bridge inspection, as Michigan is developing.

AASHTOWare Bridge Management has a feature, known as the protection factor, that is described as allowing the rate of deterioration of a steel element or a deck slab to deteriorate more slowly if the paint or wearing surface protecting it is in place and in good condition. The same functionality can also be used to model the protective capability of joint seals, and the loss of protection as joints deteriorate. Virginia DOT has been experimenting with this possibility, though it is too soon to know if the experiments will be successful in improving the planning of joint repairs. Florida DOT has built similar functionality into its Project Level Analysis Tool. The effect is to increase the benefit of joint repair by taking into account the higher life-cycle cost of underlying elements when the joint seal is not fully effective.

Table 5.2 - Example Project Planning Report (costs in $000)

Element and location (qty units)	Condition	Treatment	Quantity	Cost
Deck spans 12-18, north side				
12/4 - Re Concrete Deck (sf.)		Repair spalls and delaminations	32.5	3
301/4 - Pourable Joint Seal (lf.)		Replace expansion joint seals	202.4	14
302/4 - Compressn Joint Seal (lf.)		Replace expansion joints	941.9	84
321/4 - Re Conc Approach Slab (ea.)		Repair spalls and delaminations	12.0	1
331/4 - Re Conc Bridge Railing (lf.)		Repair spall, span 14 + 65'	2.0	0
Superstructure spans 8-15, north side				
107/4 - Steel Opn Girder/Beam (lf.)		Reinforce exterior girder end, span 13	1940.0	276
+ 8516/4 - Painted Steel (sf.)		Replace paint system	1034.0	142
Substructure piers 1-12				
311/4 - Moveable Bearing (ea.)		Replace bearing, pier 5 #1, adjust #2-4	1.0	14
+ 8516/4 - Painted Steel (sf.)		Replace paint system	1034.0	142
313/4 - Fixed Bearing (ea.)		Replace bearing, pier 4 #1, adjust #2-5	1.0	9
+ 8516/4 - Painted Steel (sf.)		Replace paint system	1034.0	142
River channel				
8290/4 - Channel (ea.)		Place rip rap NE side nav channel	1.0	35
8387/4 - P/S Fender/Dolphin (lf.)		Repair spalls	12.0	2
Appurtenances				
8563/4 - Acc Ladd & Plat (ea.)		Replace north side ladders and platform	3.0	25
8572/4 - Conduit & Junc. Box (ea.)		Rehab nav lighting system	14.0	15
8580/4 - Navigational Lights (ea.)		Rehab nav lighting system	23.0	18
Total cost				924

AASHTOWare Bridge Management currently does not model the deterioration of defects, only of elements. There is no conceptual reason why defects cannot be modeled, but the system would require additional functionality to convert a listing of deteriorated defects into an estimate of element-level condition state quantities. It would also be necessary for the agency to consistently track all defects in every inspection, regardless of significance, something that no state DOT is currently doing.

This type of project planning functionality can be used on any bridge, but is of considerably more value to big bridges than to average-size structures. Rather than reconfigure its enterprise inspection process and bridge management system to incorporate these features, the agency may want to supplement its BMS with a more detailed inspection process and a detailed spreadsheet analysis that is used only on big bridges, keeping all other bridges in a simpler framework.

Appendix C provides an example of an existing spreadsheet-based system that is well suited to this application. The models in a BMS can be rather complex, so development of this type of spreadsheet is non-trivial. However, the additional complexity of a Big Bridge is more readily handled in a separate spreadsheet. For example, agencies can tailor the level of detail of subdivided units to best fit their knowledge of the areas of special concern on each structure, as an alternative to finely dividing an entire bridge into potentially thousands of separate structural units that would all have to be assessed and recorded. Even if the number of units is large, a spreadsheet has a very flexible set of tools for sorting, filtering, grouping and summarizing condition and analysis data to make it easier to find patterns and to identify efficient preservation strategies. Where inspectors are appropriately qualified, a spreadsheet approach can help them assess needed preservation costs and potential deterioration in the field, as a way of supporting more rapid decisions about maintenance needs.

5.2.7 Priority Programming (Network, Program, and Bridge Level)

The priority programming process is the means that most agencies have to allocate resources between bridges and other needs, and to reconcile the total list of needs with resource constraints. It is common practice to over-program work in order to protect funding sources against funding uncertainties and project delays. Even in cases where agencies have formulas or other structured methods to allocate budgets, in practice competition often remains at the margins to squeeze in additional projects where possible, especially for projects having a motivated constituency within the agency.

In the interviews conducted as a part of Task 4 (see Chapter 3), it was noted that agencies having particularly large bridges, typically 8,000 to 12,000 feet in length or larger, often had special procedures for programming big bridge preservation work, often dividing projects into multiple phases, or identifying special funding sources for them that are partly outside the normal programming process. The funding requirements for these structures is “lumpy,” i.e., highly variable from year to year.

Bridge management systems typically have features to sort a listing of bridges according to indications of priority. It has often been noted, as in Gordon et al. (2011), that this capability has limited usefulness to an agency’s program planning office because it does not support combining lists of bridge projects with projects for other asset classes, or projects consisting of multiple asset classes. The typical agency owning one or more big bridges also owns the approaches, with their pavements and smaller bridges, as well as traffic control devices, toll equipment, drainage and earth retaining infrastructure, buildings, and other assets. In addition, BMS often are not able to consider the full list of objectives important to agency stakeholders. By nature, the programming process is cross-asset and multi-objective.

Table 5.3 shows an example of a bridge priority list that is more asset-generic, adapted from a Florida DOT report. Notably it does not contain structural information, but instead shows the result of converting structural considerations into economic considerations. Projects for pavements, traffic control devices, and other asset classes can be expressed in the same terms. In this report, the long-term (LT) cost savings come from a life-cycle cost analysis. The safety and mobility benefits come from an analysis of functional deficiencies and risk. IBC is the incremental benefit/cost ratio, the benefit column divided by the cost column. These calculations are provided in bridge management systems such as AASHTOWare Bridge Management, or can be performed in spreadsheets. The analytical methods are described in more detail later in this Chapter.

All types of bridges can be included in a report like Table 5.3, but a particular feature is more likely to be seen with big bridges. The two yellow-highlighted lines in the report are two different activities on the same bridge. They are prioritized separately and might or might not occur in the same year, depending on relative priorities and funding availability. The second activity (deck overlay) is an incremental upscoping of the project, with incremental costs and benefits if programmed in the same year as the first activity (repairs). Dividing the project ensures that the higher-priority repairs will be done right away, even if there is not enough funding available to complete the full project. Similarly, the two green-highlighted rows show the possibility of temporary repairs to a bridge if funding is not available to replace it soon.

The Task 4 interviews found that dividing up big bridge projects in this way is often something agencies are forced to do, because of fiscal constraints, even if they would prefer not to do so. Agencies are careful to define the projects in a way that tries to keep traffic disruption to a minimum, but additional indirect costs and road user inconvenience are often difficult to avoid in this situation. The cost and benefit calculations can take that into account.

Table 5.3. - Example Priority List Focusing on Cross-Asset Economic Measures

Bridge_ID	Structure Name	ADT	Action category	Fiscal Year	Total Cost ($000)	LT cost savings ($000)	Safety benefit ($000)	Mobility benefit ($000)	Total Benefit ($000)	IBC
130082	US 41 OVER BOWLEES CREEK	45735	Repairs	2018	2022	10513	0	0	10513	5.199
030083	US-41 OVER TURNER RIVER	27756	Recoat	2018	204399	91556	200561	639907	932023	4.560
130144	SR-70 OVER BRADEN RIVER	48665	Repairs	2020	3419	12316	0	0	12316	3.602
050031	SR-29 OVER TURKEY BRANCH	26600	Improve	2018	29064	2479	9186	43227	54892	1.889
170164	US-41 OVER PHILLIPPI CREEK	48363	Repairs		3074	5290	0	0	5290	1.721
030091	US-41 OVER SHADOW CANAL	30786	Replace		46204	2523	11029	59244	72796	1.576
090053	SR-70 OVER SLOUGH DITCH	46260	Repairs		3090	4426	0	0	4426	1.432
130144	SR-70 OVER BRADEN RIVER	48665	Overlay	2028	5369	7282	0	0	7282	1.356
030088	US-41 OVER DOLANS CANAL	30786	Replace	2025	46163	3197	10828	47502	61526	1.333
030058	US-41 OVER BRUFRED CANAL	34483	Repairs	2024	2880	3827	0	0	3827	1.329
030066	US-41/WHOFLUNGPOO SLOUGH	35852	Improve		31908	16827	8438	12669	37933	1.189
030069	US-41 OVER FLAMER CANAL	35852	Recoat		32011	7205	9245	21107	37556	1.173
030060	US 41 OVER YAZOO SLOUGH	34483	Improve		31666	171	2315	33715	36200	1.143
030059	US-41/ LITTLE ANNIE SLOUGH	34483	Improve		30842	2914	7100	24400	34413	1.116
170164	US-41 OVER PHILLIPPI CREEK	48363	Replace		60171	25405	14366	22489	62260	1.035
030052	US-41/DRAINAGE CANAL 052	34483	Repairs	2021	2469	2436	0	0	2436	0.987
050073	SR-78 OVER JR'S CANAL	30069	Replace		42467	31195	4865	5624	41684	0.982
030075	US 41 OVER XEBEC CANAL	35852	Overlay		36872	9466	8885	17224	35575	0.965

Another way of visualizing prioritization and resource allocation can be seen in Figure 5.8, which shows priorities within a single big bridge in both a spatial and time dimension. Red indicates portions of the bridge that are programmed for immediate work, while green indicates long-term needs that have been identified. This is also a mock-up example because Tasks 3 and 4 did not uncover any examples of this type of graphic in current practice. A bridge database containing a structural model, such as AASHTOWare Bridge Rating, might be adapted to present this type of information if it is interfaced with the program planning module of AASHTOWare Bridge Management.

Graphic representations such as Figure 5.8 can be of significant value in communicating program plans to non-technical personnel and to stakeholders in senior leadership and governance. One limitation of this approach is that there will be new long-term needs after five years, which might not yet be identified because they respond to the inevitable effects of future deterioration. It may be appropriate, therefore, to qualify the yellow and green regions of Figure 5.8 with a notation that additional needs will be added to the program as appropriate when inspections identify them.

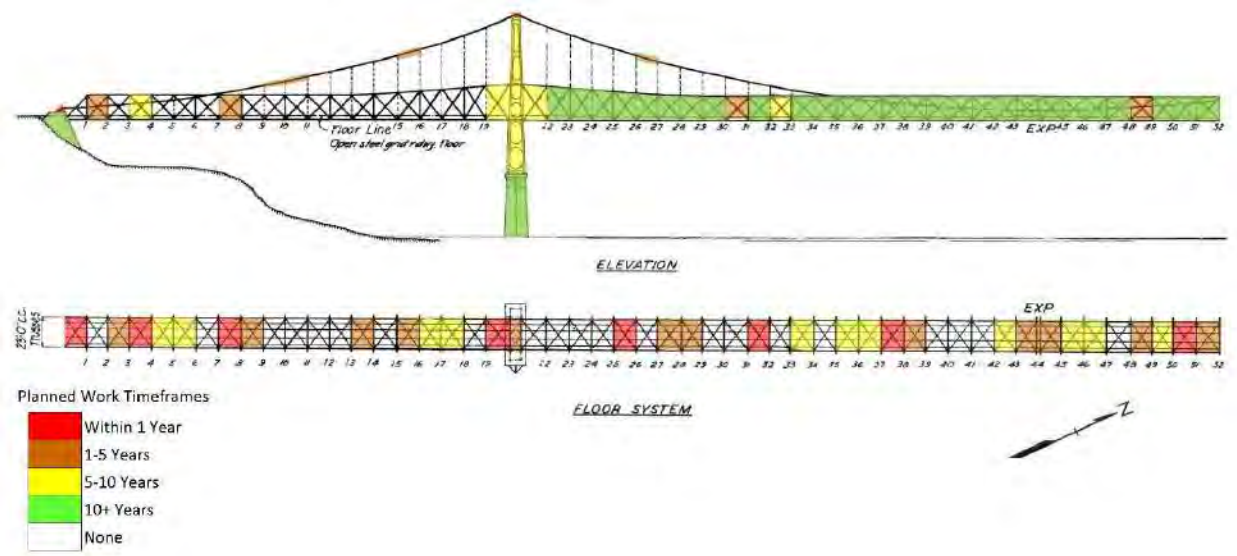


Figure 5.8 - Example Graphic Presentation of Priorities on a Single Bridge.

5.2.8 Project Delivery (Project Level)

Element-level bridge inspection data are intended to be usable for developing programmatic cost estimates, but not necessarily for detailed design of rehabilitation actions. For program planning, element condition state quantities from the inspection are likely to need adjustment to take into account:

- Likely deterioration between the most recent inspection and the date of actual work. The BMS deterioration model should be sufficient to account for this.
- Expansion of work quantities due to defects that were unobserved in inspections, or for convenience of preservation work methods. For example, even a spot painting or zone painting project will typically cover more than just the deteriorated quantity of paint recorded in the inspection. An allowance for this should be included in the unit cost estimate used in the BMS, to ensure consistent costing throughout the analytical process.

For design purposes, it is necessary to know the locations of defects to be repaired, at least to the extent that the location affects work quantities, access, traffic control requirements, or structural capacity. This may require additional site visits. Part of the potential benefit of a 3D inspection tool, similar to that used in Figures 4.22 and 4.23, is the ability to have this information in the office so repeat visits are less likely to be needed.

Once the work is completed, there is value in following up to compare estimated work requirements to actual outcomes. Typically this is done by comparing inspections before and after the work. Conditions after completion of a preservation project will not necessarily be 100% in condition state 1, but should satisfy agency expectations for the type of work involved. A common follow-up task in BMS implementation is the tracking of actual work effectiveness in order to ensure that the BMS models reflect realistic preservation outcomes.

An extension of the functionality offered in a 3D inspection process is the potential for 3D recording of crew activities, as a part of a construction or maintenance inspection process or a project close-out process. This information not only ensures crew or contractor compliance, but also provides data useful for improving the BMS cost estimation functionality.

5.3 Key Analysis Issues

Figure 5.1 and the use-case analysis in the preceding section discussed a variety of business processes conducted by multiple organizational units, each having their own time scales, leadership, and pressures. It has often been observed that these units can become "silos" of independent decision-making even though, as Figure 5.1 shows, the path from long-range planning to delivery is a continuous, repeating flow.

A basic theme of transportation asset management is that there is an underlying database and analytical process that ties the silos together, that ensures that they are all working under consistent data, objectives, and assumptions even as their roles may differ substantially (Gordon et al. 2011). This is as true for big bridges as for any other asset class, especially because big bridges often have their own dedicated organizational units that can become isolated or siloed.

Certain parts of the asset management process generate data not only for their own use, but also for the benefit of other parts of the agency, or for other agencies (FHWA, for example). A role of standardization is the agreement on data standards, timeliness, level of detail, and assumptions that all other parts of the process can rely upon. Bridge inspection, for example, serves near-term requirements such as STIP development and project delivery, and also serves long-term requirements such as planning and forecasting.

The following sections discuss some cross-cutting issues affecting many parts of the decision making process and the analytical process, where decisions made at one level may restrict the options available at other levels for big bridge management. An underlying theme is that big bridge management, while having special requirements of its own, still relies upon, and must remain consistent with, many other agency processes that are not focused on big bridges.

5.3.1 Relating Tools to Business Processes

As context for the cross-cutting issues and analytical methods discussed in the rest of this document, it is useful to show a general overview of the mapping between analytical methods and business processes, as an interface between two parallel flows of activity (Figure 5.9). Section 5.2 presented a discussion of the upper flow with examples of the desired products of those activities. Sections 5.4 and 5.5 will discuss the lower flow of the analytical process. Some key features of the interface between the two flows are the following:

- In the center is a performance model, a major product of the analytical process and a major input to many of the business processes related to forecasting of funding requirements and performance expectations. It should reflect the accumulated knowledge of deterioration rates, costs, and action effectiveness inherent in the data stored in the BMS.
- Project development is supported by a set of criteria for selecting appropriate treatments, including preservation warrants, level of service standards, and other decision rules. It should reflect the accumulated wisdom of the agency's engineers and of the industry in understanding the ideal application of various forms of preservation and risk mitigation treatments.
- Capital programming is supported by a set of analytical calculations of performance measures significant to prioritization, including long-term cost savings to the agency and users of preservation and risk mitigation work. The analytical process should ensure that priority-setting criteria are fair, consistently applied, and reflective of the agency mission and objectives.
- As work is delivered, the effectiveness of the results is fed back to the planning process through research, to improve future planning. These data are meant to ensure that planning metrics are as realistic as possible.

The performance model serves a purpose analogous to the structural model that might be produced by a bridge design system. A structural model not only supports the initial construction of the bridge, but if preserved and managed it can also serve future activities of load rating, exceptional load processing, and structural modifications. (A structural model can also support

3D inspection, as discussed later.) The performance model in Figure 5.6 supports long-term and network level planning functions which influence the flow of funds and the establishment of stakeholder expectations for outcomes to be purchased with those funds. It serves to harness detailed element and defect data familiar to bridge engineers and translate it into forms useful to other agency officials who might not be bridge engineers. If successful, this will improve the quality and consistency of decisions made by all of the participants.

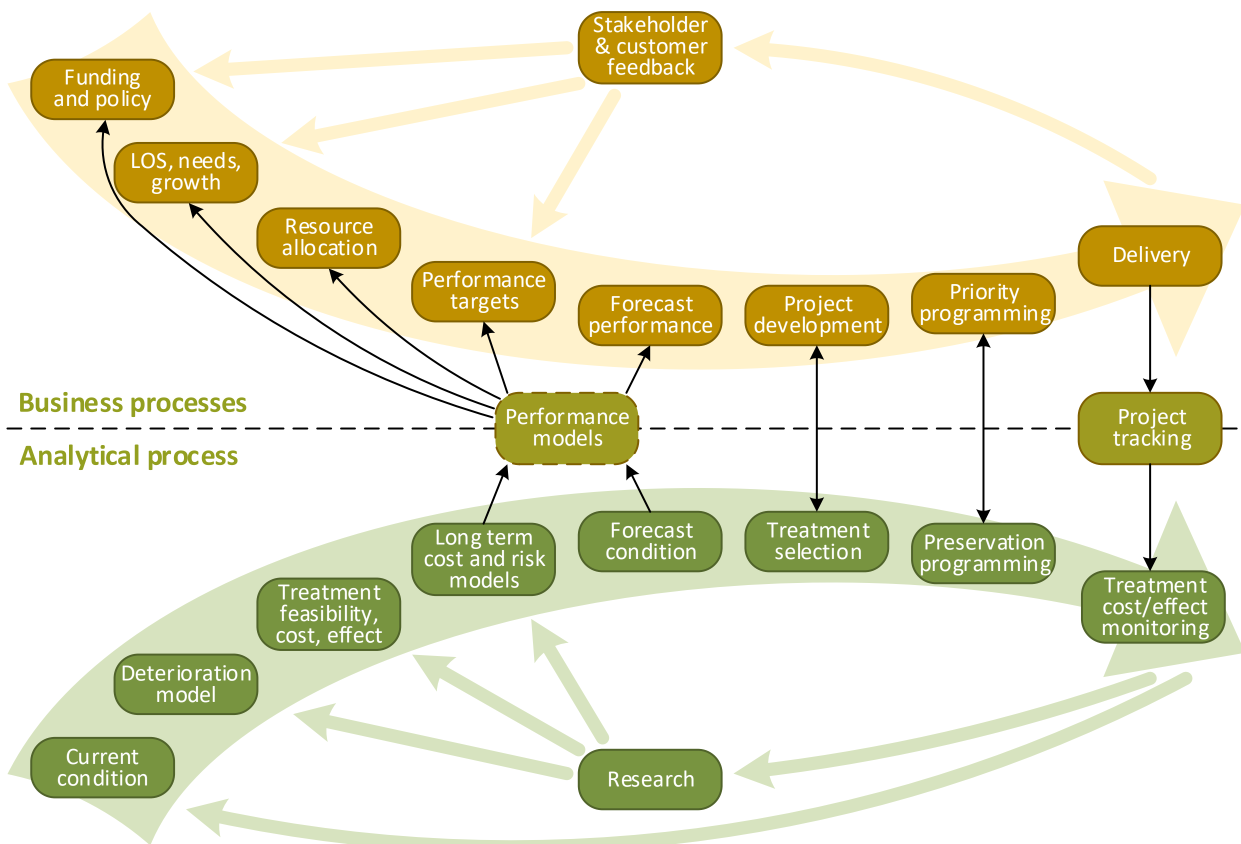


Figure 5.9 - Analytical process flow in parallel with business process flow.

5.3.2 Level of Detail of Condition Data

Since element inspections on big bridges have greater economic consequences than on smaller structures, agencies may find it cost-effective to gather more detailed data for ongoing deterioration processes. Significant potential benefits were introduced in Task 5 related to giving engineers a more precise understanding of the causes and progression of defects, the effects on structure performance, and potential corrective action.

Existing BMS have followed two basic approaches for collecting and managing the more detailed data:

- Subdivided units – the structure is permanently sectioned into spans, panels, and other physically-defined areas, which in every inspection are treated as though they were separate structures.
- Enumerated damages – the structure may be divided into structure units and/or spans, but each inspection further divides the structure into damaged areas, which can change in size from one inspection to the next due to deterioration and preservation work.

Figure 5.10, reproduced from Task 5 (see Chapter 4), contrasts these two approaches. In both cases, a big bridge is divided into one or more structure units, and for each inspection is further divided into element inspections. In both cases, the listing of elements and their quantities is intended to represent the total substance of the structure for bridge preservation management. The entire quantity of each element is subject to deterioration and may potentially need preservation work at some time in the future.

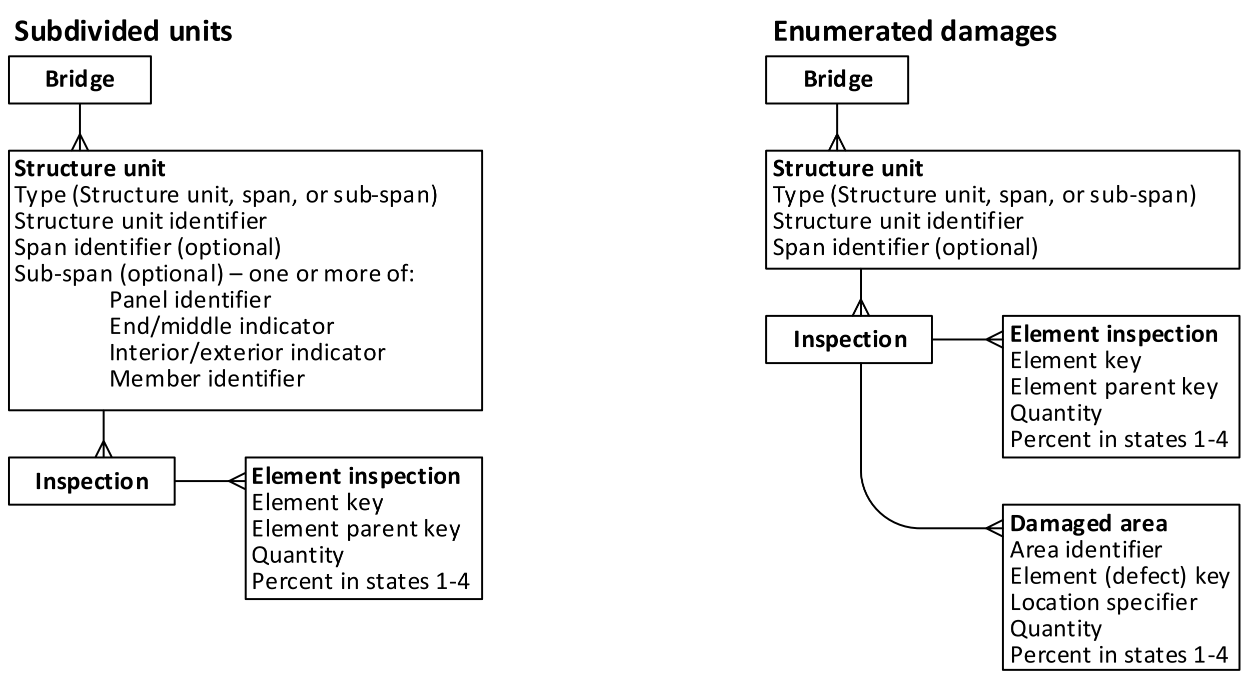


Figure 5.10 - Two approaches for more detailed defect data

In the subdivided units approach, structure units are further divided to the span or sub-span level. A sub-span identifier may indicate portions of a span such as truss or floor system panels, ends or middles of beams, interior or exterior members, or even individual members (such as separate bearings). Each piece of the subdivided structure is given a permanent identifier according to a standardized labeling system for which all inspectors are trained. Each sub-span has its own listing of one or more elements, and its own separate listing of defects.

In the enumerated damages approach, the structure may still be permanently divided, but typically into larger units. Instances of observed damage are recorded in a separate listing of damaged areas. Each damaged area has an element key identifying the type of defect, a location specified in a standardized three-dimensional manner within the structure, and a quantity. The quantity would typically be smaller than the quantity recorded for the element because it represents just the size of the damaged area.

Unlike the subdivided units approach, enumerated damages allow multiple instances of the same defect on the same element, at different locations. Damaged areas of the same or different types can overlap. For example, the ends of a deck might be spalled, with evidence of corrosion in the spalled areas and extending further toward the center of each slab beyond the spalls. Cracked areas visible on the top of the deck may be in different locations than cracked areas visible on the bottom of the deck. From one inspection to the next, the listing of damages can change substantially, because new damaged areas arise and old ones are repaired.

Compared to the subdivided units approach, the enumerated damages approach requires an additional database table to hold the listing of damaged areas, and benefits greatly from a graphical user interface for specifying damaged areas because they can be irregular in size and shape.

Deterioration modeling and life-cycle cost analysis in the subdivided units approach treat each unit as though it were a separate element. Although this is a significantly more detailed calculation than is generally done in a BMS, it is mathematically the same and produces the same result as element level deterioration.

Alternatively, modeling of deterioration in the enumerated damages approach would require modeling the formation of damaged areas in places not previously damaged, and the growth of size and severity of existing damaged areas. There are no current bridge management systems with this capability, but it could be a fertile area for future research. Because the data provide a precise and separate description of each type of damage, enumerated damages might be benefited by research on mechanistic modeling of bridge element deterioration.

An approach that might lead to usable deterioration models more quickly with enumerated damages is a data reduction process, adding up the quantities of damaged and undamaged areas to produce a total defect or element quantity by condition state. The challenge here is deciding how to handle damaged areas that overlap. A 3D inspection system that is able to show damaged areas graphically would naturally also have the ability to determine, at any given point, the most severe condition state of all defects active at that location (refer to Figures 4.22 and 4.23). Level of severity could be rendered graphically on a computer screen by different colors. Summing over the entire element would then produce an estimate of the percent of element quantity in each condition state.

5.3.3 Coverage of Defect Data

Another data collection question with far-reaching consequences is the decision whether to gather complete defect data, and to model deterioration and life-cycle costs separately for each defect. This is a significant question for all bridges, but especially for big bridges where access is difficult and expensive, where there is additional value in gathering as much useful data as possible and avoiding return visits. Several aspects should be considered:

- The type of defect most significant on a given element is often sufficient to develop an initial decision about the type of preservation approach to undertake. This is the basis for the common practice (no longer recommended in the AASHTO Manual on Bridge Element Inspection) of recording only the most significant defect in inspections. However, areas where multiple defects overlap might change the choice of treatment.
- The relative significance of various defects may change over time. For example, cracking may be most significant at first, but in subsequent inspections corrosion may become a greater concern. In this situation, an agency that records only the most significant defect might track cracking for one or two inspection cycles and then switch to corrosion as the most significant defect subsequently, thus losing the ability to track the cracking process.
- In addition, it is unknown at this time how consistently inspectors will be able to judge which defect is the most significant on a given element at a given time.

- If more than one deterioration process is active on an element, then more than one preservation approach may be required, especially on bridge decks where waterproofing, corrosion treatment, crack sealing, and spall patching might all be necessary, each treatment having its own materials, skills, equipment, and costs.
- Different deterioration processes proceed at different rates. In order to research the question of deterioration rates for separate defects, it would be necessary to have complete data on the extent and state of each defect, including the extent of area where the defect is insignificant or absent.
- Further complications are introduced as defect deterioration (and their rates) interact, e.g., cracking/corrosion described above.
- In some cases the preservation treatment may address more than one defect on the same element. For example, element replacement cures all defects. This complicates the life-cycle cost analysis because it may be necessary to consider all defects together rather than the simpler case where each defect is modeled as though it were a separate element.

Given the complexity of these considerations and the importance of unanswered questions about data quality and defect interaction, AASHTOWare Bridge Management does not currently attempt to model the deterioration or life-cycle cost of defects. This is an excellent topic for future research, but such research would require the willingness of agencies to gather the more detailed defect data, at least on a representative sample of bridges, even if they are not fully able to make use of these data in the near term.

5.4 Network Level Analysis Tools

The purpose of analysis in bridge management is to improve the quality of decisions by forecasting outcomes. When long-term objectives are clear, decision makers can use this information to select courses of action that are most likely to accomplish those objectives.

If decision making is a group process, outcome forecasts can help the participants to come to agreement on a set of actions and associated predicted outcomes that satisfy their mutual needs. This leads to network level analysis.

Network level analysis is distinguished from project level analysis in that it accounts for all of the transportation infrastructure within an agency's responsibility, not necessarily limited to one bridge or even to one asset class. Similar concepts can apply when managing the individual components of a single large structure. The decisions that are made using network level analysis involve establishment of policies affecting groups of similar structures; estimation of the amount of money or other resources (e.g., staffing, equipment, market capacity, etc.) required over a long time period to:

- meet agency objectives,
- allocate resources among activities, among parts of the network, and over time,
- establish performance expectations and targets for the agency as a whole and for organizational units (e.g., districts), and
- prioritize among competing projects to maximize the accomplishment of objectives, all within fiscal constraints.

The analytical requirements of network level bridge management were first described in an AASHTO Guide in 1993 (Hyman and Thompson 1993), and reaffirmed in a manner applicable to many asset classes in Gordon et al. (2011). Over the course of its life, each asset undergoes deterioration because of age, traffic, weather, water and earth movement, freeze/thaw, and other factors. The effect of deterioration is to increase the likelihood of service disruptions, and to increase the frequency and cost of routine, reactive maintenance such as pothole filling and sealing of cracks. Occasionally it is necessary for the agency to intervene with preservation action to counteract this deterioration. Occasionally changes in a bridge's environment (stream-bed configuration, for example), material characteristics (e.g., steel cracking), utilization (e.g., heavy truck traffic) or in risk management standards may make it necessary to perform risk mitigation activities.

Preservation and risk mitigation treatments have important inter-temporal tradeoffs. In many cases a small timely investment in preservation can extend the life of an asset or component and postpone the day when a major reconstruction might be necessary. If such a treatment is feasible but is not accomplished in a timely way, further deterioration may render it infeasible or increase the rehabilitation cost substantially. In network level bridge management, all of these costs are expressed in dollars and combined in a framework where tradeoffs in scope and timing of work can be evaluated. Figure 5.11 shows the ingredients:

- A treatment model (green) forecasts the costs and effects of mitigation and preservation activities in each condition or resilience state. The amount of each treatment is guided by a treatment policy and constrained by available funding.

- A deterioration model (yellow) forecasts the change in condition from year to year when no treatment is applied, starting with current conditions from the most recent inspection.
- The risk model (red) uses a site assessment of potential safety, mobility, and environmental impacts, along with data on traffic and detour routes. The resilience of each asset affects the likelihood of service disruptions, thus affecting the expected value of disruption costs borne by the agency and road users.

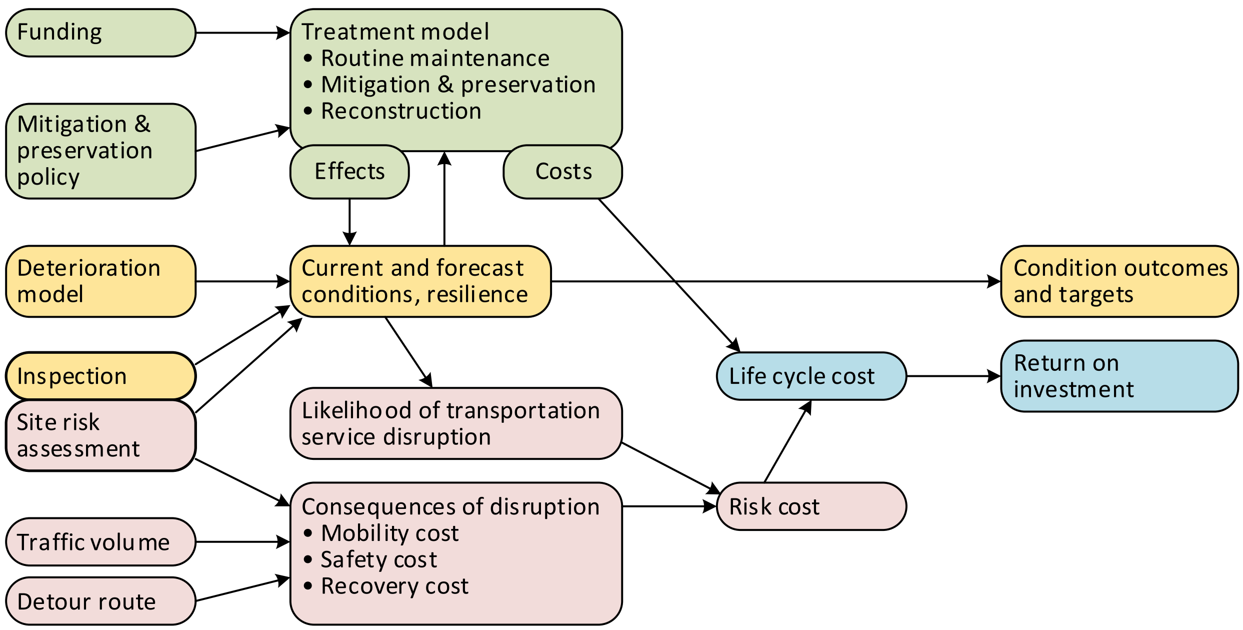


Figure 5.11 - Analytical framework for network level bridge management

- Agency- and user-costs are combined into life-cycle cost. All costs are discounted, based on the year in which the costs are incurred, to reflect the time value of money. By comparing different policy and funding alternatives, the agency can compute economic metrics such as long-term social cost savings and return on investment.

Most bridge management systems having forecast and analysis capability follow the pattern described in Figure 5.11, including AASHTOWare's Pontis and BrM software systems. Most of the green treatment model and the yellow deterioration model rely on element level data from bridge inspections. Recent risk analysis models in AASHTOWare BrM, in Minnesota and Florida spreadsheet tools, and in the guidelines produced by NCHRP Project 20-07(378) use a subset of element data in the form of risk-related defects, formerly known as Smart Flags, for scour, cracking, settlement, and other problems related to the likelihood of service disruption. Florida DOT has also developed a model at the element level to forecast the probability of service disruption caused by advanced deterioration of any primary load-bearing structural element.

5.4.1 Analytical Process

The analysis described in Figure 5.11 can produce cost and benefit estimates for an entire inventory or a portion thereof, exploring the potential outcomes of alternative policies or expenditure levels. It can also estimate this information at the project level. On a big bridge, where projects may be implemented in phases, the process can identify needs at the same level of detail as the inspection data, which may be by element, span, or smaller units if the subdivided units approach is used.

Figure 5.12 shows the general pattern of a bridge management analysis for structures of all sizes. This is described as a "pattern" because the detailed methodology can vary quite significantly depending on the use cases being served. It is nearly universal in practical bridge management systems to perform a separate analysis, with separate resource constraints, for each year or biennium of a program horizon, typically ten years. An asset-based or component-based analysis, surrounded by a large box in Figure 5.12, addresses each bridge individually and may create one or more investment candidates. The following sections discuss the individual parts of the analysis in more detail. Once the list of candidate investments has been compiled, it is prioritized using benefit/cost analysis, and the highest-priority investments are selected up to the limits of resource constraints. Network outcomes are updated, and then the process is repeated for the following period.

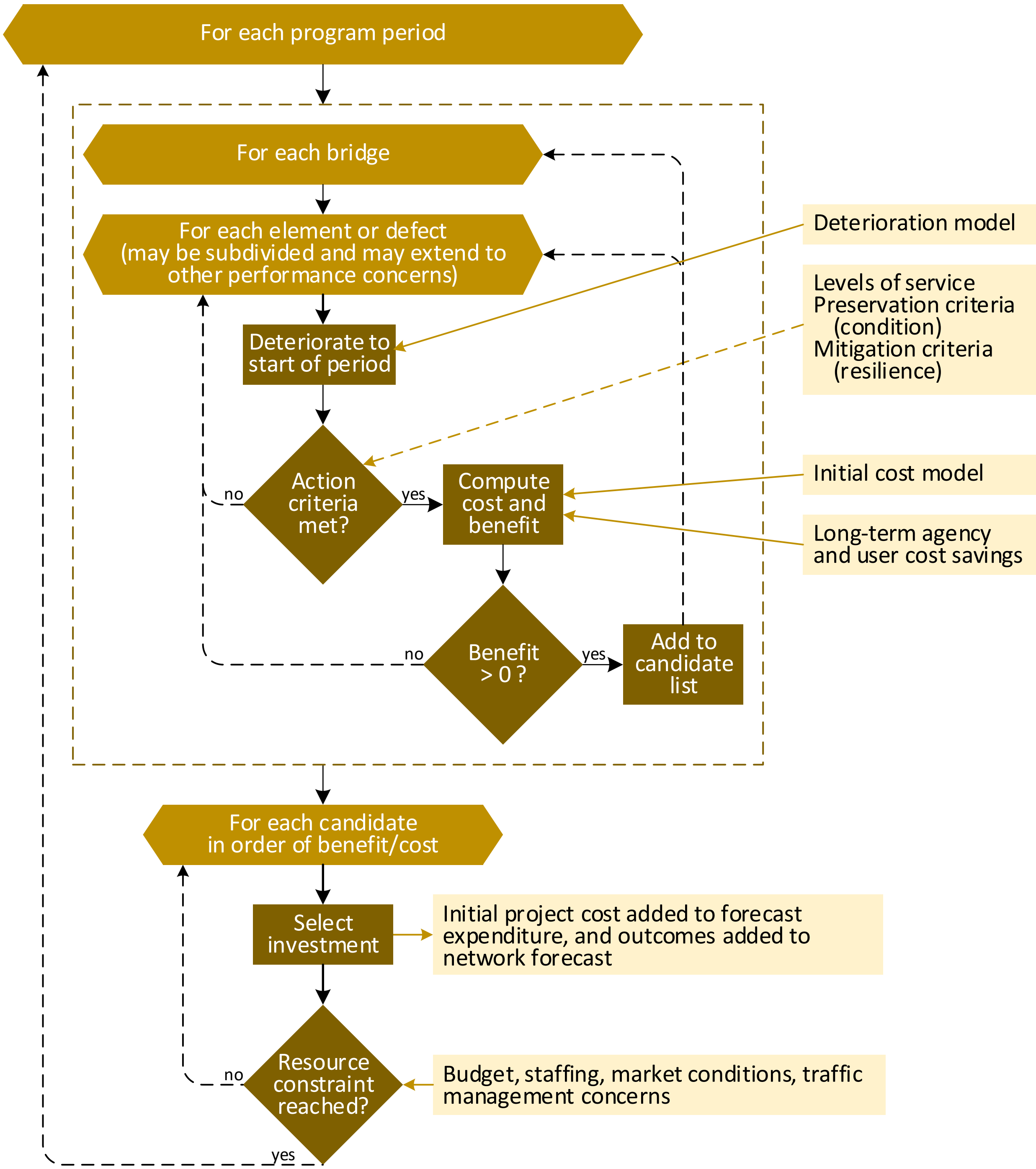


Figure 5.12 - General pattern of bridge management analysis.

5.4.2 Program Periods

Most bridge management systems forecast needs over a ten-year horizon year-by-year. The reports, survey, and interviews conducted earlier in the present study found that some agencies prefer to program funds biennially, based on state budgetary processes. A few agencies have traditionally forecast preservation needs for 12 years or even longer horizons up to 30 years. Toll authority business plans often project their capital needs for horizons longer than 10 years.

A pitfall of long-range needs estimates beyond 10 years is that bridge deterioration models have considerable uncertainty, which is compounded when the choice of treatment may depend on multiple elements deteriorating at different rates. Nonetheless a long-range program may be necessary for big bridges, especially if they rely on bond financing which depends on long-range estimates of cash outlays. For this reason, a recommended approach is to develop long-range needs using periods longer than one year, such as five years, or even ten. The first five years of the analysis might have annual estimates, followed by a single estimate encompassing years 6-10, followed by estimates for each decade following.

Currently no bridge management systems offer support for irregular program periods, and the research did not find any agencies requiring this for a statewide bridge inventory. This is one reason why, for big bridges, there is value in preparing bridge-specific investment analyses using spreadsheet models, where the analytical parameters can be customized to the needs of each facility, perhaps to fit the calendar specified in bonding documents, or a calendar that a supervisory board is accustomed to seeing.

The magnitude and timing of future investments are subject to considerable uncertainty, and this uncertainty has a significant effect on decision making regardless of the length of the program horizon. Figure 5.13 is a simple example where uncertainty is important. A type of expansion joint seals has a median lifespan of 12 years in this example. However, this lifespan is uncertain. In planning a 10-year preservation program, it would be erroneous to assume that no funding for replacement seals is required during the next 10 years. If actual inspection data show that 20% of the seals fail by 10 years of age, then the funding for this activity will need to be included in the program, or it will be under-funded. This is a general issue with bridge elements, that the probability distribution of preservation needs always has a leading tail requiring funding sooner than the average.

This is further complicated by the interaction of elements such as the failure of a joint that leads to accelerated corrosion of a girder or bearing that theoretically would have a much longer life expectancy.

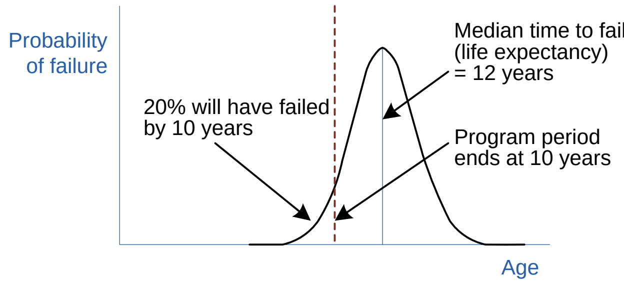
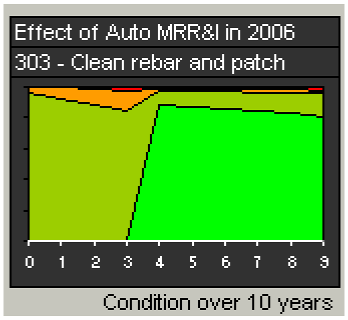


Figure 5.13 - Example of uncertainty in program development.

5.4.3 Deterioration Models

This uncertainty in deterioration modeling is the reason why all fully-implemented bridge management systems worldwide having a forecasting capability rely on Markov probabilistic deterioration models and element level data to predict future bridge condition (Mirzaei et al. 2014). A few other model types, particularly Weibull models, have been partially implemented for selected elements or for predicting the onset of deterioration of elements in condition state 1. NCHRP Report 713 (Thompson et al. 2012) describes these methodologies in detail.

A strength of Markov models is that they explicitly allow for the existence of every possible condition state on an element, and are able to model the progression of each state, including new condition in condition state 1. At every point in time, the sum of quantities across all possible condition states is equal to the total quantity of element on the bridge. This is shown graphically for a single element in Figure 5.14. The figure shows a prestressed girder element starting with almost all of its length in state 2 (lime green), the quantities in states 3 (orange) and 4 (red) growing gradually in the first, second, and third years. In the fourth year a preservation project (denoted “Auto MRR&I”) moves almost all of the element to state 1 (bright green), where it subsequently resumes deterioration for the remainder of the analysis.



Forecast needs Jan 1, 2006
109/4 - P/S Conc Open Girder

State	Qty	Action
1	0.00	DN
2	3388	Seal&Patch
3	561.13	Cln&Patch
4	79.76	Replace
5		
Total	4029	(LF)

Figure 5.14 - Graph of four condition states over ten years, with quantities in one of the years.

Figure 5.14 is produced by Florida's Project Level Analysis Tool (PLAT), using a combination of Markov and Weibull models in an Excel spreadsheet. At any point in time the model can estimate the quantity in each condition state and the total quantity requiring work, as in the table on the right side of Figure 5.14. A cost estimate is prepared from this information.

Provided that a reasonable allowance is made for hidden distresses, indirect costs, and other practical considerations, an estimate of needs prepared using a Markov deterioration model can provide a reasonable approximation of future funding requirements over a long-time frame. The model is not able to forecast the location of defects, nor the potential effect on bridge load rating. A more location-aware inspection process would be required for that level of detail, as discussed later. But the network-level model does provide an envelope for the total amount of preservation need that is likely to arise from future deterioration.

A considerable amount of research has been conducted by states and by FHWA to quantify Markov models. In fact, the National Bridge Investment Analysis System (NBIAS) has a model for each climate zone across the USA, developed using Pontis element inspection data contributed by 15 states and migrated for compatibility with AASHTO's 2013 Manual on Bridge Element Inspection. Big bridges are included in the data set but no separate models were developed for big bridges. All of these models are at the element level, limited to NBI elements.

No research has been conducted thus far at the defect level or for subdivided elements. Florida DOT in work for its own use in PLAT, did develop deterioration models for Pontis smart flags and for certain elements common on big bridges, especially the electrical, mechanical, and hydraulic components of moveable bridges as well as cables, pile jackets, fenders, and dolphins. Because big bridges can have unique environmental and operating conditions affecting deterioration rates, it is recommended that their deterioration models be developed by compiling groups of bridges experiencing similar conditions. The bridges in that data set would not all necessarily have to be big bridges and would not necessarily have to be from the same agency or state. The Florida research determined that a data set containing at least 500 inspection pairs is necessary in order to develop deterioration models using the methodology developed in that agency's research. An inspection pair consists of two element inspections, spaced roughly two years apart, with no preservation action performed between the inspections.

5.4.4 Cost Estimation

Bridge management systems compute the direct costs of each action by multiplying the quantity in applicable condition states by the unit cost of the action. The units of the unit cost factor are the same as the units of measure defined for the element. For example, the unit cost of repairing a girder is expressed in dollars per linear foot, as is the cost of painting the girder.

Direct unit costs are customarily estimated by summing the costs of labor, materials, and equipment usage (or corresponding contract pay items) for all similar projects conducted in the state over one or more years. This total cost is then divided by the total element quantity in condition states where the work is applicable, from inspection data gathered before the work was done on the bridges that received the work. This calculation then incorporates an allowance for excess coverage and hidden distress, and provides smoothing of inconsistencies from project to project. Because the data used for this computation are often unclear on the exact scope of work, various mathematical methods have been employed to attempt to allocate costs based on project descriptions and other data.

If employing these same unit costs on big bridges, it is important to review each element to correct unintentional biases that the methodology might introduce. For example, if girders on an agency's big bridges are deeper or more complex (because of stiffeners and bracing) than average girders in the inventory, then a unit cost consistent with average bridges might under-estimate big bridge costs. Most bridge elements are potentially subject to this type of bias, and the correction might vary from bridge to bridge and element to element. This fact makes it especially important that each agency track its costs and develop appropriate metrics from actual cost experience.

Many bridge management systems provide an additional unit cost or another estimation method for indirect costs of traffic control, mobilization, demolition, design, construction engineering, land acquisition, and other activities. These items are notoriously difficult to estimate at the network level. For long-range estimates of need, it is common practice to apply an overhead factor, developed in the same way as described above for direct costs. For near-term projects, it is better to prepare a work zone conceptual plan and cost estimate with a specific project in mind, as would be done during the initial stages of project design. This is especially valuable on big bridges because work zone planning can have an over-sized impact on project costs and on public inconvenience.

5.4.5 Treatment Effectiveness

Generally the models used for estimating treatment effectiveness are empirical, comparing element condition before and after treatment, and attributing the change to the effectiveness of the treatment. This is expressed as a transition probability for Markov modeling. It is possible in theory to use the same statistical analysis methods for estimating treatment effectiveness as are used for deterioration models, as in NCHRP Report 713. In practice, however, the data sets available for action effectiveness modeling are often too small for statistical confidence. As a result, most action effectiveness models are derived from expert judgment. At present, this is the approach recommended for big bridges as well.

Great potential exists for industry-level research on action effectiveness for using data sets gathered from multiple states in order to improve statistical performance of models. An NCHRP research problem statement has been prepared by the Transportation Research Board Committee on Bridge Management to pursue this line of investigation.

5.4.6 Risk Analysis

In the Task 4 interviews (see Chapter 3) it was noticed that big bridge owners may take two very different perspectives on risk, depending on the circumstances of their facilities. One perspective the researchers heard was that the facilities are consistent with modern standards, are in excellent condition, and the agency works diligently to keep it that way. In these agencies, risk analysis was not actively used in the capital programming process. A second perspective heard from a number of agencies was that their facilities had attributes not up to modern standards, or were in deteriorated condition, and that a lack of funding might lead to a degradation in service offered to road users. For these agencies risk was a significant concern. Concerns similar to the second case are cited frequently from state DOTs about their larger inventories, especially for bridges that are not on the National Highway System.

In most of these cases the concern is not catastrophic failure, but instead is the possibility that service might be disrupted: for example, that expansion joint armoring might come loose and cause accidents, or that the agency might need to load-post, or a collision with an over-height truck might occur, or a natural extreme event of collision, scour, or earthquake might close a bridge without total collapse.

National Cooperative Highway Research Program (NCHRP) Project 20-07, Task 378 was commissioned by the AASHTO Subcommittee on Bridges and Structures to develop a Guideline for Risk Assessment for Bridge Management Systems, to be used within a bridge management system (BMS) to estimate the beneficial effects of bridge preservation, risk mitigation, and replacement on transportation performance, as a part of methods for project utility and benefit/cost analysis. AASHTOWare Bridge Management was explicitly targeted, but the methodology is intended to be usable with any BMS or in spreadsheet analyses separate from a BMS.

The final Guideline, now complete and due to be published in late 2017 (Thompson et al. 2017), describes methods for developing service disruption scenarios, and then estimating the likelihood and consequences of these scenarios. Likelihood probability models are provided for 16 hazards including earthquake, landslide, storm surge, high wind, flood, scour, wildfire, temperature extremes, permafrost instability, overload, over-height collision, truck collision, vessel collision, sabotage, advanced deterioration, and fatigue. Consequences of service disruption are estimated in dollars for recovery cost, safety, mobility, and environmental sustainability. All of these models are based on published research gathered from a wide variety of sources, and consistent with the AASHTO Guide for User and Non-User Benefit Analysis for Highways (the “Red Book”, AASHTO 2010).

Figure 5.15 shows a worksheet from the new AASHTO guide, which illustrates the structure of the analysis. NBI inventory and element condition data feed into a likelihood model, while utilization, network characteristics, and economic parameters determine the consequences. The bottom line is an annual social cost attributed to the combined effect of all risk factors. Because it is expressed in dollars, it is readily usable in benefit/cost analysis for priority setting or project selection.

The economic basis for risk assessment is designed to be compatible with existing use of life-cycle cost analysis in BMS, as well as with the utility framework provided in AASHTOWare

Bridge Management. It is meant for bridges of any size, but because risk exposure is proportional to traffic volume and detour length, big bridges carry a disproportionate share of inventory risk.

NCHRP 20-07 (378) Risk Analysis
Sheet B - Project summary

Bridge ID	**010001**		
Alternative	**Do nothing**	Deck area (sq.ft)	20,000
Program year	**2017**	Program cost ($000)	12,345

Roadways	On structure				Under structure			
Func class	11 - Urban interstate				14 - Urban other principal arterial			
Utilization	ADT	54,000	Trucks	5.50%	ADT	21,000	Trucks	3.00%
Roadway	Length (ft)	200	MPH	55	Length (ft)	100	MPH	45
Detour	Miles	2.1	MPH	45	Miles	1.0	MPH	45

From BMS data. If multiple roadways, use the total ADT and most significant roadway, projected to program year.
Length on-structure is bridge length. Length under-structure is bridge width..

Hazard scenarios		Consequences ($000)				Likelihood			Risk
ID	**Scenario**	**Cost**	**Safety**	**Mobility**	**Environment**	**Extreme**	**Disruption**	**Weight**	**Cost ($k)**
1	Earthquake-100	12,345	50	6,000	600	1.00%	5.00%	1.00	9.50
2	Flood 100a	12,345	50	6,000	600	1.00%	10.00%	1.00	19.00
3	Flood 100b	100	0	2,000	200	1.00%	20.00%	1.00	4.60
4	Flood 500	12,345	50	6,000	600	0.20%	50.00%	1.00	19.00
5	Overheight	100	70	200	40	--	5.00%	1.00	20.50
6	Deterioration	50	0	200	40	--	10.00%	1.00	29.00
7	Fracture	12,345	0	6,000	600	--	0.50%	1.00	94.73
8								1.00	0.00
9								1.00	0.00
10								1.00	0.00

Risk cost and vulnerability	Cost	Safety	Mobility	Environment
Struc weight	20,000	75,000	134,400	134,400
Criteria weight	1.00	1.00	1.00	1.00
Risk cost ($k)	102.79	3.63	79.00	10.90
Vulnerability	5.1394	0.0483	0.5878	0.0811

Risk analysis results	
Maximum unit risk cost:	100.00
Vulnerability index:	0.0586
Utility:	**94.14**
Social cost of risk ($000):	**196.31**

Figure 5.15 - Project summary worksheet from upcoming AASHTO risk assessment guide.

5.4.7 Life-Cycle Cost Analysis

The key tradeoff in planning of preservation work is the ability to spend a small amount of money in the near future in order to postpone a much larger expenditure, such as bridge replacement. Economists use a metric known as a discount rate to measure the benefit of postponing costs. If a 2% discount rate is used, for example, then the benefit of postponing a $1 million expenditure for one year is 2% of that amount, or $20,000. It would be worth spending up to $20,000 today in order to postpone that $1 million expenditure for a year.

The concept of discount rate is essentially the same as the interest rate that many consumers pay on mortgage loans. By paying 4% interest each year on the outstanding balance, the homeowner is able to postpone having to pay off the much larger principal amount, instead paying just a small fraction of it each month.

If a large expense can be postponed long enough, it might become nearly insignificant in near-term decision making, because the delay in having to pay the expense is valuable in itself. In life-cycle cost analysis, if a cost can be delayed its magnitude is reduced, or discounted, according to the discount rate and the length of the delay. The present value of a future cost, known as the discount factor (*DF*), can be computed from the discount rate *d* and the number of years of delay *t* using

$$DF = \left(\frac{1}{1+d}\right)^t$$

If the discount rate is 2%, delaying an expenditure of $1 million for 10 years reduces the value of that expenditure to $820,348 and delaying it for 100 years reduces it to $138,033.

NCHRP Report 483 (Hawk 2003) has a thorough discussion of how discount rates are determined. In short, they are determined by agency policy, which should be consistent across all types of assets and all investments of similar lifespan. A common source of guidance is The White House Office of Management and Budget (OMB) Circular A-94[1]. Typically inflation is omitted from life-cycle cost analyses because this practice simplifies the computations. A riskless and inflationless cost of capital for long-lived investments may use 30-year US Treasury bonds for guidance, with a 2017 real interest rate of 0.7%[2]. Transportation agencies usually specify higher discount rates than this, in the 2-3 percent range, because of uncertainties in long-term future travel demand and infrastructure requirements.

A life-cycle cost model follows an asset through its life, simulating deterioration and appropriate actions to correct or limit deterioration, using a set of decision rules to select these

[1] http://www.whitehouse.gov/omb/circulars_a094/
[2] http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c/

hypothetical future actions. Future costs are discounted to reflect the value of delaying expenditures as long as possible.

In a typical program-level analysis, budget constraints are applied year by year. The highest priority projects are identified for the first year's budget, and then the remaining projects are delayed for consideration in the following year. If a project is delayed, there will be an increased risk of service disruption, and preservation work may become infeasible due to further deterioration. This might shorten the asset's lifespan. Therefore, it is necessary to consider all of the forecast costs over the entire life of the asset in order to make a fair comparison between alternatives.

The total length of a life-cycle cost analysis must be long enough to make further costs negligible, after discounting. This depends on the lifespan of the bridge and the discount rate. Transportation asset management plans using discount rates of 2-3 percent often extend their life-cycle cost analyses to 200 years, especially if long-life assets, such as concrete culverts or big bridges, are included.

The main components of a life-cycle cost analysis are the same as those shown in Figure 5.12 above, except that the process extends over a much longer time horizon and there is no resource constraint or prioritization. The analysis starts with current asset condition, and forecasts events into the future. The first agency action in the sequence is the candidate project under evaluation. Remaining actions, further in the future, are projected. The year in which the work is under consideration is the "program year." The sequence of steps is as follows:

0. Start with the first year in which work is to be considered. This is the first "analysis year".
1. Forecast condition for the start of the analysis year, based on normal deterioration rates.
2. Estimate normal maintenance costs ($) and the likelihood (probability, %) and consequence ($) of adverse events for the analysis year. These methods are discussed with risk analysis in the preceding section.
3. If the analysis year is also the program year:
    a. then estimate the initial cost of the candidate project and forecast the condition immediately following completion of the project;

b. otherwise evaluate a set of decision rules based on forecast condition, to determine whether any preservation actions are warranted. If so, estimate the initial cost of the warranted project and forecast the condition immediately following completion of the project. If not, carry forward the condition forecast from Step 1, and do not add any additional project cost.

4. Compute life-cycle social cost as follows:
   c. Add maintenance cost and project cost (if any) to the product of likelihood × consequence of service disruption from the risk analysis.
   d. Multiply the result by the discount factor.
   e. Add the result to the accumulated life-cycle social cost.

5. Return to step 1 for the next analysis year. Continue the year-by-year simulation until the end of the analysis period.

The result of the computation is life-cycle social cost, which is the sum of life cycle agency cost and life cycle user cost. Many of the above computations have probabilistic inputs (such as the deterioration model) and therefore have economic results which are a statistical expected value computed over the range of possible inputs.

While some of these estimates are highly uncertain, the important thing is to use the best-available methods possible under the current state of understanding and data availability, and to use these methods consistently. No one expects forecasts made 200 years in advance to be accurate. All that is expected is a reasonable, defensible, and consistent basis for setting priorities among competing actions.

5.5 Project Level Analysis Tools

In Chapter 4, titled: "Big Bridge Inspection Methodology Using Element Level Inspection Data", which presents the findings from Task 5, advanced non-destruction evaluation (NDE) methods and remote sensing techniques were reviewed to indicate how each technology could significantly reduce manual inspection times and improve safety of bridge inspectors. Examples of four advancing NDE methods that are becoming more practical for deployment, 3D Optical Remote Sensing, Thermography, Light Detection and Ranging (LiDAR), and At-speed Ground-Penetrating Radar (GPR), were analyzed to determine how each technology could be applied to big bridge inspections. These technologies were selected as the Task 5 and 6 focus in part because they have become more commonly deployed in recent years via unmanned aerial systems (UAS or "drones") and via vehicles moving at highway minimum speeds (approximately 45 mph). They are also NDE technologies that have the capability to help meet big bridge inspection needs. Ultimately, each individual technology was determined to be best suited for:

- 3D Optical Remote Sensing: prompt, up-close inspections, involving the use of photogrammetry to build 3D models of bridge elements and to take high-resolution photos of difficult to access bridge areas;
- Thermography: inspection of concrete superstructure / substructure to find unsound and delaminated concrete, and/or inspection of steel superstructure / substructure elements obscured by protective coatings and to detect hidden areas of corrosion;
- LiDAR: detailed measurements for load ratings or inventory data collection and to monitor deflections;
- At-speed GPR: quick, repeatable concrete bridge deck monitoring to detect unsound and delaminated concrete.

Additionally, as part of Chapter 4, 16 proposed new MBEI elements were identified as being applicable to big bridge inspections. Under this task, these proposed elements have had specific performance rankings assigned to their defects, based on how well the four advancing NDE methods are able to identify the individual defects. The results from the rating table provide big bridge managers and inspectors input into which NDE technologies are best applicable to specific defects and elements.

Methodology

In Vaghefi et al. 2011, performance rankings of different commercial remote sensing technologies were developed to assess their capability to measure different "challenges" (distress types) as part of a larger USDOT-funded project on "Bridge Condition Assessment using Remote Sensors" (led by Dr. Ahlborn, http://mtri.org/bridgecondition/). Twelve different remote sensing NDE technologies were ranked to evaluate how well they could be used to sense these distresses at needed resolutions as noted in element level condition assessments (Table 5.4). This task builds from these efforts by focusing on four technologies that have been advancing rapidly since the original Vaghefi et al. (2011) paper as describe above. The methodology used to evaluate the remote sensing tools herein is being largely repeated, but focuses on application for new elements recommended in Chapter 4.

Table 5.4 - The Vaghefi et al. 2011 Table Showing Performance Rankings of Commercial Remote Sensing Technologies for Various Bridge Challenges or Defects.

Location	Challenges	Indicator	GPR	Spectra	3D Photo-grammetry	EO Airborne/ Satellite Imagery	Optical Inter-ferometry	LiDAR	Thermal IR	Acoustics	DIC	Radar (Backscatter/ Speckle)	InSAR	Streetview-Style Photography
			Rating Based, in Part, on Theoretical Sensitivity for Measurement Technologies											
Deck Surface	Expansion Joint	Torn/Missing Seal	0	8	14	12	11	13	11	0	0	9	0	13
		Armored Plated Damage	0	0	14	12	11	13	11	0	0	0	0	13
		Cracks within 2 Feet	0	8	14	0	12	12	11	0	0	9	0	13
		Spalls within 2 Feet	0	8	14	12	12	12	11	0	0	9	0	13
		Chemical Leaching on Bottom	0	11	0	0	0	0	0	0	0	0	0	0
	Map Cracking	Surface Cracks	0	8	14	12	12	12	11	8	0	9	0	13
	Scaling	Depression in Surface	0	8	14	12	12	12	11	0	0	9	0	13
	Spalling	Depression with Parallel Fracture	0	8	14	12	12	12	11	0	0	9	0	13
Deck Subsurface	Expansion Joint	Material in Joint	0	0	0	0	11	0	0	0	0	0	0	0
	Delamination	Moisture in Cracks	11	0	0	0	0	0	11	0	0	0	0	0
		Internal Horizontal Crack	0	0	0	0	0	0	11	8	0	0	0	0
		Hollow Sound	0	0	0	0	0	0	0	8	0	0	0	0
		Fracture Planes / Open Spaces	12	0	0	0	0	0	0	8	0	12	0	0
	Scaling	Depression in Surface	12	0	0	0	0	0	11	0	0	0	0	0
	Spalling	Depression with Parallel Fracture	12	0	0	0	0	0	11	0	0	0	0	0
	Corrosion	Corrosion Rate (Resistivity)	0	0	0	0	0	0	0	0	0	0	0	0
		Change in Cross-Sectional Area	13	0	0	0	0	0	0	8	0	13	0	0
	Choride Ingress	Choride Content through the Depth	12	0	0	0	0	0	0	0	0	12	0	0
Girder Surface	Steel Structural Cracking	Surface Cracks	0	8	11	0	12	0	11	0	0	0	0	0
	Concr. Structural Cracking	Surface Cracks	0	8	11	0	12	0	11	8	0	0	0	0
	Steel Section Loss	Change in Cross-Sectional Area	0	0	11	12	0	13	11	0	0	11	0	0
	Paint	Paint Condition	0	9	0	0	0	0	11	0	0	0	0	0
	Concrete Section Loss	Change in Cross-Sectional Area	0	0	11	12	0	13	11	7	0	11	0	0
Girder Subsurface	Concr. Structural Cracking	Internal Cracks (e.g. Box Beam)	0	0	0	0	0	0	11	8	0	0	0	0
	Concrete Section Loss	Change in Cross-Sectional Area	0	0	0	0	0	0	0	7	0	11	0	0
	Prestress Strand Breakage	Change in Cross-Sectional Area	9	0	0	0	0	0	0	8	0	9	0	0
	Corrosion	Corrosion Rate (Resistivity)	0	0	0	0	0	0	0	0	0	0	0	0
		Change in Cross-Sectional Area	8	0	0	0	0	0	0	8	0	13	0	0
	Choride Ingress	Choride Content through the Depth	10	0	0	0	0	0	0	0	0	11	0	0
Global Metrics	Bridge Length	Change in Bridge Length	0	0	15	13	0	0	0	0	9	0	12	0
	Bridge Settlement	Vertical Movement of Bridge	0	0	12	0	0	12	0	0	9	0	12	0
	Bridge Movement	Transverse Directions	0	0	12	0	0	12	0	0	9	0	12	0
	Surface Roughness	Surface Roughness	0	9	14	13	12	12	0	0	0	11	13	13
	Vibration	Vibration	0	0	0	0	12	0	0	0	10	12	12	0

For each of the proposed new MBEI elements for big bridges, the types of defects and respective (color-coded) condition state indicators were placed into the performance rating table (Figure 5.16). Using the rating table developed by Vaghefi et al. (2011), each of the NDE technologies were rated on how well each defect could be detected (Table 5.5).

The ranking system is based on eight categories, with each category having rankings of 0 (lowest rating), 1, or 2 (highest rating), meaning that the highest rating value that can be obtained per defect is 16, as was done in the Vaghefi paper. However, if a technology was not applicable or able to sense the defined defect, it is automatically assigned a null ("-") value. The rankings were based on what is known about the defect, NDE technology, and scientific literature.

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	3-D Optical	Thermography	LiDAR	At-speed GPR
Concrete Pier Tower (237)		Delamination/Spall/Patched Area	None; Delaminated. Spall 1" or less deep or 6" or less in diameter. Patched area that is sound; Spall greater than 1"deep or greater than 6" in diameter. Patched area that is unsound or showing distress. Does not warrant structural review; Beyond CS 3	14	12	11	-
		Exposed Rebar	None; Present without measureable section loss; Present with measureable section loss but does not warrant structural review; Beyond CS 3	14	12	11	-
		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyond CS 3	14	-	-	-
		Cracking (RC and Other)	Insignificant cracks or moderate-width cracks that have been sealed; Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking; Wide cracks or heavy pattern (map) cracking; Beyond CS 3	12	-	11	-
		Abrasion/Wear	No abrasion or wearing; Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete; Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear; Beyond CS 3	14	11	12	-
		Settlement	None; Exists within tolerable limits or arrested with no observed structural distress; Exceeds tolerable limits but does not warrant structural review; Beyond CS 3	13	-	12	-
		Scour	None; Exists within tolerable limits or has been arrested with effective countermeasures; Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review; Beyond CS 3	-	-	-	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure 5.16 - Table for Proposed MBI Element 237 – Concrete Pier Tower.

Table 5.5 - Ranking Categories (from Vaghefi et al. 2011).

A	Is requirement met?	2	Resolution is specifically within the current capabilities of the technology Full range of measurements are met or better Other requirements directly measured
		1	Lower limit of resolution/requirements is not within capabilities, but upper limit is Technology can measure somewhere between the range or within 25 % of upper limit Some requirements are only indirectly measured
		0	Upper limit of resolution not met within 25 % Current capabilities do not allow direct measurement at any necessary resolution
		N/A	Not practical or appropriate for the given technology, or not investigated in this study.
B	Availability of instrument	2	Technology is currently commercially available and used for similar application(s) Technologies components are immediately available for use as manufacturer intends (e.g. no commercial DIC or 3D Photogrammetry platform, but digital cameras are widely available for the same purpose)
		1	Technology is available only for research purposes; Components are available commercially but they may have not been applied to this purpose and are not specifically designed for the application
		0	A complete system has not been demonstrated in research The technology is only theoretically available and would have to be built from very fundamental components
C	Cost of measurement	2	Low capital cost Moderate capital cost with reuse (low operational cost)
		1	Moderate capital cost Low capital cost with high operational cost (e.g. dedicated equipment that can't quickly be reused)
		0	High capital cost Moderate capital cost with high operational cost
D	Pre-collection preparation	2	Absolutely no preparation of the structure No/minimal calibration of the instrument are required
		1	The structure requires moderate preparation The instrument requires moderate calibration
		0	Both the structure and/or instrument require extensive preparation
E	Complexity of analysis	2	Analysis consists of either pattern recognition by user (Bridge inspector can easily understand the output) Automated "turn-key" processing by a computer (Software commercially available)
		1	Analysis consists of detailed measurements made by a human user from raw data Processing by an algorithm that must be tuned or trained for each dataset More than one algorithm is needed
		0	Analysis consists of very complex calculations and measurements made by a human user from raw data Processing by an algorithm that either i) requires extensive human supervision ii) a large amount of time per bridge (more than a day) iii) requires multiple algorithms chained together WITH human-in-the-loop I/O
F	Ease of data collection	2	Instrument is used in a straightforward manner as intended by manufacturer AND requires little more from the operator than supervision (i.e. "push the start button and start collecting") Easily accessible structure components
		1	Instrument is used in a custom fashion (may have been modified for this purpose) Requires input from operator Requires real-time verification (QA/QC) of results Environmentally dependent Considerable time window for data collection Physical challenges
		0	Instrument is used in a custom fashion AND requires EITHER input from the operator OR real-time verification (QA/QC) of results Hidden components Team needed
G	Stand-off distance rating	2	No part of the platform is touching the earth
		1	Part of the platform is on the earth or bridge (i.e. on a ground-based vehicle or some other grounded mount) AND the instrument is NOT in contact with the structure
		0	Instrument is in direct contact with structure; technique is not traditional remote sensing
H	Traffic Disruption	2	Absolutely no lane closure(s)
		1	Minor/ short term lane closure with limited effect on traffic
		0	Major/ long term lane closure with limited effect on traffic

Results

Performance ranking results of the four advancing NDE technologies for the 16 proposed new elements can be seen in Figure B-1 to Figure B-16 (See Appendix B). In reviewing the ranking table, the following conclusions can be made.

3D Optical Remote Sensing is a very applicable NDE technology that can assist bridge managers and inspectors in evaluating elements of big bridges. At the completion of the rankings, 3D Optical Remote Sensing was applicable to a large majority of defects with high rankings (13-16, highlighted in green). However, there were some defects that were ranked with medium values (10-12, yellow); cracking, distortion, misalignment, mortar breakdown, split/spall, and check/shake. These defects were ranked lower than the other applicable defects due to the current state of research and capabilities of using 3D Optical Remote Sensing for these purposes. For example, using 3D data to detect cracks is still an ongoing area of research. Depending on the quantity of and extent of these defects, 3D Optical Remote Sensing is an applicable NDE technology that can assist in the identification and quantification of such features. The only defect that 3D Optical Remote Sensing was determined as not being applicable (a null "-" value) was scour, due to the fact that scour identification and quantification typically involve the need for underwater capable sensors such as sonar. Recent research has shown that 3D Optical Remote Sensing can be deployed on a practical basis from drone and vehicle platforms for high resolution transportation infrastructure assessment (Dobson et al. 2014a, Dobson et al. 2014b, Lattanzi and Miller 2014, Brooks et al. 2015, Ahlborn et al. 2016, Chen et al. 2016, Harris et al. 2016).

Although not as applicable as 3D Optical Remote Sensing, infrared thermography can still be applied to a number of elements and defects. Performance rankings were not as strong; the highest rankings were in the medium range (10-12, yellow). The absence of any high rankings (13-16, green) was due to the generally higher costs of thermal sensors and the complexity of analysis. Multiple defects were not applicable to thermography sensing and were assigned a null (-) value, including efflorescense/rust staining, cracking, settlement, scour, mortar breakdown, split/spall, distortion, wear, movement, misalignment, debris impact, and check/shake. One point of interest is that many of the "null" ranked defects require optical sensing and cannot be solely detected using thermography. Therefore, to potentially use thermography for any of these null valued defects, this technology should be used in combination with 3D Optical Remote Sensing technologies. Deploying thermal IR sensors from drones to detect bridge defects has been advancing (Brooks et al. 2015) and has become commercially available from vehicles moving at highway speeds, such as the BridgeGuard LLC system from GS Infrastructure (http://gsinfrastructure.com/inspection/bridgeguard) and the combined thermal IR / GPR / video system from Infrasense (http://www.infrasense.com/bridge-deck-scanning/).

Similar to thermography, LiDAR technology can be applied to a majority of elements and defects, but is still not as applicable as 3D Optical Remote Sensing. This is in part because the highest resolutions of LiDAR are normally available only from fixed (non-mobile) terrestrial platforms. Mobile (vehicle-based) provides a more rapid but generally lower resolution platform for collecting 3D point clouds, and has become a standard part of many firms assessing infrastructure. UAV-based LiDAR provides a flexible platform for deployment that can reach otherwise difficult to sense areas, but sensors are generally lower resolution than fixed or mobile-based LiDAR units. Performance rankings for LiDAR, at their highest, were in the medium range (10-12, yellow), with an absence of high rankings (13-16, green) mainly due to the cost of LiDAR systems, the complexity of analysis required to process data, and more flexible UAV-based sensing being lower resolution. Two defects were not rated as being applicable to LiDAR technology, including efflorescence/rust staining and scour. In order to increase the applicability of LiDAR technology, it should be used in combination with 3D Optical Remote Sensing and/or thermography.

At-Speed GPR is not an applicable NDE technology for the new proposed big bridge elements reviewed in Task 5 (Chapter 4). Although the NDE technology has been demonstrated to be applicable to detecting delaminations within a bridge deck (Ahlborn et al. 2013), including at highway speeds (Ahlborn et al., 2016), based on current limitations, assessment of elements that are not on a bridge deck cannot be assessed using at-speed mobile GPR. For that reason, a ranking of “not applicable” was assigned to all of the defects for each proposed MBEI elements.

5.5.1 Cost Estimation

During a previous MDOT research project, Michigan Tech estimated the collection and processing times for future analyses of large-deck bridges using 3D Optical Remote Sensing (Ahlborn et al. 2016). A representative scenario was evaluated using a large deck bridge with six lanes and a deck length of 1,500 ft (Table 5.6). Labor costs were a straight hourly rate suggested by MDOT. Most of the estimated processing time is computer-based (currently no costs are charged within MDOT) and included using 3D image processing computer software such as Agisoft PhotoScan, but also included personnel time. The total amount of time needed for computer processing was 93 hours, and the total time needed for an analyst was about 20 hours using desktop computing power widely available at the time. It is therefore estimated that the total processing time for one analyst on a single computer to complete a one bridge's worth of data was approximately five days. However, another potential data / imagery processing option is cloud-based processing, which can take significantly less time. This is the direction that commercial close-range photogrammetry software (including Agisoft Photoscan, Pix4D, and others) is going for more rapid production of processed results. The example indicates the total cost of data collection, processing and reporting time, and can be used to compare to costs of traditional methods that include rolling lane closures and large inspection teams to be efficient on large deck inspections.

Table 5.6 - Example of Data Collection, Processing, and Reporting Time for Creating a 3D Surface Usable for Defect Detection and Rating for a 1500-ft Long Bridge Deck with Six Lanes.

Task	Personnel Time (hr)	Computer Time (hr)	Cost ($60/hr)	Comments
Equipment Setup	0.25		$30	Two inspectors
Data Collection	1		$120	Two inspectors
Data Processing	5.25	93	$315	
Data Analysis	8		$480	
Quality Analysis	4		$240	
Reporting Results	2		$120	
Total	20.5	93	$1,350	

5.5.2 Treatment Effectiveness

As discussed in Chapter 4, 3D inspection software (such as the 3D B^RIDG^E Application) allow bridge inspectors to build a full scale model of the bridge that can be used to record and display the spatial locations of defects recorded in the field (through manual or NDE methods) as well as detailed notes and information. By storing this type of information within the application, bridge inspectors are able to review previous inspections and compare individual distress features as well as deterioration over time.

This type of location-specific information can also be used to track and evaluate treatment effectiveness. For example, applying a treatment should lead to a state of good repair where defects are no longer present. 3D inspection and NDE techniques would show the number and/or area of defects had been eliminated or reduced. Treatments depend on the element being preserved or repaired, and include (but are not limited to):

- Repairing spalls on a bridge deck (concrete replacement)
- Applying new paint to steel members / protective coatings

- Crack sealing
- Polymer overlays
- Healer/sealers
- Fatigue crack repair for steel bridges
- Joint sealing
- Cable replacement, cable repair (sheathing, strand replacement)

Tracking the presence – and then documenting absence or reduction after treatment – would enable the calculation of the amount of defect eliminated per unit of repair cost. To capture this potential, recording the locations and severity of defects before and after treatment would be needed. Tracking repaired areas, including those which were repaired with alternative materials, would help understand how rapidly defects may be returning at the repaired locations. While there are no known case studies documenting these new technologies in measurement of treatment effectiveness based on location-specific data, this is a next logical step to assess before broad implementation.

5.5.3 Life Cycle Cost Analysis

By tracking location and severity of defects (enumerated damages) over time, enough data could potentially be collected to tie the trend in condition to location-specific treatments. This would enable greater understanding of how different repair and preservation efforts contributed to maintaining a bridge in higher overall condition for parts of the bridge, such as specific elements. Bridge inspectors and managers will need to develop a framework that can be used to justify inspection method (NDE or manual), with the goal of maximizing the minimum internal rate of return for different options, including comparisons between the current methods and new methods. The following procedure was developed for a state-transportation research project:

1. Develop a meaningful system boundary for each of the processes.
2. Identify a functional unit for comparing processes.
3. Construct a list of all the hardware and platforms that are necessary to deliver the NDE technology and develop meaningful estimate of cost of initial and long-term costs.
4. For each of the methods, identify the monetary value of the benefits delivered.
5. Identify a time horizon during which processes delivering similar outcomes go through a cycle of change and replacement.
6. Construct a diagram that identifies the costs (as described in item 3 above) and benefits (as described in item 4 above).

7. The minimum internal rate of return for each process can be compared and decisions made accordingly to meet the DOT requirements.

Analyses such as this will allow for decisions to be made to maximize the internal rate of return. These include choice of specific hardware/sensors and design of process for the most optimal rate of return given the functionality, goal, and budget constraints. The development of such a decision-support system will be crucial to the assessment and choice of alternative inspection methodologies.

5.6 CHAPTER SUMMARY

The information compiled in this Chapter under Task 6 can provide useful insight on the use of analysis methods to improve the practice of managing big bridges.

5.6.1 Findings

The analysis of big bridges is conducted for supporting management in making decisions about policy, resource allocation, and project development. Analytical tools help to identify needed work, to estimate when the work might be needed, and to forecast the likely outcomes of current decisions. Some key conclusions about the analytical needs of big bridges are summarized as follows:

- Part of the effective communication of bridge preservation and risk mitigation benefits involves expressing decision outcomes in terms of published and widely agreed agency objectives, usually stated in TAM Plans, business plans, enabling legislation, mission statements, or strategic plans.
- Effective participation in the agency's resource allocation functions requires translating the engineering concerns of bridge management into the economic and planning concerns of other stakeholders.
- Forecasting of future condition, performance, and costs is an essential element of bridge management analysis just as it is for all asset classes.
- Engineering problem solving is the first step in executing a preservation strategy. Successful implementation also requires actions to ensure that sufficient resources are allocated to execute the optimal strategy.
- While big bridges have unique characteristics affecting how they are analyzed and funded, they still must participate in the agency's broader management processes.

- Funding, traffic management, market conditions, and other considerations often make it desirable to develop projects affecting entire corridors, where all asset classes may be included and a big bridge is just one component within that corridor. This is another reason why project justification often relies on broad agency objectives and is quantified in economic concepts that are not specific to bridges.

Each agency has multiple planning processes affecting big bridges, including policy making, revenue enhancement, development and application of action criteria, resource allocation, establishment and tracking of performance targets, priority setting, and project scoping. The analytical process serves each business process using different reports at different times, but a basic requirement of best practice asset management is that all reports rely on a consistent set of data and assumptions.

5.6.2 Recommendations

Bridge management systems require a long list of functions essential to asset management. Full implementation, including for big bridges, is best practice and is also mandatory under rules applicable to most big bridge owners. The following recommendations address the ways in which bridge management systems and related processes might be enhanced or supplemented in order to satisfy the specific needs of big bridges:

- Because of their utilization and role in the network, big bridges are usually subject to the agency's highest standards for levels of service and condition. The unique structural configuration of each big bridge leads to unique treatment alternatives and life-cycle costs. As a result, it may be useful to establish a unique set of preservation action warrant criteria for each big bridge. The level of detail of a preservation manual may depend on bridge inspector certification requirements and the discretion granted to bridge inspectors to recommend preservation treatments.
- Many agencies have adopted a "preservation first" philosophy for resource allocation. Such a philosophy is also applicable to big bridges. In this case it is recommended that agencies maintain for each big bridge an optimal preservation plan to minimize life-cycle costs subject to level-of-service requirements. The plan would describe the full set of preservation needs and their resource requirements for each budgeting period within the program horizon, to help ensure that the correct amount of resources is allocated.

- The bridge health index, rather than Good-Fair-Poor, is recommended as the condition metric to be used for expressing and tracking condition trends and targets for big bridges. This cannot replace the federally-mandated performance measures and is not generally applicable for treatment selection, but is useful for stakeholder communication because it is more precise than NBI ratings, simpler than a condition state level of presentation, but still derived from element level data.
- Deterioration, traffic growth, and risk are all factors having significant effects on the generation of new big bridge capital needs. It is recommended that each big bridge owner develop, maintain, and use the best available predictive modeling tools available at any given time. In some cases, these models might be based on judgment, but an effort should be made over time to ensure that predictive models are grounded in measured data and validated against measured outcomes. In some cases, industry-sponsored research may be the most cost-effective way to develop such models, while in other cases each agency or each big bridge may need its own unique model.
- While many agencies have developed deterioration models for structural elements, none have yet developed such models for defects as defined in the 2013 AASHTO Manual on Bridge Element Inspection. There may be value in having such models to forecast future preservation and risk mitigation needs more precisely. It is recommended that individual agencies or industry research sponsors consider whether such models would be cost-effective, perform the analysis needed to ascertain cost effectiveness, and follow up with full development as appropriate. In order to conduct such research, a sufficient body of defect inspection history would need to be aggregated by one or more agencies.
- It is recommended that agencies employ the subdivided units approach to element and defect inspection of big bridges in order to develop capital needs at the level of detail they require for asset management. It is recommended that bridge management system developers increase the level of support they offer for agencies choosing to inspect their structures using this method, especially for agencies wishing to inspect span-by-span and those wishing to inspect girder and deck ends, or exterior girders and parapets, separately from the remainder of each element. If the industry is not able to provide this support, it is recommended that big bridge owners supplement their inventories with this information to the extent that it improves their process of accurately forecasting preservation needs.

- It is recommended that agencies consider the cost effectiveness of the enumerated damages approach and conduct such research as may be necessary to determine its cost effectiveness and appropriate application. Agencies wishing to lead the implementation of this approach may need to develop tools that later are enhanced for broader industry use.
- All bridge element deterioration models have uncertainty, with significant leading tails of a probability distribution deteriorating more quickly than average. It is therefore recommended that big bridge owners employ probabilistic deterioration models, take care to ensure that their models match the actual behavior of their structures, and use this information to accurately plan for premature deterioration of parts of the inventory.
- Because the number of big bridges owned by each agency is small, it is recommended that an industry-level research effort be mounted that would enable agencies to pool their data to estimate element deterioration models that fit the unique environmental and operating characteristics of big bridges.
- For agencies requiring estimates of preservation needs beyond ten years, it is recommended that needs be expressed in time increments longer than one year, perhaps in periods of five or ten years, because of the imprecise nature of bridge deterioration models as well as uncertainties in long-range financial forecasts.
- It is recommended that the industry proceed with research on the effectiveness of preservation actions in improving the condition states of bridge elements, for all bridges big and small.

Big bridges are sufficiently different from average-size bridges in their analytical needs and level of detail, that agencies may wish to consider developing separate bridge management models for them. These could each be a spreadsheet model that addresses the program periods, subdivided units, deterioration and risk behavior, action criteria, unit costs, work zone plans, and other attributes specific to one Big Bridge. It would feed work candidates and projects into the agency's enterprise bridge management system and would serve as the documentation of the bridge's preservation plan.

CHAPTER 6 - CONCLUSIONS

6.1 Conclusions from This Study

This chapter provides summaries of the major findings of the research project organized by the chapter headings. Following the chapter summaries, implementation plans are presented for both short-term and long-term implementation.

The primary goal of the research project was to develop a methodology for the collection and enhanced analysis of bridge element level data collected for big bridges. As a result, a number of recommendations were made, including:

- Recommended additions and changes to the list of currently recognized AASHTO National Bridge Elements and Bridge Management Elements contained in the *AASHTO Manual for Bridge Element Inspection*, see Chapter 4 Section 4.2 and Appendix A
- Guidelines for the breakdown of big bridges into smaller units, see Chapter 4 Section 4.3
- Methodology for the inspection and collection of element level data for big bridges, see Chapter 4 Section 4.4
- A framework for modifications to the AASHTOWare BrM software, see Section 6.2.4.
- Recommended approaches for asset management, including adapting and supplementing existing tools as a part of network level decision making
- Recommended a migration path to location aware recording of damage instances while maintaining long-term cost analysis
- Recommendations for future research, see Chapter 6 Section 6.2

The project was organized in five chapters. Conclusions derived from each chapter are presented next.

Chapter 1 – Recent Research Review

This chapter presents a brief history of bridge inspections in the United States, the development of bridge management systems and bridge elements. A few fundamental concepts of probability modelling applied to bridge element data are also discussed. A review of several types of structure health monitoring systems are also presented with several notable examples.

Review findings indicate that big bridges are currently subjected to the same inspection and reporting criteria as non-complex bridges. The review also discovered that, because each state agency is responsible for defining and setting inspection standards for complex bridges, there is very little consistency between agencies, and there is a need for nation-wide standardization. Current research in the U.S. regarding the consideration of big bridges as a series of interactive networks is limited. European and Asian efforts can provide lessons learned and guidance, particularly towards SHM in long-span cable structures. The review concluded with an investigation of current inspection techniques including a description of many common NDE methods followed by brief descriptions of ongoing research into 3D bridge inspection devices.

Chapter 2 – Review of Big Bridge Inspection and Management Reports and Owner Survey

Findings from this review effort indicate that although AASHTO's Manual for Bridge Element Inspection (MBEI) is an indispensable tool in the risk-based assessment required to effectively manage the multitude of structures comprising our transportation network, it is not possible to express all the unique and complicated defects through the current condition rating based assessment. With the current element quantity calculation definitions in AASHTO's MBEI, the typical details used to describe defects in inspection reports are often not sufficient to immediately convert to defect quantities. Furthermore, the element quantities are often not conducive to the inspection methods which are used, lending much importance to the proper preparation and developing efficient methods required for the initial inspections when defect quantities are to be established. It is important that element level assessment of unique and complex structures be understood by the agencies, owners, and inspectors involved so that the proper quantification and condition assessment of the complex elements is performed in a standardized manner. This would ensure that the defect data properly represents the condition of the structures for their risk-based assessment, whether to compare the increasing number of complex structures, or for the assessment of the multitudes of complex elements for a single bridge; such as the hundreds of stay cables required for some cable stayed bridge designs.

Results from the nationwide survey, which included responses from 26 participants who own or manage big bridges, indicated that the vast majority are using electronic data or software in management of their inventory. The most common uses of management software or data indicated was for relatively simple inspection data management and repair tracking or prioritization. State Departments of Transportation are generally using analysis methods such as life cycle cost or risk analysis for big bridges in the same way ant to the same extent as for all other bridges. Few toll/bridge authorities are currently using these analytical methods for their big bridges. Approximately half of the respondents, believe that the current list of NBEs and BMEs in the MBEI do not sufficiently represent their bridges or did not have enough information to assess. Numerous bridge elements were named which are not currently represented in the MBEI or which had been created as ADEs. This feedback, combined with the review of numerous big bridge inspection reports in Task 2, was considered in the proposal of new elements and modifications to the MBEI which was part of Task 5 and are included in Chapter 4 of this report.

Chapter 3 – Review of Big Bridge Management Methodology

Chapter 3 provided a review of current big bridge management methodologies including the evaluation of analytical tools and processes and was based on the materials gathered in the previous chapters and a series of interviews with appropriate bridge management personnel. The review yielded the following observations:

The following typical methodologies of bridge owners were highlighted:

- Development of ADEs to more accurately represent their bridges in BMS and to facilitate inspections.
- Some state DOTs inspect all bridges span-by-span; however many more divide bridges into separate structure units based on structure type or configuration to organize inspection records and help define projects.
- Creation of business plans that focused on long-range capital needs estimates, public service goals, physical operations, revenue and customer satisfaction. These plans often overlap TAM plans but often lack analytical content such as condition tracking, life-cycle cost analysis and risk management.
- Capital needs estimates are often based on engineering judgement and bridge-specific history instead of analytical tools for deterioration, risk and life-cycle modelling available in BMS. Using engineering judgement may understate long-range needs because it does not adequately address potential needs which may arise from deterioration and various hazards, whose probability and timing are uncertain.
- Development of Big Bridge capital programs that are separate from all other bridges. Since big bridge yearly preservation needs are large and highly variable, this strategy may help decision makers understand and accept variable annual needs.

- Federally-mandated performance targets are weighted by deck area, giving disproportionate importance to big bridges. This is starting to affect the way in which agencies establish targets and leading some agencies to develop different targets for its big bridges than for other bridges.
- Big bridge owners typically divide projects into smaller phased projects for rehabilitation activities; however, managers of smaller bridges often avoid this strategy due to traffic flow concerns.

The following typical capabilities of bridge management systems were highlighted:

- BMS readily support the addition of new elements and model their deterioration, costs, action effectiveness and life-cycle costs. These models could be customized by owners to more accurately reflect the unique characteristics of big bridge elements.
- BMS have the ability to divide bridges by span or structure unit for inspection management.
- Existing BMS lack the ability to automatically develop limited project scopes for the divided segments. Manual capabilities do exist to divide work candidates by bridge segments and assign them to various projects and timeframes.
- Existing BMS systems lack the flexibility to store variations in bridge characteristics such as multiple structure types and multiple roadways.
- Most BMS lack the ability to record and track individual damaged areas as separate objects or the ability to model the onset and progression of these defects.
- BMS typically focus on the biennial inspection process yet lack the means to record more frequent inspection types (safety, NDE, etc.).
- Risk models such as those contained in AASHTOWare BrM are especially important for big bridges because of the large number of road users exposed to risks at any given time.
- Big bridges are sufficiently different from average-sized bridges in their analytical needs and level of detail that agencies may wish to consider developing separate bridge management models for them.

Chapter 4 – Big Bridge Inspection Methodology Using Element Level Inspection Data

It was concluded that element level inspections, as guided by the MBEI, have generally produced highly consistent inspections by standardizing bridge condition assessment. The collected data provides owners with quantitative results which can be used to prioritize improvement and conservation efforts to maintain their bridges. Current bridge inspection and reporting practices are tedious, often requiring intensive manipulation of disparate inspection notes and measurements stored in various media in an effort to produce an organized, comprehensive inspection report. For big bridges, this problem is compounded due to the complex and greater volume of elements involved. The review of several inspection reports, survey results and interviews revealed that the use of element data was minimal and in most cases only the "Element Quantity and Condition State Summary" was completed for the entire structure to comply with federal requirements for NHS bridges. These summaries are valuable for prioritization of many small and simple bridges but have limited use for big bridges. Significant modifications and enhancements to the data type, its collection and organization, are needed to improve the use of this data for analysis of big bridges.

This chapter also introduced the concepts of 'Subdivided Units' and 'Enumerated Damages' for the organization, collection and analysis of element level data. These two approaches provide options for the enhancement of bridge element data collection and analysis. Both methods provide greater precision, accuracy, reliability and overall understanding of bridge condition to owners and engineers. The 'Subdivided Units' approach involves dividing the bridge into much smaller sub-span units in order to more accurately model the behavior, interactions, exposure and defects affecting that sub-span unit. The 'Enumerated Damages' approach does not modify the overall bridge model but, instead, treats each individual damage, defect or deficiency present on a particular element, as a unique influence on the element. Exact location information is key for the proper application of the 'Enumerated Damages' approach since the elements are not as finely divided as they are in the 'Subdivided Units' approach.

Chapter 5 – Recommend Analytical Tools and Processes for Big Bridge Management

The goal of Chapter 5 was to provide useful insight on the use of analysis methods to improve the management of big bridges and to recommend enhancements to bridge management systems and related processes to satisfy the needs of big bridges. Important factors that help define the analytical needs of big bridges are summarized as follows:

- Most agencies have published objectives meant to guide asset management.
- There is a need for bridge managers to translate engineering needs to economic concerns of stakeholders.

- A basic principle of asset management is the need to justify programming decisions based on desired future outcomes.
- To optimize performance, it is necessary to have a strategy to allocate sufficient resources.
- Big bridges must participate in the agency's broader management processes.
- Increasingly the work on a big bridge is just a part of a broader corridor project.

The following recommendations address the ways in which bridge management systems and related processes might be enhanced or supplemented in order to satisfy the specific needs of Big Bridges:

- Big bridges are often held to higher standards. Each bridge may require a unique set of action warrants to trigger work.
- Maintain a 10-year (or longer) preservation plan to minimize long term cost, provide for uncertainty, and ensure sufficient funding.
- Use a health index for tracking element or bridge condition trends and targets on individual bridges, or for comparing conditions on two or more individual bridges, for applications where the required level of detail is intermediate between element lists and National Bridge Inventory condition ratings.
- Maintain the best available forecasting models for condition and performance. Use historical data to keep them up-to-date. Work cooperatively with other states to develop and improve models specific to big bridges.
- Develop improved tools to support inspection and analysis of element and defect data using subdivided units.
- Ensure that 10-year estimates of needs explicitly allow for premature deterioration of parts of the inventory due to inherent uncertainty.
- For needs estimates longer than 10 years, consider 5-10 year time increments to help mitigate uncertainties in long-range financial forecasts.

Big bridges are sufficiently different from average-size bridges in their analytical needs and level of detail that agencies may wish to consider developing separate bridge management models for them.

Throughout the course of this project, the need for further research into topics relating to this project were realized. Some of these topics may be best investigated by individual bridge owners or agencies while others may be better suited to the combined efforts of many research partners.

- Research sponsors should consider the value in developing deterioration models for defects as defined in the MBEI. In order to conduct such research, a sufficient body of defect inspection history would need to be amassed by one or more agencies.
- Agencies should consider the cost effectiveness of the enumerated damages approach to enhance the collection, organization and analysis of element level inspection data, and conduct such research as necessary to determine its cost effectiveness and appropriate application. Agencies wishing to lead the implementation of this approach may need to develop tools that later are enhanced for broader industry use.
- An industry-level research effort could be mounted by big bridge owners to pool their data to estimate element deterioration models that fit the unique environmental and operating characteristics of big bridges.
- Industry should proceed with research on the effectiveness of preservation actions to improve element condition states, but give consideration to the special big bridge needs.
- As part of future software development, or separate research, develop graphic user interface concepts and design specifications for bridge inspection using a large number of subdivided units on each big bridge, and/or for enumerated damages information. This would entail creation of a structural model (possibly from AASHTOWare BrR), providing means to establish the subdivided units, to collect condition data reliably and efficiently at that level of detail, and to report the information in a user-friendly manner.
- Develop algorithms and software, using statistical methods, life cycle cost, and potentially artificial intelligence, to generate optimal big bridge project scopes, sequencing, and cost and benefit estimates, considering inspection data in subdivided units or enumerated damages form, and accounting for work zone traffic requirements, user costs, and potential hazards.

6.2 Implementation Plan

In order to realize the goals of this research, significant updates/alterations to the AASHTOWare BrM™ software and the Manual for Bridge Element Inspection are anticipated. Additional training or modifications to existing training programs for bridge inspectors engaged in the inspection of big bridges may be necessary to facilitate the proposed changes to the element level data collection process and inspection guidelines for big bridges. Owners may also need additional training in the use of updated capabilities of the AASHTOWare BrM™ software. While software revisions are beyond the scope of this research project, the framework to be developed is a logical first step in the planning and implementation of such changes.

Potential barriers to the successful implementation of recommendations resulting from the research exist in the presentation and approval of changes to the AASHTO MBEI and the AASHTOWare BrM™ software by the appropriate AASHTO subcommittee(s). As previously indicated, the product of this research is only the first step in the successful implementation of a usable product for the end user. The implementation of the proposed framework must gain acceptance by various stakeholders including AASHTO, the AASHTOWare BrM™ Task Force and ultimately state DOTs and other bridge-owner agencies. The framework will then serve as a guide for necessary revisions to the BrM software and the National Bridge Elements database. The successful implementation of a usable end product will rely on the effective implementation of these software changes, proper documentation of the revised standards in system, and user manuals and training of the end users and bridge management staff to effectively utilize this new functionality.

6.2.1 Short-Term Implementation Plan for Inspection

The following suggestions and guidelines are actions big bridge owners can implement ***immediately*** to help improve the collection and use of bridge element level inspection data. They are listed in order of impact to overall bridge management.

1. Divide big bridges into subunits at transitions between differing span types/configurations to divide inspection and rehabilitation efforts into projects of smaller scope.
2. Retain element condition state and defect data by span or panel to enable finer analysis of the element data and to pinpoint specific areas of need.

3. Review actual bridge components that are present for each big bridge to determine what information is needed to accurately monitor and/or analyze the bridge. Compare these needs with the currently available NBEs and BMEs. If deficits exist, follow MBEI procedures to create necessary ADEs. If the needed elements coincide with the proposed NBEs and BMEs suggested in this research, consider using the language presented in Appendix A.
4. Apply the 'Enumerated Damages' approach to enhance the collection, organization and analysis of inspection data.
    - Based on the current methods being used by each bridge owner, this may only involve appending their bridge deficiency tables with element and defect types, quantities and condition states. For others, this might be a more involved process of detailing specific defect locations and descriptions, in addition to the element level information.
    - A defect timeline should be created which establishes the discovery date and dates of significant changes.
    - The information should be organized in such a way that it can be sorted, filtered or grouped by location, element, defect type, date, or condition state.
    - The element level data should be organized so that it can easily or automatically be exported to the format required for MBEI reporting requirements.
    - Additionally, the tracking of repair effectiveness including repair date and subsequent deterioration could greatly benefit bridge owner's evaluation of repair success.
    - Analysis using 'Enumerated Damages' would need to take place outside of any available analysis programs through customized spreadsheets set up for each big bridge.
    - Again, many big bridge owners already use custom-built spreadsheets for their analysis and the level of effort needed to modify these spreadsheets would vary on a case-by-case basis.
5. Create bridge-specific inspection manuals for big or complex bridges to document information which inspectors may require. Specific information provided may include:
    - Location orientation and numbering system for all elements of the structure.

- Plan, elevation, and cross sectional drawings of the structure and elements for inspectors to reference during inspection.
- Schedule for inspection of the subunits of the structure and additional elements or appurtenances which are maintained by the bridge owner such as the right-of-way properties, security fencing, light standards or signage on the structure or in the approaches, or separate approach structures.
- Explanation of structural function and intention of unique elements or details on the structure and guidelines for their inspection and condition rating.
- Details of previous unique or typical repairs or retrofits.
- Original calculations or details of exactly how initial element total quantities were calculated for unique or all present elements.
- Guidelines or examples for quantitative defect data collection for unique or complex elements.
- Guidelines or examples of qualitative condition rating or repair prioritization coding using actual photos or representative photos or drawings of the elements comprising the structure.
- Details and locations of available built-in access elements such as doorways, hatches, ladders, maintenance walkways, handlines or travelers, to assist inspectors in accessing the structure.
- Details of additional equipment which is required to access elements such as required working height of bucket trucks or lifts, range of UBIU, or length of ropes required for technical rope access techniques.
- Answers to frequently asked questions.

6. Provide basic inspection training courses to inspectors prior to their inspection of big or complex bridges to ensure results.
    - Review the information in the bridge-specific inspection manual.
    - Ensure that inspectors understand methods for consistent quantification and qualitative assessment of defects data to result in meaningful element data and analysis.
    - Course should ensure understanding of structural functions of unique bridge elements and details.

7. Clearly label members of the structure to ease location noting for inspectors. Ensure that labeling is visible from the typical vantage points for inspection.
    - Floorbeam or panel point labels should be visible from underbridge maintenance walkways or travelers, top of the bridge deck, main cables and top chord and bottom chord of trusses.
    - Each interior cell of steel towers or hollow concrete substructure units should be labeled.
    - Approach substructure units should be labeled at the ground or water level at two opposite faces.

8. Invest in mobile tablets which can be used offline or in conjunction with WiFi hotspots to enable internet access and use of collaborative applications by inspection teams.
9. Invest in UAVs with high-resolution cameras or 3D photogrammetry capabilities to enable prompt, close-up emergency inspections of damaged elements, routine inspections or more frequent monitoring of specific areas of concern on elements which are difficult to access.
10. Invest in thermal sensors which can be used from the ground or mounted to UAVs to more efficiently perform quantitative inspections of concrete substructure and superstructure elements which can also reveal latent areas of unsound and delaminated concrete.
11. Utilize At-speed GPR for concrete bridge deck assessments which can reveal latent areas of unsound and delaminated concrete.

6.2.2 Long-Term Implementation Plan for Inspection

The following long-term implementation goals would require significant alterations to the MBEI, modifications to AASHTOWare BrM™, or would require further research and software development and testing.

6.2.2.1 Manual for Bridge Element Inspection Revisions

- Revise existing MBEI element descriptions as outlined in Section 4.2.4 to more accurately define and quantify existing elements for consistent results.
- Create additional element defect types as outlined in Section 4.2.5 and add to the defect tables for applicable element material types.

- Create additional complex bridge element articles to the MBEI as presented in Appendix A.

6.2.2.2 Inspection Software and Data Management

- Further develop 3D bridge inspection software to assist inspectors in efficiently updating defect and element data. Consideration should be given to the software's ability to interact with analysis tools.
- Continue research into advancing nondestructive testing methods, including at-speed GPR, thermography from UAVs, LiDAR, etc. The possibility of direct integration of data collected by these methods into element level inspection data should be investigated.
- Begin program to pool inspection/element level data with other big bridge owners in an effort to improve deterioration models, cost analysis and repair effectiveness tracking.

6.2.2.3 Summary of AASHTOWare Bridge Management (BrM) Enhancements

The survey and interviews in earlier tasks found that many agencies had already been storing big bridge inventory and inspection data in Pontis, and were planning to continue to do so in AASHTOWare Bridge Management (BrM). In some cases the agencies reported that they use the Structure Unit table to manage separate lists of elements for subdivided parts of their big bridges. Other agencies have been using separate databases, outside the AASHTOWare systems, to store span-by-span or structure unit data. For example, Texas DOT, which inspects all of its bridges span-by-span, uses a database known as PonTex to store and manage this information. Most agencies were omitting big bridge preservation needs from their life cycle cost and investment analysis in Pontis, but would like to include such needs in AASHTOWare Bridge Management.

Chapters 4 and 5 have discussed three potential sets of enhancements that would facilitate big bridge management by helping agencies implement the recommendations. These are discussed in the following sections.

New Elements

Chapter 4 discussed a group of new elements as well as some improvements in the definition and quantification of certain elements to better serve the needs of big bridges. AASHTOWare Bridge Management already provides all of the software capability required to accommodate these elements. Any agency can implement the recommended elements as Agency-Defined Elements, and some have already done so to a limited extent. However, it would be desirable to incorporate the recommended new elements into the software's sample and working databases as delivered, either as sub-elements related to National Bridge Elements, or as Bridge Management Elements.

The main advantage of standardizing these new elements is that it would encourage multiple agencies to implement a common set of element and condition state definitions, making it possible for them to pool their data sets for research purposes. Most of these elements are uncommon, so it would require many inspection cycles for any one agency to amass a statistically significant population for deterioration modeling. On the other hand, if multiple agencies are able to pool their data, the modeling work can be done sooner.

The process for accomplishing this will depend on AASHTO subcommittee discussions which have not yet taken place. It is not known, for example, whether the members will want to issue a new edition or addendum of the Manual on Bridge Element Inspection. Therefore, for the purpose of this report, the recommendation is that the relevant AASHTO committees begin a conversation about how best to implement these enhancements to big bridge inspection methodology.

Subdivided Units

Figure 7 in section 3.2 showed a portion of the BrM logical data model as it might be enhanced to better accommodate the subdivided units approach. The primary changes involve the addition of data items to properly label each element list on a bridge that is divided into more than just main and approach units. In the BrM data model, each structure unit is associated with a separate list of elements, which can have differing element composition, defects, protective systems, and conditions. The added data items would be as follows:

- Span identifier – a field to distinguish among spans or span groups within a bridge, for bridges that are inspected at the span level.
- Panel identifier – this would be used for subdividing a deck or truss into panels smaller than one span length, enabling the inspector to record additional detail and potentially affecting treatment selection and cost estimation.
- End/middle indicator – a structure unit might be defined for girder ends, to distinguish them from another unit designated for the remainder of the girders. Deteriorated

conditions on girder ends might be associated with difficulties maintaining an adequate seal at the joints, potentially affecting agency decisions about the joint treatment. Girder ends might be assigned to a more aggressive environment with faster deterioration rates.

- Interior/exterior indicator – similar to the end/middle indicator, an agency may wish to distinguish interior girders from exterior girders to reflect the more aggressive environment often found on the more exposed members.
- Member identifier – for a maximum level of detail where the agency considers it to be warranted, individual members on a structure might have their conditions recorded separately. This could be done with structure units in the same manner as for the previously-listed items, or might be done by allowing multiple elements of the same element type on the same structure unit, distinguished for the user's benefit using a notation for labeling each member.

Agencies that are using a BridgeWare database integrated with AASHTOWare's Bridge Rating BrR or Bridge Design BrD software systems may be interested in implementing a 3D inspection system using the structural model that already exists in those systems. The integrated BridgeWare database was designed with this specific application in mind, though the authors are not aware of any existing products that take advantage of this for an enhanced inspection process.

All of these data items or linkages are optional because many agencies would choose to use them only for their large or complex structures. A big bridge can have an enormous number of panels and members, so as a practical matter the use of panel and member subdivided units might be limited to areas of special management concern. Agencies would differ on the criteria they employ for decisions on the inspection level of detail. Each agency choosing to use these fields would need to establish a system for identifying the structure units unambiguously.

A software logic decision that the AASHTOWare developers will want to consider is that structure unit identifiers might be used in different ways for different groups of elements. For example, the trusses on a big bridge might be divided into panels while the substructure units are not. This places a burden on the graphic user interface of the inspection software to help inspectors accurately identify the appropriate structure unit for each observation of condition. The system would also need to help the inspector determine that a structure is fully recorded: in other words, that there are no structure units missing from the report.

It was noted earlier that, for a variety of reasons including funding availability and maintenance of traffic flows, agencies often must subdivide a bridge rehabilitation into separate projects that are implemented at different times. There is some limited support for this in AASHTOWare Bridge Management, since the project planner can choose which elements to include in each work candidate. However, in a system where big bridges are subdivided into a potentially large number of structure units, some additional functionality in the graphic user interface would make it easier to graphically associate each structure unit with a work candidate or set of candidates, thus carrying along all of the elements that are a part of the structure unit. In the database this might be represented as a many-to-many relationship between structure units and projects, as an alternative to the existing many-to-many relationship between bridges and projects.

The changes required in AASHTOWare Bridge Management (or in any bridge management system) to support subdivided units in a user-friendly manner, or to link the inspection process to BrR/BrD, can be implemented relatively soon if the software licensees regard it as a priority for them. The developers would need to conduct a software design exercise to generate and evaluate graphic user interface concepts with end user assistance, much as they have done for other enhancements to the system. Examples of this type of software, such as the Swiss KUBA software discussed in Task 4, can serve as a starting point for generating new ideas for AASHTOWare bridge management.

Enumerated Damages

Chapter 5 discussed the promising capabilities of 3D inspection processes for more precisely describing bridge conditions, by showing the locations of damages and providing a framework for tracking each instance of damage over time. It was noted that each damage instance has a separate lifespan, which necessitates a change in the data model to support recording the changes in location, size, and severity separately for each damage instance (Figure 5.9). If an interface is developed with AASHTOWare's BrR system, locations of severe section loss could be used in the load rating system to help the engineer specify the load rating structural model.

The damage instances are determined by deterioration and might not correspond with any pre-defined scheme for permanent elements or subdivided units on the structure. For any realistic implementation of sub-divided units having a reasonable number of units, the potential number of damaged areas is considerably greater. Each structure unit may have multiple damaged areas, which can be represented by the modified data model in the in the enumerated damages approach.

In order for bridge management software to take advantage of this information, it would need to be fully supported by a graphic user interface for visualizing the damage instances, and technology for capturing deteriorated conditions in three dimensions at the necessary level of detail.

Michigan DOT has been conducting a separate research project focused on the data capture and visualization issues, resulting in a tool that other agencies can evaluate. Thus far the tools are focused on project level presentation, so additional work would be needed to determine how to interface this information with the network-wide planning capabilities of a bridge management system. In particular, the initiation and progression of damage instances would not be a Markovian process, as it is for bridge elements, so a different form of deterioration model would be necessary in order to fully exploit the spatial qualities of the data beyond a conventional element-level analysis. Development of such models will require further research and data gathering over a period of time sufficient for estimation of time-series models of damage progression.

It is possible that the enumerated damages approach might yield benefits more quickly if implemented first within AASHTOWare Bridge Rating, since that system is already capable of using section loss information for load rating without the need for further research, and it already has a robust data model to represent the unique configuration of each structure. It is recommended that the users of BrR be consulted to determine their level of interest in that type of functionality. As more agencies gain experience with using this form of tool at the project level, the industry will gain knowledge of the strengths and weaknesses of the approach for planning of future bridge preservation work at the network level. This would lay the ground work for future integration of an enumerated damages approach into routine asset management, at least for Big Bridges and perhaps eventually for all bridges.

CHAPTER 7 - BIBLIOGRAPHY

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7.2 Acronyms

3DBRIDGE	3D Wireless Bridge Inspection System
3DOBS	Three Dimensional Optical Bridge-evaluation System
AASHTO	American Association of State Highway and Transportation Officials
ADE	Agency Developed Elements
AHP	Analytical Hierarchy Process
BCBC	Burlington County Bridge Commission
BIRM	Bridge Inspection Reference Manual
BME	Bridge Management Elements
BMS	Bridge Management Software
BrM	Bridge Management
BTC	Bridge Technology Consulting

BVRCS	Bridge Viewer Remote Camera System
CAD	Computer Aided Drafting
CFIRE	National Center for Freight and Infrastructure Research and Education
CoRe	Commonly Recognized
CRS&SI	Commercial Remote Sensing and Spatial Information Program
DEM	Digital Elevation Model
DOT	Department of Transportation
DUAP	Data Use Analysis Processing
EFS	Electrochemical Fatigue Sensor
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
IAB	Integral Abutment Bridge
IABMAS	International Association for Bridge Maintenance and Safety
IR	Infrared
LADOTD	Louisiana Department of Transportation and Development
LCCA	Life-Cycle Cost Analysis
LiDAR	Light Detection and Ranging
LPR	Linear Polarization Resistance
LTBPP	Long-Term Bridge Performance Program
MAP-21	The Moving Ahead for Progress in the 21st Century Act
MBEI	Manual for Bridge Element Inspection
MCEER	Earthquake Engineering to Extreme Events
MDOT	Michigan Department of Transportation
MdTA	Maryland Transportation Authority
MnDOT	Minnesota Department of transportation
MoDOT	Missouri Department of Transportaion
MOOS	Multi-Objective Optimization System
MRR&I	Management, Repair, Rehabilitation, and Improvement

MS	Magnetostrictive
MT	Magnetic Particle Testing
NBE	National Bridge Elements
NBI	National Bridge Inventory
NBIP	National Bridge Inspection Program
NBIS	National Bridge Inspection Standards
NCHRP	National Cooperative Highway Research Program
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NDOT	Nevada Department of Transportation
NHS	National Highway System
NJDOT	New Jersey Department of Transportation
NYCDOT	New York City Department of Transportation
NYSBA	New York State Bridge Authority
NYSDOT	New York State Department of Transportation
ODOT	Ohio Department of Transportation
OMOT	Ontario Ministry of Transportation
PennDOT	Pennsylvania Department of Transportation
PT	Penetrant Testing
PTC	Pennsylvania Turnpike Commission
RABIT	Robotics Assisted Bridge Inspection Tool
RBI	Risk-Based Inspection
SCADA	Supervisory Control and Data Acquisition
SHM	Structural Health Monitoring
SLR	Single Lens Reflex
TBSI	Temperature-Based Structural Identification
TIR	Thermal Infrared
TPB	Tacony-Palmyra Bridge
TPFP	Transportation Pooled Fund Program
TxDOT	Texas Department of Transportation
UAV	Unmanned Aerial Vehicle

USDOT	United States Department of Transportation
USGS	United States Geological Survey
UT	Ultrasonic Testing
VTT	Research Centre of Finland
WBGEMS	Wireless Global Bridge Evaluation and Monitoring System
WisDOT	Wisconsin Department of Transportation

7.3 Inspection Reports

International Bridge Administration, Sault Ste. Marie International Bridge 2015 Annual Inspection Report

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Mackinac Bridge Authority, Mackinac Bridge 57th (2014) Annual/FCM Inspection Report

Maryland Transportation Authority, Chesapeake Bay Bridge 2015 Biennial Inspection Report

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Michigan Department of Transportation/Blue Water Bridge Canada, Blue Water Bridge Approach Structures 2014 Annual Inspection Report

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New York State Bridge Authority, Bear Mountain Bridge 2014 Biennial Inspection Report

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New York State Bridge Authority, Mid-Hudson Bridge 2014 Biennial Inspection Report

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7.4 Management Reports

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Delaware River Port Authority, 2016 Capital Program

Indiana Department of Transportation, Indiana's 2013-2035 Future Transportation Needs Report

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Maryland Transportation Authority, Business Plan FY 2015-2017

Minnesota Department of Transportation, Fiscal Year 2016 through 2020 Bridge Preservation and Improvement Guidelines

New York State Bridge Authority, Capital Improvement Program 2016-2020

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Rhode Island Turnpike and Bridge Authority, 2015 Ten Year Renewal and Replacement Plan

Sault Ste. Marie Bridge Authority, 2015-2019 Business Plan

Virginia Department of Transportation, State of the Structures and Bridges Report Fiscal Year 2015

Appendix A – Proposed New MBEI Elements

Table of Contents

Element 237—Concrete Pier Tower

Description: All concrete pier towers regardless of protective or reinforcing system.
Classification: NBE
Units of Measurement: ft
Quantity Calculation: Sum of the heights of individual legs of concrete pier towers.

Condition State Definitions

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Delamination/ Spall/ Patched Area (1080)	None.	Delaminated. Spall 1” or less deep or 6” or less in diameter. Patched area that is sound.	Spall greater than 1” deep or greater than 6” in diameter. Patched area that is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Exposed Rebar (1090)	None.	Present without measurable section loss.	Present with measurable section loss but does not warrant structural review.	
Efflorescence/ Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC and Other) (1130)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Abrasion/Wear (PSC/RC) (1190)	No abrasion or wearing.	Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete.	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.	
Settlement (4000)	None.	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None.	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
None.

Element 238—Masonry Pier Tower

Description: All masonry pier towers regardless of protective system.
Classification: NBE
Units of Measurement: ft
Quantity Calculation: Sum of the heights of individual legs of masonry pier towers.

Condition State Definitions

Defects	Condition States 1 GOOD	2 FAIR	3 POOR	4 SEVERE
Efflorescence/ Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Mortar Breakdown (Masonry) (1610)	None.	Cracking or voids in less than 10% of joints.	Cracking or voids in 10% or more of the joints.	
Split/Spall (Masonry) (1620)	None.	Block or stone has split or spalled with no shifting.	Block or stone has split or spalled with shifting but does not warrant a structural review.	
Patched Area (Masonry) (1630)	None.	Sound patch.	Unsound patch.	
Masonry Displacement (1640)	None.	Block or stone has shifted slightly out of alignment.	Block or stone has shifted significantly out of alignment or is missing but does not warrant structural review.	
Settlement (4000)	None.	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None.	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
None.

Element 221—Concrete Anchorage Chamber

Description: Exterior walls of concrete anchorage chambers regardless of protective or reinforcing system.
Classification: NBE
Units of Measurement: ft
Quantity Calculation: Sum of the lengths of the exterior walls (perimeter).

Condition State Definitions

	Condition States			
	1	2	3	4
Defects	GOOD	FAIR	POOR	SEVERE
Delamination/ Spall/ Patched Area (1080)	None.	Delaminated. Spall 1" or less deep or 6" or less in diameter. Patched area that is sound.	Spall greater than 1" deep or greater than 6" in diameter. Patched area that is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Exposed Rebar (1090)	None.	Present without measurable section loss.	Present with measurable section loss but does not warrant structural review.	
Efflorescence/ Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC and Other) (1130)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Abrasion/Wear (PSC/RC) (1190)	No abrasion or wearing.	Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete.	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.	
Settlement (4000)	None.	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None.	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
None.

Element 222—Concrete Anchorage Chamber Interior Walls

Description: Primary load-path interior walls of concrete anchorage chambers regardless of protective system.
Classification: NBE
Units of Measurement: ft
Quantity Calculation: Sum of the lengths of all of the interior walls.

Condition State Definitions

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Delamination/ Spall/ Patched Area (1080)	None.	Delaminated. Spall 1” or less deep or 6” or less in diameter. Patched area that is sound.	Spall greater than 1” deep or greater than 6” in diameter. Patched area that is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Exposed Rebar (1090)	None.	Present without measurable section loss.	Present with measurable section loss but does not warrant structural review.	
Efflorescence/ Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC and Other) (1130)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Abrasion/Wear (PSC/RC) (1190)	No abrasion or wearing.	Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete.	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.	
Settlement (4000)	None.	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None.	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
This element is applicable only to primary load-path interior walls of anchorage chambers which are within the primary load path for the anchorage roof.

Element 223—Masonry Anchorage Chamber

Description: Exterior walls of masonry anchorage chambers regardless of protective system.
Classification: NBE
Units of Measurement: ft
Quantity Calculation: Sum of the lengths of the exterior walls (perimeter).

Condition State Definitions

<table>
<tr><th rowspan="3">Defects</th><th colspan="4">Condition States</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><th>GOOD</th><th>FAIR</th><th>POOR</th><th>SEVERE</th></tr>
<tr><td>Efflorescence/ Rust Staining (1120)</td><td>None.</td><td>Surface white without build-up or leaching without rust staining.</td><td>Heavy build-up with rust staining.</td><td rowspan="7">The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.</td></tr>
<tr><td>Mortar Breakdown (Masonry) (1610)</td><td>None.</td><td>Cracking or voids in less than 10% of joints.</td><td>Cracking or voids in 10% or more of the joints.</td></tr>
<tr><td>Split/Spall (Masonry) (1620)</td><td>None.</td><td>Block or stone has split or spalled with no shifting.</td><td>Block or stone has split or spalled with shifting but does not warrant a structural review.</td></tr>
<tr><td>Patched Area (Masonry) (1630)</td><td>None.</td><td>Sound patch.</td><td>Unsound patch.</td></tr>
<tr><td>Masonry Displacement (1640)</td><td>None.</td><td>Block or stone has shifted slightly out of alignment.</td><td>Block or stone has shifted significantly out of alignment or is missing but does not warrant structural review.</td></tr>
<tr><td>Settlement (4000)</td><td>None.</td><td>Exists within tolerable limits or arrested with no observed structural distress.</td><td>Exceeds tolerable limits but does not warrant structural review.</td></tr>
<tr><td>Scour (6000)</td><td>None.</td><td>Exists within tolerable limits or has been arrested with effective countermeasures.</td><td>Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.</td></tr>
<tr><td>Damage (7000)</td><td>Not applicable.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.</td></tr>
</table>

Element Commentary
None.

Element 224—Masonry Anchorage Chamber Interior Walls

Description: Primary load-path interior walls of masonry anchorage chambers regardless of protective or reinforcing system.
Classification: NBE
Units of Measurement: ft
Quantity Calculation: Sum of the lengths of all of the interior walls.

Condition State Definitions

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Efflorescence/ Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Mortar Breakdown (Masonry) (1610)	None.	Cracking or voids in less than 10% of joints.	Cracking or voids in 10% or more of the joints.	
Split/Spall (Masonry) (1620)	None.	Block or stone has split or spalled with no shifting.	Block or stone has split or spalled with shifting but does not warrant a structural review.	
Patched Area (Masonry) (1630)	None.	Sound patch.	Unsound patch.	
Masonry Displacement (1640)	None.	Block or stone has shifted slightly out of alignment.	Block or stone has shifted significantly out of alignment or is missing but does not warrant structural review.	
Settlement (4000)	None.	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None.	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
This element is applicable only to primary load-path interior walls of anchorage chambers which are within the primary load path for the anchorage roof.

Element 163—Steel Main Cable Bands/Splay Castings

Description: Steel main cable bands and splay castings regardless of protective system.
Classification: NBE
Units of Measurement: each
Quantity Calculation: Sum of the number of individual cable bands and splay castings.

Condition State Definitions

<table>
<tr><th rowspan="3">Defects</th><th colspan="4">Condition States</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><th>GOOD</th><th>FAIR</th><th>POOR</th><th>SEVERE</th></tr>
<tr><td>Corrosion (1000)</td><td>None.</td><td>Freckled rust. Corrosion of the steel has initiated.</td><td>Section loss is evident or pack rust is present but does not warrant structural review.</td><td rowspan="5">The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.</td></tr>
<tr><td>Cracking (1010)</td><td>None.</td><td>Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.</td><td>Identified crack that is not arrested but does not warrant structural review.</td></tr>
<tr><td>Connection (1020)</td><td>Connection is in place and functioning as intended.</td><td>Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.</td><td>Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.</td></tr>
<tr><td>Distortion (1900)</td><td>None.</td><td>Distortion not requiring mitigation or mitigated distortion.</td><td>Distortion that requires mitigation that has not been addressed but does not warrant structural review.</td></tr>
<tr><td>Misalignment (XXXX)</td><td>None.</td><td>Tolerable misalignment.</td><td>Significant misalignment but does not warrant structural review.</td></tr>
<tr><td>Damage (7000)</td><td>Not applicable.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.</td></tr>
</table>

Element Commentary
This element is intended to distinguish deficiencies of the main cable bands and splay castings from those of the main cable strands and wrapping wires.

Element 164—Steel Main Cable Saddles

Description: Steel main cable saddles regardless of protective system.
Classification: NBE
Units of Measurement: each
Quantity Calculation: Sum of the number of individual main cable saddles.

Condition State Definitions

Defects	Condition States 1 GOOD	2 FAIR	3 POOR	4 SEVERE
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Cracking (1010)	None.	Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.	Identified crack that is not arrested but does not warrant structural review.	
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Movement (2210)	Free to move.	Minor restriction.	Restricted but not warranting structural review.	
Misalignment (XXXX)	None.	Tolerable misalignment.	Significant misalignment but does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
This element is intended to distinguish deficiencies of the suspension main cable saddles from those of the main cable strands and wrapping wires of suspension bridges or cable-stayed bridges.

Element 165—Steel Cable Anchorage Socket or Assembly

Description: Steel cable anchorage sockets or assemblies for main or secondary cables regardless of protective system.
Classification: NBE
Units of Measurement: each
Quantity Calculation: Sum of the number of individual main and secondary cable anchorage sockets or assemblies.

Condition State Definitions

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Cracking (1010)	None.	Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.	Identified crack that is not arrested but does not warrant structural review.	
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Wear (XXXX)	None.	Minor wear or fretting corrosion.	Moderate to significant wear or fretting corrosion is present but does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
This element is intended to distinguish deficiencies of the suspension main cable anchorage and secondary suspender rope sockets or assemblies from those of the main cable strands and wrapping wires or suspension or cable-stayed bridges.

Element 166—Post-Tensioning Assembly

Description: Internal and external post-tensioning assemblies, including respective ducts and embedment materials, regardless of protective system.
Classification: NBE
Units of Measurement: each
Quantity Calculation: Sum of the number of individual post-tensioning assemblies.

Condition State Definitions

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Delamination/ Spall/ Patched Area (1080)	None.	Delaminated. Spall 1" or less deep or 6" or less in diameter. Patched area that is sound.	Spall greater than 1" deep or greater than 6" in diameter. Patched area that is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Efflorescence/ Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC and Other) (1130)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	
Cracking (1010)	None.	Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.	Identified crack that is not arrested but does not warrant structural review.	
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	
Deterioration (Other) (1220)	None.	Initiated breakdown or deterioration.	Significant deterioration or breakdown.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Misalignment (XXXX)	None.	Tolerable misalignment.	Significant misalignment but does not warrant structural review.	

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
Applicable concrete and other material defects are included to accommodate deficiencies in embedment materials.

Element 170—Steel Curved Bridge/Primary Load Path Diaphragm or Bracing Assembly

Description: Primary load-path or curved bridge steel diaphragms or bracing assemblies regardless of protective system.
Classification: NBE
Units of Measurement: each
Quantity Calculation: Sum of the number of individual steel diaphragms/bracing assemblies.

Condition State Definitions

<table>
<tr><th rowspan="3">Defects</th><th colspan="4">Condition States</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><th>GOOD</th><th>FAIR</th><th>POOR</th><th>SEVERE</th></tr>
<tr><td>Corrosion (1000)</td><td>None.</td><td>Freckled rust. Corrosion of the steel has initiated.</td><td>Section loss is evident or pack rust is present but does not warrant structural review.</td><td rowspan="4">The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.</td></tr>
<tr><td>Cracking (1010)</td><td>None.</td><td>Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.</td><td>Identified crack that is not arrested but does not warrant structural review.</td></tr>
<tr><td>Connection (1020)</td><td>Connection is in place and functioning as intended.</td><td>Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.</td><td>Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.</td></tr>
<tr><td>Distortion (1900)</td><td>None.</td><td>Distortion not requiring mitigation or mitigated distortion.</td><td>Distortion that requires mitigation that has not been addressed but does not warrant structural review.</td></tr>
<tr><td>Damage (7000)</td><td>Not applicable.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.</td></tr>
</table>

Element Commentary

This element is intended to be used for steel diaphragms/bracing assemblies which directly support primary loads and those at curved portions of structures at which diaphragms resist primary loading. Condition evaluation for this element also includes connection plates which connect diaphragms/bracing members to primary NBEs.

Element 171—Concrete Curved Bridge/Primary Load Path Diaphragm

Description: Primary load-path or curved bridge concrete diaphragms regardless of protective system.
Classification: NBE
Units of Measurement: each
Quantity Calculation: Sum of the number of individual concrete diaphragms.

Condition State Definitions

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Cracking (1010)	None.	Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.	Identified crack that is not arrested but does not warrant structural review.	
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
This element is intended to be used for concrete diaphragms which directly support primary loads and those at curved portions of structures at which diaphragms resist primary loading.

Element 518—Cable Protective System

Description: Weatherproofing protective systems on main cables of suspension or cable-stayed structures. Does not include additional conventional paint coatings.
Classification: BME
Units of Measurement: ft^2
Quantity Calculation: Should include the entire outer surface area of the protective system on the cable element.

Condition State Definitions

	Condition States			
	1	2	3	4
Defects	**GOOD**	**FAIR**	**POOR**	**SEVERE**
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Bulging, Splitting, or Tearing (Cable Protective System) (XXXX)	None.	Bulging less than 15% of the thickness.	Bulging 15% or more of the thickness. Splitting or tearing of waterproofing material.	Failure of protective system, no protection of underlying cable.
Deterioration (Cable Protective System) (XXXX)	None.	Initiated breakdown or deterioration.	Significant deterioration or breakdown.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
This element should not include the wrapping wires which compact the main cable strands, those wires should be assessed as part of the Steel Main Cable (Element 147). Assessment for this element may include blast protection or cable dehumidification systems which obscure the protected cable. Various material defect categories are included to accommodate all materials which may comprise the protective system.

Element 308—Vibration Damper

Description: For vibration damper systems of all types which may be present on main cables of cable-stayed bridges, secondary suspender ropes of suspension bridges, or truss members.
Classification: BME
Units of Measurement: each
Quantity Calculation: Sum of the number of individual damper assemblies.

Condition State Definitions

	Condition States			
	1	2	3	4
Defects	**GOOD**	**FAIR**	**POOR**	**SEVERE**
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Movement (2210)	Free to move.	Minor restriction.	Restricted but not warranting structural review.	
Misalignment (XXXX)	None.	Tolerable misalignment.	Significant misalignment but does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
None.

Element 340—Deck Drainage

Description: All elements which facilitate drainage of runoff from the deck, including troughs beneath open joints, scuppers, and deck drainage basins and the connected drainage pipes. Collector pipes to which numerous drain pipes connect may be considered an additional separate drainage element.
Classification: BME
Units of Measurement: each
Quantity Calculation: Sum of the number of individual drainage devices or assemblies.

Condition State Definitions

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Deterioration (Other) (1220)	None.	Initiated breakdown or deterioration.	Significant deterioration or breakdown.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Leakage (2310)	None.	Minimal. Minor dripping of water from the drainage pipe.	Moderate. More than a drip and less than free flow of water.	Free flow of water from the drainage pipe.
Debris Impaction (2350)	No debris to a shallow cover of loose debris may be evident but does not affect performance.	Partially filled with hard-packed material but still allowing drainage.	Completely filled and impacts drainage considerably.	Completely filled and prevents drainage.
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary
None.

Element 350—Substructure Impact Protection

Description: All elements which protect substructure elements from direct collision and resulting damages, including placed riprap, crash walls, dolphins, and fenders of all material types, regardless of protective system.
Classification: BME
Units of Measurement: each
Quantity Calculation: Sum of the number of individual crash protection devices.

Condition State Definitions

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Delamination/ Spall/ Patched Area (1080)	None.	Delaminated. Spall 1” or less deep or 6” or less in diameter. Patched area that is sound.	Spall greater than 1” deep or greater than 6” in diameter. Patched area that is unsound or showing distress. Does not warrant structural review.	
Efflorescence/ Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC and Other) (1130)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Abrasion/Wear (PSC/RC) (1190)	No abrasion or wearing.	Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete.	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.	
Decay/Section Loss (Timber) (1140)	None.	Affects less than 10% of the member section.	Affects 10% or more of the member but does not warrant structural review.	
Check/Shake (Timber) (1150)	Surface penetration less than 5% of the member thickness regardless of location.	Penetrates 5% to 50% of the thickness of the member and not in a tension zone.	Penetrates more than 50% of the thickness of the member or more than 5% of the member thickness in a tension zone. Does not warrant structural review.	
Deterioration (Other) (1220)	None.	Initiated breakdown or deterioration.	Significant deterioration or breakdown but does not warrant structural review.	
Settlement (4000)	None.	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	

Defects	Condition States 1 GOOD	2 FAIR	3 POOR	4 SEVERE
Scour (6000)	None.	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Element Commentary

Various material defect categories are included to accommodate all materials which may comprise the crash protection system.

Appendix B – Evaluation of Four Advancing Remote Sensing Techniques for Recommended New Big Bridge Elements

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	TECHNOLOGIES: Thermography	TECHNOLOGIES: LiDAR	TECHNOLOGIES: At-speed GPR
Concrete Pier Tower (237)		Delamination/Spall/Patched Area	None; Delaminated. Spall 1" or less deep or 6" or less in diameter. Patched area that is sound; Spall greater than 1"deep or greater than 6" in diameter. Patched area that is unsound or showing distress. Does not warrant structural review; Beyond CS 3	14	12	11	-
		Exposed Rebar	None; Present without measureable section loss; Present with measureable section loss but does not warrant structural review; Beyond CS 3	14	12	11	-
		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyond CS 3	14	-	-	-
		Cracking (RC and Other)	Insignificant cracks or moderate-width cracks that have been sealed; Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking; Wide cracks or heavy pattern (map) cracking; Beyond CS 3	12	-	11	-
		Abrasion/Wear	No abrasion or wearing; Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete; Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear; Beyond CS 3	14	11	12	-
		Settlement	None; Exists within tolerable limits or arrested with no observed structural distress; Exceeds tolerable limits but does not warrant structural review; Beyond CS 3	13	-	12	-
		Scour	None; Exists within tolerable limits or has been arrested with effective countermeasures; Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review; Beyond CS 3	-	-	-	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-1 - Ratings for Element 237 – Concrete Pier Tower.

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Masonry Pier Tower (238)		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyond CS 3	14	-	10	-
		Mortar Breakdown	None; Cracking or voids in less than 10% of joints; Creacking or voids in 10% or more of the joints; Beyond CS 3	12	-	11	-
		Split/Spall	None; Block or stone has split or spalled with no shifting; Block or stone has split or spalled with shifting but does not warrant a structural review; Beyond CS 3	12	-	12	-
		Patched Area	None; Sound patch; Unsound patch; Beyond CS 3	14	12	11	-
		Masonry Displacement	None; Block or stone has shifted slightly out of alignment; Block or stone has shifted significantly out of alignment or is missing but does not warrant structural review; Beyond CS 3	14	11	12	-
		Settlement	None; Exists within tolerable limits or arrested with no observed structural distress; Exceeds tolderable limits but does not warrant structural review; Beyond CS 3	13	-	12	-
		Scour	None; Exists within tolerable limits or has been arrested with effective countermeasures; Exceeds tolderable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review; Beyond CS 3	-	-	12	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-2 - Ratings for Element 238 – Masonry Pier Tower

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	TECHNOLOGIES: Thermography	TECHNOLOGIES: LiDAR	TECHNOLOGIES: At-speed GPR
Reinforced Concrete Anchorage Chamber (221)		Delamination/Spall/Patched Area	None; Delaminated. Spall 1" or less deep or 6" or less in diameter. Patched area that is sound; Spall greater than 1"deep or greater than 6" in diameter. Patched area that is unsound or showing distress. Does not warrant structural review; Beyond CS 3	14	12	11	-
		Exposed Rebar	None; Present without measureable section loss; Present with measureable section loss but does not warrant structural review; Beyond CS 3	14	12	11	-
		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyond CS 3	14	-	-	-
		Cracking (RC and Other)	Insignificant cracks or moderate-width cracks that have been sealed; Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking; Wide cracks or heavy pattern (map) cracking; Beyond CS 3	12	-	11	-
		Abrasion/Wear	No abrasion or wearing; Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete; Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear; Beyond CS 3	14	11	12	-
		Settlement	None; Exists within tolerable limits or arrested with no observed structural distress; Exceeds tolerable limits but does not warrant structural review; Beyond CS 3	13	-	12	-
		Scour	None; Exists within tolerable limits or has been arrested with effective countermeasures; Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review; Beyond CS 3	-	-	-	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-3 - Ratings for Element 221 – Reinforced Concrete Anchorage Chamber

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	TECHNOLOGIES: Thermography	TECHNOLOGIES: LiDAR	TECHNOLOGIES: At-speed GPR
Reinforced Concrete Anchorage Chamber Interior Walls (222)		Delamination/Spall/Patched Area	None; Delaminated. Spall 1" or less deep or 6" or less in diameter. Patched area that is sound; Spall greater than 1"deep or greater than 6" in diameter. Patched area that is unsound or showing distress. Does not warrant structural review; Beyond CS 3	14	12	11	-
		Exposed Rebar	None; Present without measureable section loss; Present with measureable section loss but does not warrant structural review; Beyond CS 3	14	12	11	-
		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyone CS 3	14	-	-	-
		Cracking (RC and Other)	Insignificant cracks or moderate-width cracks that have been sealed; Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking; Wide cracks or heavy pattern (map) cracking; Beyond CS 3	12	-	11	-
		Abrasion/Wear	No abrasion or wearing; Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete; Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear; Beyond CS 3	14	11	12	-
		Settlement	None; Exists within tolerable limits or arrested with no observed structural distress; Exceeds tolerable limits but does not warrant structural review; Beyond CS 3	13	-	12	-
		Scour	None; Exists within tolerable limits or has been arrested with effective countermeasures; Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review; Beyond CS 3	-	-	-	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-4 - Ratings for Element 222 – Reinforced Concrete Anchorage Chamber Interior Walls

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Masonry Anchorage Chamber (223)		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyond CS 3	14	-	10	-
		Mortar Breakdown	None; Cracking or voids in less than 10% of joints; Creacking or voids in 10% or more of the joints; Beyond CS 3	12	-	11	-
		Split/Spall	None; Block or stone has split or spalled with no shifting; Block or stone has split or spalled with shifting but does not warrant a structural review; Beyond CS 3	12	-	12	-
		Patched Area	None; Sound patch; Unsound patch; Beyond CS 3	14	12	11	-
		Masonry Displacement	None; Block or stone has shifted slightly out of alignment; Block or stone has shifted significantly out of alignment or is missing but does not warrant structural review; Beyond CS 3	14	11	12	-
		Settlement	None; Exists within tolerable limits or arrested with no observed structural distress; Exceeds tolderable limits but does not warrant structural review; Beyond CS 3	13	-	12	-
		Scour	None; Exists within tolerable limits or has been arrested with effective countermeasures; Exceeds tolderable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review; Beyond CS 3	-	-	10	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-5 - Ratings for Element 223 – Masonry Anchorage Chamber

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Masonry Anchorage Chamber Interior Walls (224)		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyond CS 3	14	-	10	-
		Mortar Breakdown	None; Cracking or voids in less than 10% of joints; Creacking or voids in 10% or more of the joints; Beyond CS 3	12	-	11	-
		Split/Spall	None; Block or stone has split or spalled with no shifting; Block or stone has split or spalled with shifting but does not warrant a structural review; Beyond CS 3	12	-	12	-
		Patched Area	None; Sound patch; Unsound patch; Beyond CS 3	14	12	11	-
		Masonry Displacement	None; Block or stone has shifted slightly out of alignment; Block or stone has shifted significantly out of alignment or is missing but does not warrant structural review; Beyond CS 3	14	11	12	-
		Settlement	None; Exists within tolerable limits or arrested with no observed structural distress; Exceeds tolderable limits but does not warrant structural review; Beyond CS 3	13	-	12	-
		Scour	None; Exists within tolerable limits or has been arrested with effective countermeasures; Exceeds tolderable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review; Beyond CS 3	-	-	10	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-6 - Ratings for Element 224 – Masonry Anchorage Chamber Interior Walls

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	TECHNOLOGIES: Thermography	TECHNOLOGIES: LiDAR	TECHNOLOGIES: At-speed GPR
Steel Main Cable Bands/Splay Castings (163)		Corrosion	None; Freckled rust. Corrosion of the steel has initiated; Section loss is evident or pack rust is present but does not warrant structural review; Beyond CS 3	14	11	11	-
		Cracking	None; Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar; Identified crack that is not arrested but does not warrant structural review; Beyond CS 3	12	-	11	-
		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	11	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyond CS 3	12	-	12	-
		Misalignment	None; Tolerable misalignment; Significant misalignment but does not warrant structural review; Beyond CS 3	12	11	12	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-7 - Ratings for Element 163 – Steel Main Cable Bands/Splay Castings

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Steel Main Cable Saddles (164)		Corrosion	None; Freckled rust. Corrosion of the steel has initiated; Section loss is evident or pack rust is present but does not warrant structural review; Beyond CS 3	14	11	11	-
		Cracking	None; Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar; Identified crack that is not arrested but does not warrant structural review; Beyond CS 3	12	-	11	-
		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	11	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyond CS 3	12	-	12	-
		Misalignment	None; Tolerable misalignment; Significant misalignment but does not warrant structural review; Beyond CS 3	12	11	12	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-8 - Ratings for Element 164 – Steel Main Cable Saddles

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Steel Cable Anchorage Socket or Assembly (165)		Corrosion	None; Freckled rust. Corrosion of the steel has initiated; Section loss is evident or pack rust is present but does not warrant structural review; Beyond CS 3	14	11	11	-
		Cracking	None; Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar; Identified crack that is not arrested but does not warrant structural review; Beyond CS 3	12	-	11	-
		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	11	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyond CS 3	12	-	12	-
		Wear	None; Minor wear or fretting corrosion; Moderate to significant wear or fretting corrosion is present but does not warrant structural review; Beyond CS 3	12	-	11	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-9 - Ratings for Element 165 – Steel Cable Anchorage Socket or Assembly

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Post-Tensioning Assembly (166)		Delamination/Spall/Patched Area	None; Delaminated. Spall 1" or less deep or 6" or less in diameter. Patched area that is sound; Spall greater than 1"deep or greater than 6" in diameter. Patched area that is unsound or showing distress. Does not warrant structural review; Beyond CS 3	14	12	11	-
		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyond CS 3	14	-	-	-
		Cracking (RC and Other)	Insignificant cracks or moderate-width cracks that have been sealed; Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking; Wide cracks or heavy pattern (map) cracking; Beyond CS 3	12	-	11	-
		Corrosion	None; Freckled rust. Corrosion of the steel has initiated; Section loss is evident or pack rust is present but does not warrant structural review; Beyond CS 3	14	11	11	-
		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	11	-
		Deterioration	None; Initiated breakdown or deterioration; Significant deterioration or breakdown; Beyond CS 3	14	11	12	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyond CS 3	12	-	12	-
		Misalignment	None; Tolerable misalignment; Significant misalignment but does not warrant structural review; Beyond CS 3	12	11	12	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-10 - Ratings for Element 166 – Post-Tensioning Assembly

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Curved Bridge Steel Diaphragm/Bracing Assembly (170)		Corrosion	None; Freckled rust. Corrosion of the steel has initiated; Section loss is evident or pack rust is present but does not warrant structural review; Beyond CS 3	14	11	11	-
		Cracking	None; Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar; Identified crack that is not arrested but does not warrant structural review; Beyond CS 3	12	-	11	-
		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	11	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyond CS 3	12	-	12	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-11 - Ratings for Element 170 – Curved Bridge Steel Diaphragm/Bracing Assembly

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	TECHNOLOGIES: Thermography	TECHNOLOGIES: LiDAR	TECHNOLOGIES: At-speed GPR
Curved Bridge Reinforcement Concrete Diaphragm (171)		Corrosion	None; Freckled rust. Corrosion of the steel has initiated; Section loss is evident or pack rust is present but does not warrant structural review; Beyond CS 3	14	11	11	-
		Cracking	None; Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar; Identified crack that is not arrested but does not warrant structural review; Beyond CS 3	12	-	11	-
		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	11	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyond CS 3	12	-	12	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-12 - Ratings for Element 171 – Curved Bridge Reinforcement Concrete Diaphragm

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Cable Protective System (518)		Corrosion	None; Freckled rust. Corrosion of the steel has initiated; Section loss is evident or pack rust is present but does not warrant structural review; Beyond CS 3	14	11	11	-
		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	11	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyond CS 3	14	-	11	-
		Peeling/Bubbling/Carcking	None; Finish coats only; Finish and primer coats; Beyond CS 3	14	11	11	-
		Bulging, Splitting, or Tearing	None; Bulging less than 15% of the thickness; Bulging 15% or more of the thickness. Splitting or tearing of waterproofing material; Beyond CS 3	14	11	11	-
		Deterioration	None; Initiated breakdown or deterioration; Significant deterioration or breakdown; Beyond CS 3	14	11	12	-
		Damage	None; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	13	11	12	-

Figure B-13 - Ratings for Element 518 – Cable Protective System

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	TECHNOLOGIES: Thermography	TECHNOLOGIES: LiDAR	TECHNOLOGIES: At-speed GPR
Vibration Damper (308)		Corrosion	None; Freckled rust. Corrosion of the steel has initiated; Section loss is evident or pack rust is present but does not warrant structural review; Beyond CS 3	13	11	11	-
		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	11	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyone CS 3	13	-	11	-
		Movement	Free to move; Minor restriction; Restricted but not warranting structural review; Beyond CS 3	13	-	12	-
		Misalignment	None; Tolerable misalignment; Significant misalignment but does not warrant structural reviewl; Beyond CS 3	13	-	12	-
		Damage	None; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-14 - Ratings for Element 308 – Vibration Damper

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	TECHNOLOGIES: Thermography	TECHNOLOGIES: LiDAR	TECHNOLOGIES: At-speed GPR
Deck Drainage (340)		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	12	-
		Deterioration	None; Initiated breakdown or deterioration; Significant deterioration or breakdown; Beyond CS 3	14	11	12	-
		Distortion	None; Distortion not requiring mitigation or mitigated distortion; Distortion that requires mitigation that has not been addressed but does not warrant structural review; Beyond CS 3	14	-	12	-
		Leakage	None; Minimal. Minor dripping of water from the drainage pipe; Moderate. More than a drip and less than free flow of water; Beyond CS 3	14	11	11	-
		Debris Impaction	No debris to a shallow cover of loose debris may be evident but does not affect performance; Partially filled with hard-packed material but still allowing drainage; Completely filled and impacts drainage considerably; Beyond CS 3	14	-	12	-
		Damage	None; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyone CS 3	14	11	12	-

Figure B-15 - Ratings for Element 340 – Deck Drainage

ELEMENT	BIG BRIDGE TYPE(S)	DEFECTS	CONDITION STATE INDICATORS (Proposed in Task 5 Report)	TECHNOLOGIES: 3-D Optical	Thermography	LiDAR	At-speed GPR
Substructure Impact Protection (350)		Connection	Connection is in place and functioning as intended; Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended; Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review; Beyond CS 3	14	11	12	-
		Delamination/Spall/Patched Area	None; Delaminated. Spall 1" or less deep or 6" or less in diameter. Patched area that is sound; Spall greater than 1"deep or greater than 6" in diameter. Patched area that is unsound or showing distress. Does not warrant structural review; Beyond CS 3	14	12	11	-
		Efflorescense/Rust Staining	None; Surface white without build-up or leaching without rust staining; Heavy build-up with rust staining; Beyond CS 3	14	-	-	-
		Cracking (RC and Other)	Insignificant cracks or moderate-width cracks that have been sealed; Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking; Wide cracks or heavy pattern (map) cracking; Beyond CS 3	13	-	11	-
		Abrasion/Wear	No abrasion or wearing; Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete; Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear; Beyond CS 3	14	11	12	-
		Decay/Section Loss	None; Affects less than 10% of the member section; Affects 10% or more of the member but does not warrant structural review; Beyone CS 3	14	11	12	-
		Check/Shake	Surface penetration less than 5% of the member thickness regardless of location; Penetrates 5% to 50% of the thickness of the member and not in a tension zone; Penetrates more than 50% of the thickness of the member or more than 5% of the member thickness in a tension zone. Does not warrant structural review; Beyond CS 3	-	-	-	10
		Deterioration	None; Initiated breakdown or deterioration; Significant deterioration or breakdown; Beyond CS 3	14	11	12	-
		Settlement	None; Exists within tolerable limits or arrested with no observed structural distress; Exceeds tolerable limits but does not warrant structural review; Beyond CS 3	13	-	12	-
		Scour	None; Exists within tolerable limits or has been arrested with effective countermeasures; Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review; Beyond CS 3	-	-	-	-
		Damage	Not applicable; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry; The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry; Beyond CS 3	14	11	12	-

Figure B-16 - Ratings for Element 350 – Substructure Impact Protection

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Appendix C – Case Study: Comparison of Current and Revised "Element Quantity and Condition State Summaries" for a Big Bridge

Appendix C - ORGANIZATION OF CASE STUDY

APPENDIX C - COMPARISON OF CURRENT AND REVISED "ELEMENT QUANTITY AND CONDITION STATE SUMMARIES" FOR A BIG BRIDGE

C.1 Bridge Description and Assumptions

C.1.1 General

- Structure is oriented from south to north.
- Spans and panels are numbered from south-to-north and stringers are numbered from east-to-west.
- Elements which are centered on a boundary between spans/panels such as joints, substructure units, gusset plates, suspender ropes or bearings are attributed to the previous span/panel.

C.1.2 Deck

- Element 28 – Steel Deck with Open Grid
  - Out-to-out deck width is 21.58 feet.
- Element 330 – Metal Bridge Railing
  - Bridge railing consists of painted W-beam guide rails attached to the vertical and diagonal members of each truss line and a painted steel curb angle attached to the floor system joists.
  - Total painted perimeter is 4.65 feet.
- Element 305 – Assembly Joint without Seal
  - Finger joint is located at the center of the main suspension span (Panel Point 44).
  - Sliding plate joints are located at the South Abutment, Anchorage Bent, and the North Abutment.

C.1.3 Superstructure

- Element 120 – Steel Truss
  - Double-intersection Warren through truss stiffening the three cable-supported suspension spans
  - Two-span continuous double-intersection Warren through truss at north approach which is identical to the stiffening truss
- Element 147 – Steel Main Cables
  - Two main cables consisting of seven strands each.
  - Cables are 7.5 inch diameter with a conventional paint coating around the perimeter which is 1.96 feet.

- Element 148 – Secondary Steel Cables
  - Suspender ropes are located at each panel point at each main cable.
  - 1 inch diameter with a painted perimeter 0.26 feet.
- Element 163 – Steel Main Cable Bands/Splay Castings **(Proposed Element)**
  - Painted area is approximately 3 ft^2 each.
- Element 164 – Steel Main Cable Saddles **(Proposed Element)**
  - Painted area is approximately 20 ft^2 each.
- Element 165 – Steel Cable Anchorage Socket or Assembly **(Proposed Element)**
  - The five main cable anchorage eyebar assemblies for each cable at each anchorage have a painted surface area totaling approximately 20 ft^2 each.
  - Suspender rope sockets have an approximately 1 ft^2 painted area each.
- Element 311 – Movable Bearing, Element 313 – Fixed Bearing
  - Fixed truss bearings at each end of the suspension spans at Panel Points 0 and 92 and at Panel Point 100 for the continuous truss.
  - Movable truss bearings are located at Panel Point 92 for the continuous truss.
  - Painted area is approximately 5 ft^2 each.

C.1.4 Floor System

- Element 152 – Steel Floorbeam
  - Located at each panel point and at each side of the mid-bridge joints.
  - Built-up members measuring 26.67 feet long with a 5.31 feet painted perimeter.
- Element 113 – Steel Stringer
  - Four W12x35 longitudinal stringers that have a 4.22 feet painted perimeter.
  - Five W6x20 transverse stringers (joists) which are 22 feet long and have a painted perimeter of 3.01 feet are seated on top of the longitudinal stringers and support the steel open grid deck.
  - Sliding plate stringer bearings are located at Panel Points 4, 8, 14, 20, 26, 32, 38, 50, 56, 62, 68, 74, 80, 86 and 96 and have a painted area of approximately 2 ft^2 each.

C.1.5 Substructure

- Element 215 – Reinforced Concrete Abutment
  - Both abutments are 35 feet in length.
  - Both stems are painted with a concrete protective coating (Element 521).

        - South Abutment stem is 20 feet high with a concrete protective coating area of 700 ft².
        - North Abutment stem is 30 feet high with a concrete protective coating area of 1050 ft².
    - Element 221 – Concrete Anchorage Chamber **(Proposed Element)**
        - Main cable anchorages are enclosed inside reinforced concrete anchorage chambers which are located behind the north and south abutments. The front wall of each anchorage is the abutment stem and backwall (Element 215); therefore, the front walls are not counted as part of the anchorage chamber element quantity.
- Element 207 – Steel Tower
    - The two 130 foot high suspension towers have two legs which each consist of four built-up columns and numerous bracing members and transverse struts.
        - All elements of the suspension towers are attributed to the panels located at the towers (Panels 21 and 68).
    - The 39 foot high steel anchorage bent is comprised of two built-up columns approximately 2'x2' with built-up transverse struts and a full-height cross brace
- Element 202 – Steel Column
    - Steel Bent A is comprised of two steel 18" x 18" columns with a single transverse strut at the top and is approximately 29 feet in height. The east column is at Panel Point 96 and the west column is in Panel 97; therefore, Bent A is attributed to Panel 97 in the element summary.
- Element 210 – Reinforced Concrete Pier Wall
    - Suspension towers are supported by reinforced concrete pier walls which are 54 feet long
        - Uncoated with a granite facing
    - The Anchorage Bent and Bent A are supported by reinforced concrete pier walls which are 30 and 27 feet long, respectively.
        - All exposed surfaces of these pier walls have a concrete protective coating which totals approximately 450 ft² and 270 ft² for the anchorage bent and Bent A, respectively.

C.2 Bridge Drawings

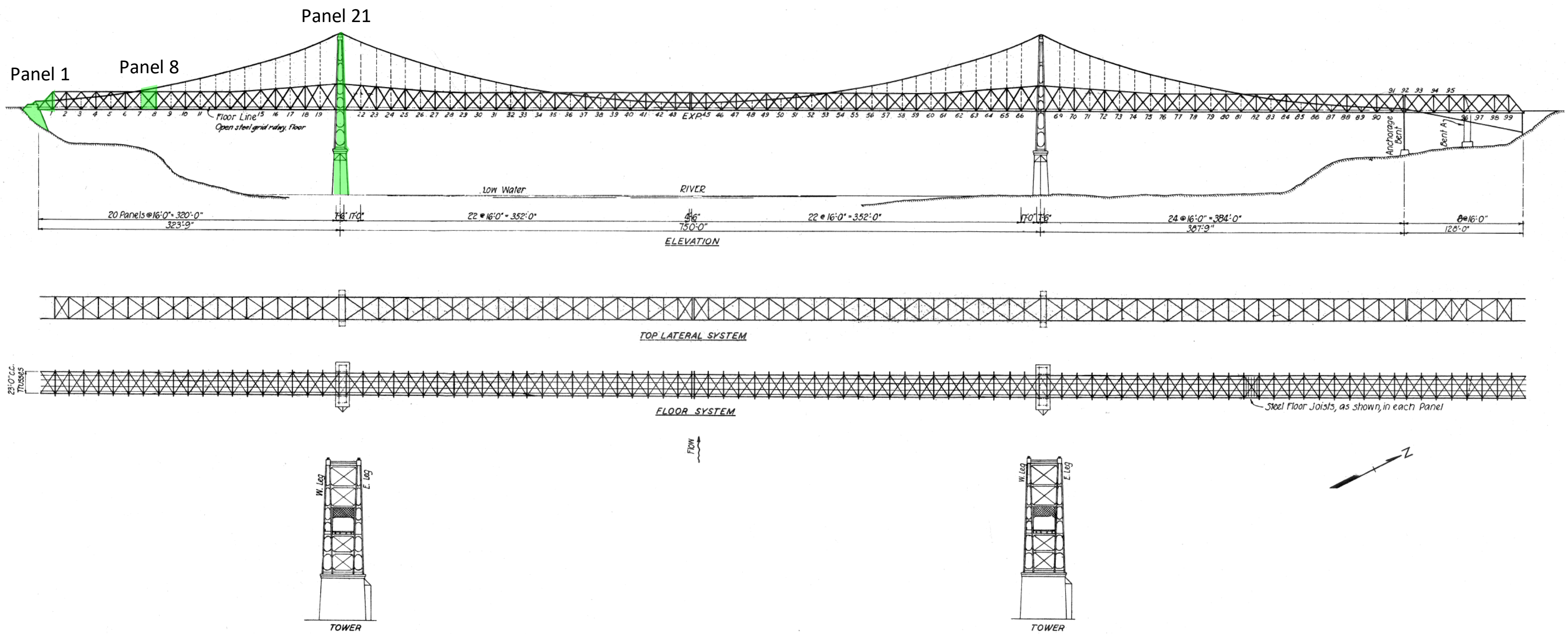
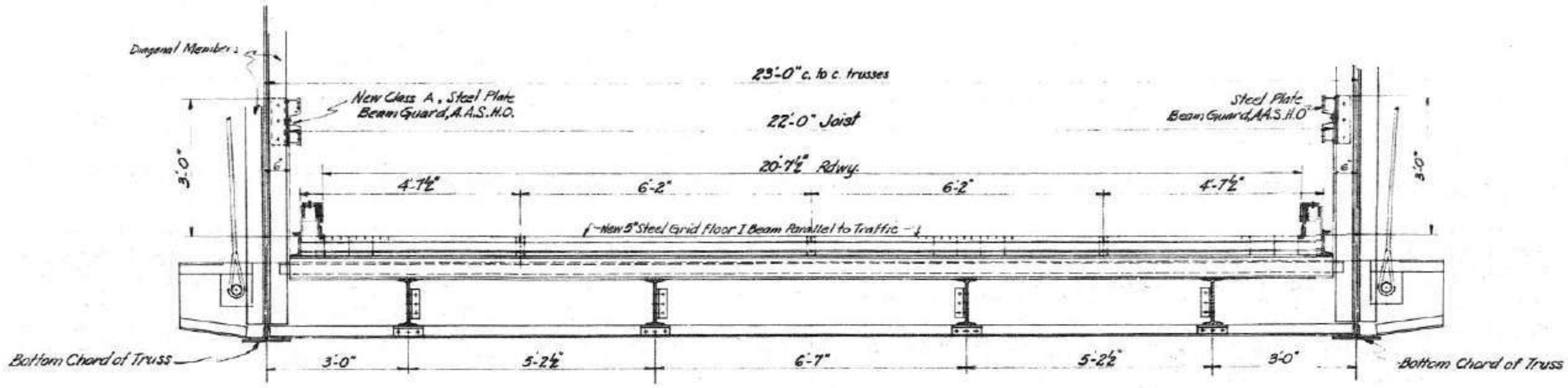
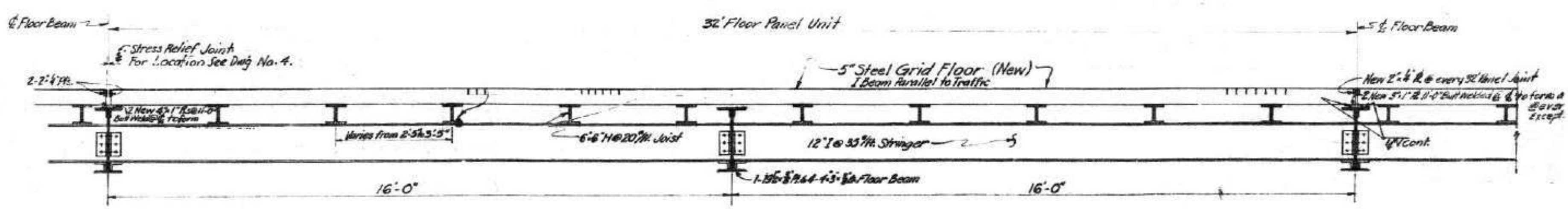


Figure C.1 - Elevation and Plan Views of Structure
(Panels selected for “Element Quantity and Condition State Summary” examples are highlighted)



Cross Section of Roadway Floor



Longitudinal Section of Roadway Floor

Figure C.2 - Transverse and Longitudinal Sections of Roadway and Floor System

C.3 Element Total Quantities (Current)

Table C.1 - Element quantities for each panel of the structure as currently defined in MBEI.

Span	Panel	Panel Length (ft)	Deck				Superstructure												
			28	330	515	305	147	515	148	515	120	515	152	515	113	515	113	515
			Steel Deck with Open Grid	Metal Bridge Railing	Steel Protective Coating (330)	Assembly Joint without Seal	Steel Main Cables	Steel Protective Coating (147)	Secondary Steel Cables	Steel Protective Coating (148)	Steel Truss	Steel Protective Coating (120)	Steel Floorbeam	Steel Protective Coating (152)	Steel Stringer	Steel Protective Coating (113)	Steel Stringer (Joists)	Steel Protective Coating (113)
			ft²	ft	ft²	ft	ft	ft²	each	ft²	ft	ft²	ft	ft²	ft	ft²	ft	ft²
S1	1	16	345	32	149	22	32	63	2	9	32	502	53	283	64	270	110	331
S1	2	16	345	32	149	—	32	63	2	11	32	442	27	142	64	270	110	331
S1	3	16	345	32	149	—	32	63	2	13	32	379	27	142	64	270	110	331
S1	4	16	345	32	149	—	32	63	2	14	32	442	27	142	64	270	110	331
S1	5	16	345	32	149	—	32	63	2	16	32	379	27	142	64	270	110	331
S1	6	16	345	32	149	—	32	63	2	17	32	442	27	142	64	270	110	331
S1	7	16	345	32	149	—	32	63	2	21	32	379	27	142	64	270	110	331
S1	8	16	345	32	149	—	32	63	2	24	32	442	27	142	64	270	110	331
S1	9	16	345	32	149	—	32	63	2	27	32	379	27	142	64	270	110	331
S1	10	16	345	32	149	—	32	63	2	31	32	442	27	142	64	270	110	331
S1	11	16	345	32	149	—	32	63	2	34	32	379	27	142	64	270	110	331
S1	12	16	345	32	149	—	32	63	2	40	32	442	27	142	64	270	110	331
S1	13	16	345	32	149	—	32	63	2	43	32	379	27	142	64	270	110	331
S1	14	16	345	32	149	—	32	63	2	48	32	442	27	142	64	270	110	331
S1	15	16	345	32	149	—	32	63	2	52	32	379	27	142	64	270	110	331
S1	16	16	345	32	149	—	32	63	2	58	32	442	27	142	64	270	110	331
S1	17	16	345	32	149	—	32	63	2	62	32	379	27	142	64	270	110	331
S1	18	16	345	32	149	—	32	63	2	70	32	442	27	142	64	270	110	331
S1	19	16	345	32	149	—	32	63	2	75	32	379	27	142	64	270	110	331
S1	20	16	345	32	149	—	32	63	--	—	32	442	27	142	64	270	110	331
S1	21	7.5	162	15	70	—	15	29	--	—	15	314	27	142	30	127	110	331
S2	22	17	367	34	158	—	34	67	2	75	34	379	27	142	68	287	110	331
S2	23	16	345	32	149	—	32	63	2	70	32	442	27	142	64	270	110	331
S2	24	16	345	32	149	—	32	63	2	62	32	379	27	142	64	270	110	331
S2	25	16	345	32	149	—	32	63	2	58	32	442	27	142	64	270	110	331
S2	26	16	345	32	149	—	32	63	2	52	32	379	27	142	64	270	110	331
S2	27	16	345	32	149	—	32	63	2	48	32	442	27	142	64	270	110	331
S2	28	16	345	32	149	—	32	63	2	43	32	379	27	142	64	270	110	331
S2	29	16	345	32	149	—	32	63	2	40	32	442	27	142	64	270	110	331
S2	30	16	345	32	149	—	32	63	2	34	32	379	27	142	64	270	110	331
S2	31	16	345	32	149	—	32	63	2	31	32	442	27	142	64	270	110	331
S2	32	16	345	32	149	—	32	63	2	27	32	379	27	142	64	270	110	331
S2	33	16	345	32	149	—	32	63	2	24	32	442	27	142	64	270	110	331
S2	34	16	345	32	149	—	32	63	2	21	32	379	27	142	64	270	110	331
S2	35	16	345	32	149	—	32	63	2	17	32	442	27	142	64	270	110	331
S2	36	16	345	32	149	—	32	63	2	16	32	379	27	142	64	270	110	331
S2	37	16	345	32	149	—	32	63	2	14	32	442	27	142	64	270	110	331
S2	38	16	345	32	149	—	32	63	2	13	32	379	27	142	64	270	110	331
S2	39	16	345	32	149	—	32	63	2	11	32	442	27	142	64	270	110	331
S2	40	16	345	32	149	—	32	63	2	9	32	379	27	142	64	270	110	331
S2	41	16	345	32	149	—	32	63	2	9	32	442	27	142	64	270	110	331
S2	42	16	345	32	149	—	32	63	2	8	32	379	27	142	64	270	110	331
S2	43	16	345	32	149	—	32	63	2	7	32	442	27	142	64	270	110	331
S2	44	18.3	361	37	170	22	37	72	2	7	37	442	27	142	64	270	110	331
S2	45	18.3	361	37	170	—	37	72	4	14	37	505	53	283	64	270	110	331
S2	46	16	345	32	149	—	32	63	2	8	32	379	27	142	64	270	110	331
S2	47	16	345	32	149	—	32	63	2	9	32	442	27	142	64	270	110	331
S2	48	16	345	32	149	—	32	63	2	9	32	379	27	142	64	270	110	331
S2	49	16	345	32	149	—	32	63	2	11	32	442	27	142	64	270	110	331
S2	50	16	345	32	149	—	32	63	2	13	32	379	27	142	64	270	110	331

Table C.1 (continued). Element quantities for each panel of the structure as currently defined in MBEI.

Span	Panel	Panel Length (ft)	Deck				Superstructure												
			28	330	515	305	147	515	148	515	120	515	152	515	113	515	113	515
			Steel Deck with Open Grid	Metal Bridge Railing	Steel Protective Coating (330)	Assembly Joint without Seal	Steel Main Cables	Steel Protective Coating (147)	Secondary Steel Cables	Steel Protective Coating (148)	Steel Truss	Steel Protective Coating (120)	Steel Floorbeam	Steel Protective Coating (152)	Steel Stringer	Steel Protective Coating (113)	Steel Stringer (Joists)	Steel Protective Coating (113)
			ft^2	ft	ft^2	ft	ft	ft^2	each	ft^2	ft	ft^2	ft	ft^2	ft	ft^2	ft	ft^2
S2	51	16	345	32	149	--	32	63	2	14	32	442	27	142	64	270	110	331
S2	52	16	345	32	149	--	32	63	2	16	32	379	27	142	64	270	110	331
S2	53	16	345	32	149	--	32	63	2	17	32	442	27	142	64	270	110	331
S2	54	16	345	32	149	--	32	63	2	21	32	379	27	142	64	270	110	331
S2	55	16	345	32	149	--	32	63	2	24	32	442	27	142	64	270	110	331
S2	56	16	345	32	149	--	32	63	2	27	32	379	27	142	64	270	110	331
S2	57	16	345	32	149	--	32	63	2	31	32	442	27	142	64	270	110	331
S2	58	16	345	32	149	--	32	63	2	34	32	379	27	142	64	270	110	331
S2	59	16	345	32	149	--	32	63	2	40	32	442	27	142	64	270	110	331
S2	60	16	345	32	149	--	32	63	2	43	32	379	27	142	64	270	110	331
S2	61	16	345	32	149	--	32	63	2	48	32	442	27	142	64	270	110	331
S2	62	16	345	32	149	--	32	63	2	52	32	379	27	142	64	270	110	331
S2	63	16	345	32	149	--	32	63	2	58	32	442	27	142	64	270	110	331
S2	64	16	345	32	149	--	32	63	2	62	32	379	27	142	64	270	110	331
S2	65	16	345	32	149	--	32	63	2	70	32	442	27	142	64	270	110	331
S2	66	16	345	32	149	--	32	63	2	75	32	379	27	142	64	270	110	331
S2	67	17	367	34	158	--	34	67	--	--	34	442	27	142	68	287	110	331
S2	68	7.5	162	15	70	--	15	29	--	--	15	314	27	142	30	127	110	331
S3	69	16	345	32	149	--	32	63	2	75	32	379	27	142	64	270	110	331
S3	70	16	345	32	149	--	32	63	2	70	32	442	27	142	64	270	110	331
S3	71	16	345	32	149	--	32	63	2	62	32	379	27	142	64	270	110	331
S3	72	16	345	32	149	--	32	63	2	58	32	442	27	142	64	270	110	331
S3	73	16	345	32	149	--	32	63	2	52	32	379	27	142	64	270	110	331
S3	74	16	345	32	149	--	32	63	2	48	32	442	27	142	64	270	110	331
S3	75	16	345	32	149	--	32	63	2	43	32	379	27	142	64	270	110	331
S3	76	16	345	32	149	--	32	63	2	40	32	442	27	142	64	270	110	331
S3	77	16	345	32	149	--	32	63	2	34	32	379	27	142	64	270	110	331
S3	78	16	345	32	149	--	32	63	2	31	32	442	27	142	64	270	110	331
S3	79	16	345	32	149	--	32	63	2	28	32	379	27	142	64	270	110	331
S3	80	16	345	32	149	--	32	63	2	25	32	442	27	142	64	270	110	331
S3	81	16	345	32	149	--	32	63	2	20	32	379	27	142	64	270	110	331
S3	82	16	345	32	149	--	32	63	2	17	32	442	27	142	64	270	110	331
S3	83	16	345	32	149	--	32	63	2	14	32	379	27	142	64	270	110	331
S3	84	16	345	32	149	--	32	63	2	12	32	442	27	142	64	270	110	331
S3	85	16	345	32	149	--	32	63	2	10	32	379	27	142	64	270	110	331
S3	86	16	345	32	149	--	32	63	2	9	32	442	27	142	64	270	110	331
S3	87	16	345	32	149	--	32	63	2	7	32	379	27	142	64	270	110	331
S3	88	16	345	32	149	--	32	63	2	7	32	442	27	142	64	270	110	331
S3	89	16	345	32	149	--	32	63	2	6	32	379	27	142	64	270	110	331
S3	90	16	345	32	149	--	32	63	2	5	32	442	27	142	64	270	110	331
S3	91	16	345	32	149	--	32	63	2	5	32	379	27	142	64	270	110	331
S3	92	16	334	32	149	22	32	63	--	--	32	442	27	142	64	270	110	331
T1	93	16	334	32	149	--	32	63	--	--	32	442	53	283	64	270	110	331
T1	94	16	345	32	149	--	32	63	--	--	32	442	27	142	64	270	110	331
T1	95	16	345	32	149	--	32	63	--	--	32	442	27	142	64	270	110	331
T1	96	16	345	32	149	--	32	63	--	--	32	442	27	142	64	270	110	331
T2	97	16	345	32	149	--	32	63	--	--	32	469	27	142	64	270	110	331
T2	98	16	345	32	149	--	32	63	--	--	32	442	27	142	64	270	110	331
T2	99	16	345	32	149	--	32	63	--	--	32	442	27	142	64	270	110	331
T2	100	16	345	32	149	22	32	63	--	--	32	439	27	142	64	270	110	331
All	All	1,590	34,215	3,179	14,782	88	3,179	6,231	176	2,736	3,179	41,349	2,747	14,587	6,340	26,755	11,000	33,110

Table C.1 (continued). Element quantities for each panel of the structure as currently defined in MBEI.

Span	Panel	Panel Length (ft)	Superstructure				Substructure							
			311	515	313	515	202	515	207	515	210	521	215	521
			Movable Bearing	Steel Protective Coating (311)	Fixed Bearing	Steel Protective Coating (313)	Steel Column	Steel Protective Coating (202)	Steel Tower	Steel Protective Coating (207)	Reinforced Concrete Pier Wall	Concrete Protective Coating (210)	Reinforced Concrete Abutment	Concrete Protective Coating (215)
			each	ft^2	each	ft^2	each	ft^2	ft	ft^2	ft	ft^2	ft	ft^2
S1	1	16	--	--	2	10	--	--	--	--	--	--	35	700
S1	2	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	3	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	4	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	5	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	6	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	7	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	8	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	9	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	10	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	11	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	12	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	13	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	14	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	15	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	16	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	17	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	18	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	19	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	20	16	--	--	--	--	--	--	--	--	--	--	--	--
S1	21	7.5	--	--	--	--	--	--	130	9984	54	--	--	--
S2	22	17	--	--	--	--	--	--	--	--	--	--	--	--
S2	23	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	24	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	25	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	26	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	27	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	28	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	29	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	30	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	31	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	32	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	33	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	34	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	35	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	36	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	37	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	38	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	39	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	40	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	41	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	42	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	43	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	44	18.3	--	--	--	--	--	--	--	--	--	--	--	--
S2	45	18.3	--	--	--	--	--	--	--	--	--	--	--	--
S2	46	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	47	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	48	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	49	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	50	16	--	--	--	--	--	--	--	--	--	--	--	--

Table C.1 (continued). Element quantities for each panel of the structure as currently defined in MBEI.

			Superstructure				Substructure							
Span	Panel	Panel Length (ft)	311 Movable Bearing	515 Steel Protective Coating (311)	313 Fixed Bearing	515 Steel Protective Coating (313)	202 Steel Column	515 Steel Protective Coating (202)	207 Steel Tower	515 Steel Protective Coating (207)	210 Reinforced Concrete Pier Wall	521 Concrete Protective Coating (210)	215 Reinforced Concrete Abutment	521 Concrete Protective Coating (215)
			each	ft²	each	ft²	each	ft²	ft	ft²	ft	ft²	ft	ft²
S2	51	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	52	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	53	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	54	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	55	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	56	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	57	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	58	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	59	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	60	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	61	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	62	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	63	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	64	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	65	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	66	16	--	--	--	--	--	--	--	--	--	--	--	--
S2	67	17	--	--	--	--	--	--	--	--	--	--	--	--
S2	68	7.5	--	--	--	--	--	--	130	9984	54	--	--	--
S3	69	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	70	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	71	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	72	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	73	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	74	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	75	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	76	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	77	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	78	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	79	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	80	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	81	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	82	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	83	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	84	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	85	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	86	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	87	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	88	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	89	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	90	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	91	16	--	--	--	--	--	--	--	--	--	--	--	--
S3	92	16	--	--	2	10	--	--	39	842	30	450	--	--
T1	93	16	2	10	--	--	--	--	--	--	--	--	--	--
T1	94	16	--	--	--	--	--	--	--	--	--	--	--	--
T1	95	16	--	--	--	--	--	--	--	--	--	--	--	--
T1	96	16	--	--	--	--	--	--	--	--	--	--	--	--
T2	97	16	--	--	--	--	2	522	--	--	27	270	--	--
T2	98	16	--	--	--	--	--	--	--	--	--	--	--	--
T2	99	16	--	--	--	--	--	--	--	--	--	--	--	--
T2	100	16	--	--	2	10	--	--	--	--	--	--	35	1050
All	**All**	**1,590**	**2**	**10**	**6**	**30**	**2**	**522**	**299**	**20,810**	**165**	**720**	**70**	**1,750**

C.4 Element Total Quantities (Revised)

Table C.2 - Element quantities for each panel of the structure with applicable revisions highlighted (additions in green, reductions in red).

			Deck				Superstructure													
			28	330	515	305	147	515	148	515	163	515	164	515	165	515	120	515	152	515
Span	Panel	Length (ft)	Steel Deck with Open Grid	Metal Bridge Railing	Steel Protective Coating (330)	Assembly Joint without Seal	Steel Main Cables	Steel Protective Coating (147)	Secondary Steel Cables	Steel Protective Coating (148)	Steel Main Cable Bands/Splay Castings	Steel Protective Coating (163)	Steel Main Cable Saddles	Steel Protective Coating (164)	Steel Cable Anchorage Socket or Assembly	Steel Protective Coating (165)	Steel Truss	Steel Protective Coating (120)	Steel Floorbeam	Steel Protective Coating (152)
			ft^2	ft	ft^2	ft	ft	ft^2	each	ft^2	each	ft^2	each	ft^2	each	ft^2	ft	ft^2	ft	ft^2
S1	1	16	345	32	149	22	32	55	2	9	4	12	2	40	10	200	32	502	53	283
S1	2	16	345	32	149	--	32	59	2	11	2	6	--	--	4	4	32	442	27	142
S1	3	16	345	32	149	--	32	59	2	13	2	6	--	--	4	4	32	379	27	142
S1	4	16	345	32	149	--	32	59	2	14	2	6	--	--	4	4	32	442	27	142
S1	5	16	345	32	149	--	32	59	2	16	2	6	--	--	4	4	32	379	27	142
S1	6	16	345	32	149	--	32	59	2	17	2	6	--	--	4	4	32	442	27	142
S1	7	16	345	32	149	--	32	59	2	21	2	6	--	--	4	4	32	379	27	142
S1	8	16	345	32	149	--	32	59	2	24	2	6	--	--	4	4	32	442	27	142
S1	9	16	345	32	149	--	32	59	2	27	2	6	--	--	4	4	32	379	27	142
S1	10	16	345	32	149	--	32	59	2	31	2	6	--	--	4	4	32	442	27	142
S1	11	16	345	32	149	--	32	59	2	34	2	6	--	--	4	4	32	379	27	142
S1	12	16	345	32	149	--	32	59	2	40	2	6	--	--	4	4	32	442	27	142
S1	13	16	345	32	149	--	32	59	2	43	2	6	--	--	4	4	32	379	27	142
S1	14	16	345	32	149	--	32	59	2	48	2	6	--	--	4	4	32	442	27	142
S1	15	16	345	32	149	--	32	59	2	52	2	6	--	--	4	4	32	379	27	142
S1	16	16	345	32	149	--	32	59	2	58	2	6	--	--	4	4	32	442	27	142
S1	17	16	345	32	149	--	32	59	2	62	2	6	--	--	4	4	32	379	27	142
S1	18	16	345	32	149	--	32	59	2	70	2	6	--	--	4	4	32	442	27	142
S1	19	16	345	32	149	--	32	59	2	75	2	6	--	--	4	4	32	379	27	142
S1	20	16	345	32	149	--	32	63	--	--	--	--	--	--	--	--	32	442	27	142
S1	21	7.5	162	15	70	--	15	22	--	--	--	--	2	40	--	--	15	314	27	142
S2	22	17	367	34	158	--	34	63	2	75	2	6	--	--	4	4	34	379	27	142
S2	23	16	345	32	149	--	32	59	2	70	2	6	--	--	4	4	32	442	27	142
S2	24	16	345	32	149	--	32	59	2	62	2	6	--	--	4	4	32	379	27	142
S2	25	16	345	32	149	--	32	59	2	58	2	6	--	--	4	4	32	442	27	142
S2	26	16	345	32	149	--	32	59	2	52	2	6	--	--	4	4	32	379	27	142
S2	27	16	345	32	149	--	32	59	2	48	2	6	--	--	4	4	32	442	27	142
S2	28	16	345	32	149	--	32	59	2	43	2	6	--	--	4	4	32	379	27	142
S2	29	16	345	32	149	--	32	59	2	40	2	6	--	--	4	4	32	442	27	142
S2	30	16	345	32	149	--	32	59	2	34	2	6	--	--	4	4	32	379	27	142
S2	31	16	345	32	149	--	32	59	2	31	2	6	--	--	4	4	32	442	27	142
S2	32	16	345	32	149	--	32	59	2	27	2	6	--	--	4	4	32	379	27	142
S2	33	16	345	32	149	--	32	59	2	24	2	6	--	--	4	4	32	442	27	142
S2	34	16	345	32	149	--	32	59	2	21	2	6	--	--	4	4	32	379	27	142
S2	35	16	345	32	149	--	32	59	2	17	2	6	--	--	4	4	32	442	27	142
S2	36	16	345	32	149	--	32	59	2	16	2	6	--	--	4	4	32	379	27	142
S2	37	16	345	32	149	--	32	59	2	14	2	6	--	--	4	4	32	442	27	142
S2	38	16	345	32	149	--	32	59	2	13	2	6	--	--	4	4	32	379	27	142
S2	39	16	345	32	149	--	32	59	2	11	2	6	--	--	4	4	32	442	27	142
S2	40	16	345	32	149	--	32	59	2	9	2	6	--	--	4	4	32	379	27	142
S2	41	16	345	32	149	--	32	59	2	9	2	6	--	--	4	4	32	442	27	142
S2	42	16	345	32	149	--	32	59	2	8	2	6	--	--	4	4	32	379	27	142
S2	43	16	345	32	149	--	32	59	2	7	2	6	--	--	4	4	32	442	27	142
S2	44	18.3	361	37	170	22	37	68	2	7	2	6	--	--	4	4	37	442	27	142
S2	45	18.3	361	37	170	--	37	68	4	14	4	12	--	--	8	8	37	505	53	283
S2	46	16	345	32	149	--	32	59	2	8	2	6	--	--	4	4	32	379	27	142
S2	47	16	345	32	149	--	32	59	2	9	2	6	--	--	4	4	32	442	27	142
S2	48	16	345	32	149	--	32	59	2	9	2	6	--	--	4	4	32	379	27	142
S2	49	16	345	32	149	--	32	59	2	11	2	6	--	--	4	4	32	442	27	142
S2	50	16	345	32	149	--	32	59	2	13	2	6	--	--	4	4	32	379	27	142
S2	51	16	345	32	149	--	32	59	2	14	2	6	--	--	4	4	32	442	27	142

Table C.2 (continued). Element quantities for each panel of the structure with applicable revisions highlighted (additions in green, reductions in red).

Span	Panel	Length (ft)	Deck				Superstructure													
			28	330	515	305	147	515	148	515	163	515	164	515	165	515	120	515	152	515
			Steel Deck with Open Grid	Metal Bridge Railing	Steel Protective Coating (330)	Assembly Joint without Seal	Steel Main Cables	Steel Protective Coating (147)	Secondary Steel Cables	Steel Protective Coating (148)	Steel Main Cable Bands/Splay Castings	Steel Protective Coating (163)	Steel Main Cable Saddles	Steel Protective Coating (164)	Steel Cable Anchorage Socket or Assembly	Steel Protective Coating (165)	Steel Truss	Steel Protective Coating (120)	Steel Floorbeam	Steel Protective Coating (152)
			ft^2	ft	ft^2	ft	ft	ft^2	each	ft^2	each	ft^2	each	ft^2	each	ft^2	ft	ft^2	ft	ft^2
S2	52	16	345	32	149	--	32	59	2	16	2	6	--	--	4	4	32	379	27	142
S2	53	16	345	32	149	--	32	59	2	17	2	6	--	--	4	4	32	442	27	142
S2	54	16	345	32	149	--	32	59	2	21	2	6	--	--	4	4	32	379	27	142
S2	55	16	345	32	149	--	32	59	2	24	2	6	--	--	4	4	32	442	27	142
S2	56	16	345	32	149	--	32	59	2	27	2	6	--	--	4	4	32	379	27	142
S2	57	16	345	32	149	--	32	59	2	31	2	6	--	--	4	4	32	442	27	142
S2	58	16	345	32	149	--	32	59	2	34	2	6	--	--	4	4	32	379	27	142
S2	59	16	345	32	149	--	32	59	2	40	2	6	--	--	4	4	32	442	27	142
S2	60	16	345	32	149	--	32	59	2	43	2	6	--	--	4	4	32	379	27	142
S2	61	16	345	32	149	--	32	59	2	48	2	6	--	--	4	4	32	442	27	142
S2	62	16	345	32	149	--	32	59	2	52	2	6	--	--	4	4	32	379	27	142
S2	63	16	345	32	149	--	32	59	2	58	2	6	--	--	4	4	32	442	27	142
S2	64	16	345	32	149	--	32	59	2	62	2	6	--	--	4	4	32	379	27	142
S2	65	16	345	32	149	--	32	59	2	70	2	6	--	--	4	4	32	442	27	142
S2	66	16	345	32	149	--	32	59	2	75	2	6	--	--	4	4	32	379	27	142
S2	67	17	367	34	158	--	34	67	--	--	--	--	--	--	--	--	34	442	27	142
S2	68	7.5	162	15	70	--	15	22	--	--	--	--	2	40	--	--	15	314	27	142
S3	69	16	345	32	149	--	32	59	2	75	2	6	--	--	4	4	32	379	27	142
S3	70	16	345	32	149	--	32	59	2	70	2	6	--	--	4	4	32	442	27	142
S3	71	16	345	32	149	--	32	59	2	62	2	6	--	--	4	4	32	379	27	142
S3	72	16	345	32	149	--	32	59	2	58	2	6	--	--	4	4	32	442	27	142
S3	73	16	345	32	149	--	32	59	2	52	2	6	--	--	4	4	32	379	27	142
S3	74	16	345	32	149	--	32	59	2	48	2	6	--	--	4	4	32	442	27	142
S3	75	16	345	32	149	--	32	59	2	43	2	6	--	--	4	4	32	379	27	142
S3	76	16	345	32	149	--	32	59	2	40	2	6	--	--	4	4	32	442	27	142
S3	77	16	345	32	149	--	32	59	2	34	2	6	--	--	4	4	32	379	27	142
S3	78	16	345	32	149	--	32	59	2	31	2	6	--	--	4	4	32	442	27	142
S3	79	16	345	32	149	--	32	59	2	28	2	6	--	--	4	4	32	379	27	142
S3	80	16	345	32	149	--	32	59	2	25	2	6	--	--	4	4	32	442	27	142
S3	81	16	345	32	149	--	32	59	2	20	2	6	--	--	4	4	32	379	27	142
S3	82	16	345	32	149	--	32	59	2	17	2	6	--	--	4	4	32	442	27	142
S3	83	16	345	32	149	--	32	59	2	14	2	6	--	--	4	4	32	379	27	142
S3	84	16	345	32	149	--	32	59	2	12	2	6	--	--	4	4	32	442	27	142
S3	85	16	345	32	149	--	32	59	2	10	2	6	--	--	4	4	32	379	27	142
S3	86	16	345	32	149	--	32	59	2	9	2	6	--	--	4	4	32	442	27	142
S3	87	16	345	32	149	--	32	59	2	7	2	6	--	--	4	4	32	379	27	142
S3	88	16	345	32	149	--	32	59	2	7	2	6	--	--	4	4	32	442	27	142
S3	89	16	345	32	149	--	32	59	2	6	2	6	--	--	4	4	32	379	27	142
S3	90	16	345	32	149	--	32	59	2	5	2	6	--	--	4	4	32	442	27	142
S3	91	16	345	32	149	--	32	59	2	5	2	6	--	--	4	4	32	379	27	142
S3	92	16	334	32	149	22	32	55	--	--	--	--	2	40	--	--	32	442	27	142
T1	93	16	334	32	149	--	32	63	--	--	--	--	--	--	--	--	32	442	53	283
T1	94	16	345	32	149	--	32	63	--	--	--	--	--	--	--	--	32	442	27	142
T1	95	16	345	32	149	--	32	63	--	--	--	--	--	--	--	--	32	442	27	142
T1	96	16	345	32	149	--	32	63	--	--	--	--	--	--	--	--	32	442	27	142
T2	97	16	345	32	149	--	32	63	--	--	--	--	--	--	--	--	32	469	27	142
T2	98	16	345	32	149	--	32	63	--	--	--	--	--	--	--	--	32	442	27	142
T2	99	16	345	32	149	--	32	63	--	--	--	--	--	--	--	--	32	442	27	142
T2	100	16	345	32	149	22	32	55	--	--	2	6	--	--	10	200	32	439	27	142
All	All	1,590	34,215	3,179	14,782	88	3,179	5,855	176	2,736	180	540	8	160	368	748	3,179	41,349	2,747	14,587

Table C.2 (continued). Element quantities for each panel of the structure with applicable revisions highlighted (additions in green).

			Superstructure (cont.)								Substructure								
			113	515	113	515	311	515	313	515	202	515	207	515	210	521	215	521	221
Span	Panel	Length (ft)	Steel Stringer	Steel Protective Coating (113)	Steel Stringer (Joists)	Steel Protective Coating (113)	Movable Bearing	Steel Protective Coating (311)	Fixed Bearing	Steel Protective Coating (313)	Steel Column	Steel Protective Coating (202)	Steel Tower	Steel Protective Coating (207)	Reinforced Concrete Pier Wall	Concrete Protective Coating (210)	Reinforced Concrete Abutment	Concrete Protective Coating (215)	Concrete Anchorage Chamber
			ft	ft^2	ft	ft^2	each	ft^2	each	ft^2	each	ft^2	ft	ft^2	ft	ft^2	ft	ft^2	ft
S1	1	16	64	270	110	331	--	--	2	10	--	--	--	--	--	--	35	700	75
S1	2	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	3	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	4	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S1	5	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	6	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	7	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	8	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S1	9	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	10	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	11	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	12	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	13	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	14	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S1	15	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	16	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	17	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	18	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	19	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S1	20	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S1	21	7.5	30	127	110	331	--	--	--	--	--	--	1040	9984	54	--	--	--	--
S2	22	17	68	287	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	23	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	24	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	25	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	26	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S2	27	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	28	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	29	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	30	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	31	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	32	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S2	33	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	34	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	35	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	36	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	37	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	38	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S2	39	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	40	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	41	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	42	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	43	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	44	18.3	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	45	18.3	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	46	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	47	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	48	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	49	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	50	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	51	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--

Table C.2 (continued). Element quantities for each panel of the structure with applicable revisions highlighted (additions in green).

Span	Panel	Length (ft)	Superstructure (cont.)								Substructure										
			113	515	113	515	311	515	313	515	202	515	207	515	210	521	215	521	221
			Steel Stringer	Steel Protective Coating (113)	Steel Stringer (Joists)	Steel Protective Coating (113)	Movable Bearing	Steel Protective Coating (311)	Fixed Bearing	Steel Protective Coating (313)	Steel Column	Steel Protective Coating (202)	Steel Tower	Steel Protective Coating (207)	Reinforced Concrete Pier Wall	Concrete Protective Coating (210)	Reinforced Concrete Abutment	Concrete Protective Coating (215)	Concrete Anchorage Chamber
			ft	ft²	ft	ft²	each	ft²	each	ft²	each	ft²	ft	ft²	ft	ft²	ft	ft²	ft
S2	52	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	53	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	54	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	55	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	56	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	57	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S2	58	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	59	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	60	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	61	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	62	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	63	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S2	64	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	65	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	66	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	67	17	68	287	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S2	68	7.5	30	127	110	331	--	--	--	--	--	--	1040	9984	54	--	--	--	--
S3	69	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S3	70	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	71	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	72	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	73	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	74	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	75	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S3	76	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	77	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	78	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	79	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	80	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	81	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S3	82	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	83	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	84	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	85	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	86	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	87	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
S3	88	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	89	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	90	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	91	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
S3	92	16	64	270	110	331	--	--	2	10	--	--	39	842	30	450	--	--	--
T1	93	16	64	270	110	331	2	10	--	--	--	--	--	--	--	--	--	--	--
T1	94	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
T1	95	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
T1	96	16	64	270	110	331	4	8	--	--	--	--	--	--	--	--	--	--	--
T2	97	16	64	270	110	331	--	--	--	--	2	522	--	--	27	270	--	--	--
T2	98	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
T2	99	16	64	270	110	331	--	--	--	--	--	--	--	--	--	--	--	--	--
T2	100	16	64	270	110	331	--	--	2	10	--	--	--	--	--	--	35	1050	75
All	All	1,590	6,340	26,755	11,000	33,110	62	130	6	30	2	522	2,119	20,810	165	720	70	1,750	150

C.5 Applied Revisions to Element Total Quantities

- Added Element 163 – Steel Main Cable Bands/Splay Castings
  - Reduced area of steel protective coating on main cables for areas covered by cable bands and splay castings
- Added Element 164 – Steel Main Cable Saddles
  - Reduced area of steel protective coating on main cables for areas covered by saddles
- Added Element 165 – Steel Cable Anchorage Socket or Assembly
- Added Element 221 – Concrete Anchorage Chamber
- Included sliding plate stringer expansion bearings as Element 311 – Movable Bearing
- Revised quantification for the Steel Tower element to be the sum of the heights of the individual legs instead of a single height for the entire built-up tower support.

C.6 Narrative Condition Report

C.6.1 Deck

Deck (Element 28 – Steel Deck with Open Grid)

The open grid steel deck is in fair condition overall. There is moderate to significant wear in the wearing surface in the wheel-paths throughout except at isolated panels which have been replaced. There is typically moderate surface corrosion on the main supporting grid members with accelerated deterioration and corrosion in the areas of the deck grating at the top flanges of the transverse joists due to accumulation of debris and moisture retention at these locations.

Bridge Railing (Element 330 – Metal Bridge Railing)

The W-beam guide rail and metal curb and their protective coatings are in satisfactory condition. There are areas of minor impact damage throughout resulting in scrapes in the paint with minor surface corrosion. There are isolated locations of paint failures, predominantly at the outboard faces which are not exposed to traffic. There are random isolated locations where the connections between the W-beam guide rail and truss, between the curb angle and posts and at railing splice connections are loose or missing.

Deck Joints (Element 305 – Assembly Joint without Seal)

The sliding plate joints and the finger joint at the center of the main suspension span are in satisfactory condition with minor surface corrosion on the metalwork, primarily at the shoulders.

The sliding plate joint at the south abutment exhibits an up to 1/2” vertical misalignment between the upper and lower plates for the full width of the roadway.

C.6.2 Superstructure

Main Cables (Element 147 – Steel Main Cable)

The main cables and protective paint coating are in good condition with isolated location with paint failures with exposed circumferential wrapping wires exhibiting minor surface corrosion. Paint at the undersides of the cables is typically more deteriorated exhibiting areas of cracking paint and minor corrosion staining. At Panel Point 8 at the south cable, the threads of the north cable band nut are not fully engaged.

Suspender Ropes (Element 148 – Secondary Steel Cables)

The suspender ropes and protective coating are in good condition with random isolated locations noted with paint failures and minor surface corrosion.

Truss (Element 120 – Steel Truss)

The through truss stiffening the suspension spans and the similar continuous through truss carrying two spans at the north approach are in good condition. There is typically section loss and deformations caused by crevice corrosion at the faying surfaces of connected members and at horizontal connection plates, primarily at the lower lateral bracing connection plates, upper transverse struts and floorbeam bracket connections. The majority of these locations have been cleaned and spot painted. There are isolated locations where paint failures have occurred with minor to moderate surface corrosion on the truss members. There are isolated minor bends and deformations in the lateral bracing and transverse strut members likely caused during construction noted throughout.

Truss Bearings (Element 311 – Movable Bearing, Element 313 – Fixed Bearing)

The truss bearings are in satisfactory condition overall. The fixed bearings typically exhibiting minor to moderate crevice corrosion between the faying surfaces which may partially restrict rotation.

C.6.3 Floor System

Floorbeams (Element 152 – Steel Floorbeam)

The floorbeams are in satisfactory condition. Minor to moderate crevice corrosion between the connected members, primarily the bottom flange cover plate and top and bottom flange connection angles, is typical. There are random isolated locations with paint failures located throughout with minor surface corrosion, primarily at the bottom flange and lower web. There are isolated broken rivets at the top flange angle due to previous crevice corrosion which was arrested. Refer to Page C-18 for a drawing depicting the floor system defects noted in Panel 8 for which the 'subdivided units' method is used to further divide the floor system elements, dividing defects at the end 5'-0" of the floorbeams from those at the interior.

Stringers (Element 113 – Steel Stringer)

The stringers are in fair condition with minor to severe crevice corrosion typically found at the faying surfaces of members, commonly between the bottom flanges of the transverse joists and the top flanges of the longitudinal stringers. Crevice corrosion is also typically found between the stringer to floorbeam connection angles and web. There are isolated areas of paint failures with minor to moderate surface corrosion, typically at the bottom flange and lower web. Refer to Page C-18 for a drawing depicting the floor system defects noted in Panel 8 for which the 'subdivided units' method is used to further divide the floor system elements, dividing defects at the end 2'-0" of the stringers from those at the interior as well as the fascia and interior stringers.

Joists (Element 113 – Steel Stringer)

As noted above and affects both the longitudinal and transverse stringers, crevice corrosion is common between the top flange of the longitudinal stringers and the bottom flanges of the joists. The hold-down bolts attaching the joists to the stringers have broken due to the crevice corrosion at numerous locations. Refer to Page C-18 for a drawing depicting the floor system defects noted in Panel 8 for which the 'subdivided units' method is used to further divide the floor system elements, dividing defects at the end 3'-0" of the joists from the interior portions.

Stringer Bearings (311 – Movable Bearing)

The stringer sliding plate bearings located at the stringer relief joints in the deck are in fair condition overall with minor to significant wear at isolated locations and fretting corrosion between the sliding surfaces due to lack of adequate lubrication. Refer to Page C-18 for a drawing depicting the floor system defects noted in Panel 8 which includes four stringers bearings exhibiting wear and fretting corrosion.

C.6.4 Substructure

Abutments (215 – Reinforced Concrete Abutment)

The north and south abutments are in satisfactory condition overall with several patched areas throughout which remain sound. There are minor spalls at the top front edge of the bridge seat and several typical full-height vertical hairline shrinkage cracks with minor efflorescence. There is an isolated moderate spall with exposed and corroded reinforcing steel at the base of the stem at the west end of the south abutment.

Anchorage Chambers (221 – Reinforced Concrete Anchorage Chamber)

The north and south anchorage chambers are in satisfactory condition. There are several typical vertical hairline shrinkage cracks with minor to moderate efflorescence. There is minor intermittent efflorescence emanating from the interface with the ceiling at the top of the walls of the anchorage chambers. In the south anchorage chamber, there is an isolated moderate spall at the interior face of the east wall near the east cable entrance with exposed and corroded reinforcing steel.

Suspension Towers (207 – Steel Tower)

The steel suspension towers are in satisfactory condition overall with numerous areas of crevice corrosion, corrosion holes and section loss throughout. The protective coating on the members is in satisfactory condition with most areas with section loss painted over; however, isolated locations with paint failures and moderate active crevice corrosion and section loss exist. At the tower struts, there are numerous cracks in the web near the connection to the towers legs which have typically been arrested with drilled holes. There are several bracing members with minor deformations which appear to have been present since construction.

Pier Walls (210 – Reinforced Concrete Pier Wall)

The reinforced concrete pier walls which support the tower bases are in good condition with several patched areas which remain sound and a few isolated minor edge spalls.

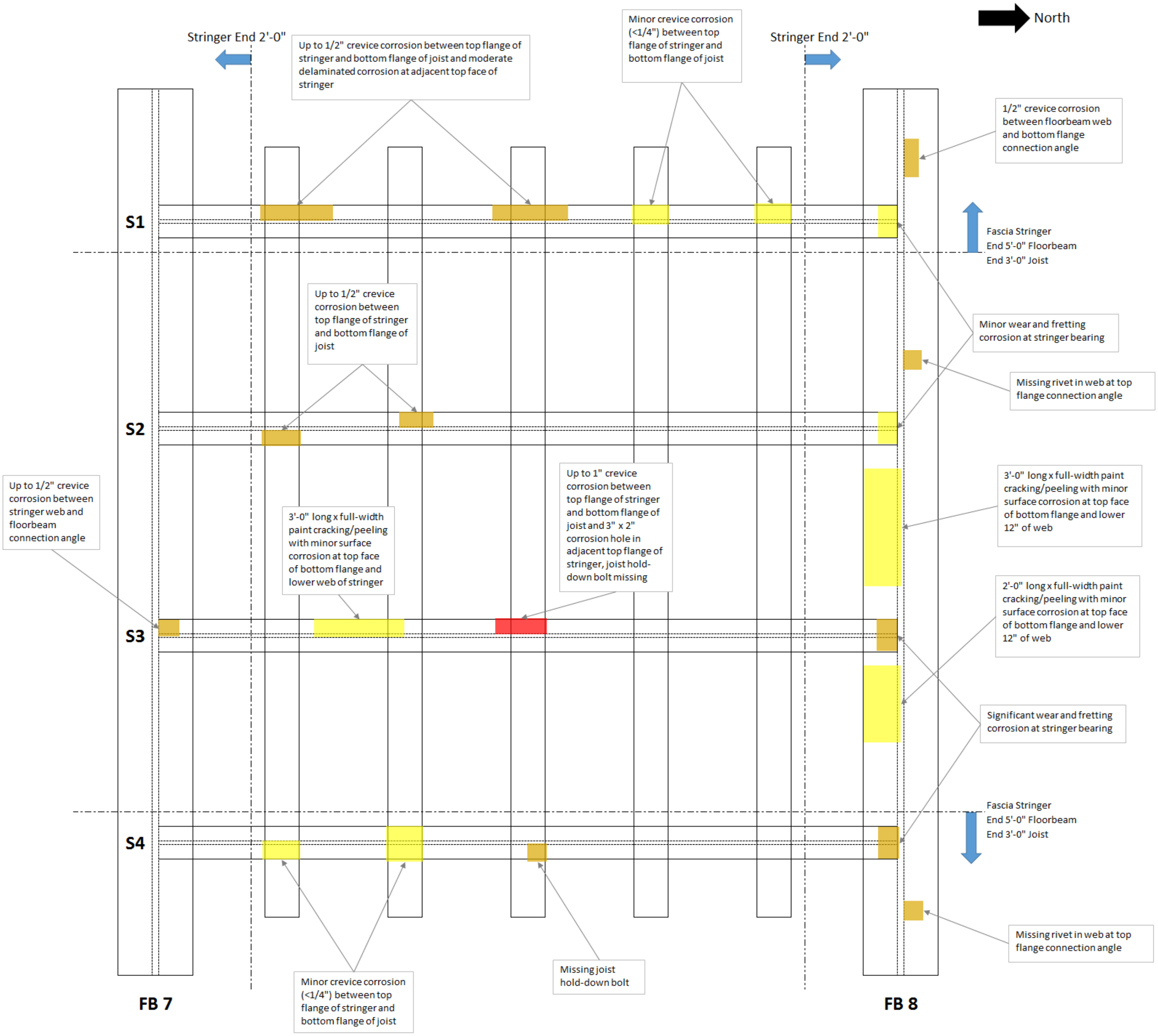


Figure C.3 - Drawing depicting the floor system defects at Panel 8 with dashed lines indicating boundaries of the subdivided units. Color indicates the condition state of the described defect (CS 2 defects shown in yellow, CS 3 defects shown in orange, CS 4 defects shown in red)

C.7 Element Quantity and Condition State Summaries (Current)

Table C.3 - Panel 1 "Element Quantity and Condition State Summary" (Current)

Legend
NBEs
BMEs
Defects

Bridge: Sample Bridge
Span: S1
Panel: 1
Length: 16 ft

Element #	Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4
28	Steel Deck with Open Grid	ft²	345	225	120	--	--
1000	*Corrosion*	*ft²*	120	--	120	--	--
330	Metal Bridge Railing	ft	32	21	10	1	--
1000	*Corrosion*	*ft*	7	--	7	--	--
1020	*Connection*	*ft*	1	--	--	1	--
7000	*Damage*	*ft*	3	--	3	--	--
515	Steel Protective Coating (330)	ft²	149	142	--	--	7
3420	*Peeling/Bubbling/Cracking*	*ft²*	5	--	--	--	5
7000	*Damage*	*ft²*	2	--	--	--	2
305	Assembly Joint without Seal	ft	22	17	5	--	--
2370	*Metal Deterioration or Damage*	*ft*	5	--	5	--	--
147	Steel Main Cables	ft	32	26	5	1	--
1000	*Corrosion*	*ft*	6	--	5	1	--
515	Steel Protective Coating (147)	ft²	63	57	--	5	1
3420	*Peeling/Bubbling/Cracking*	*ft²*	6	--	--	5	1
148	Secondary Steel Cables	each	2	1	1	--	--
1000	*Corrosion*	*each*	1	--	1	--	--
515	Steel Protective Coating (148)	ft²	9	8	--	--	1
3420	*Peeling/Bubbling/Cracking*	*ft²*	1	--	--	--	1
120	Steel Truss	ft	32	21	9	2	--
1000	*Corrosion*	*ft*	11	--	9	2	--
515	Steel Protective Coating (120)	ft²	502	478	--	20	4
3420	*Peeling/Bubbling/Cracking*	*ft²*	24	--	--	20	4
152	Steel Floorbeam	ft	53	29	21	3	--
1000	*Corrosion*	*ft*	24	--	21	3	--
515	Steel Protective Coating (152)	ft²	283	225	--	56	2
3420	*Peeling/Bubbling/Cracking*	*ft²*	58	--	--	56	2
113	Steel Stringer	ft	64	50	6	8	--
1000	*Corrosion*	*ft*	14	--	6	8	--
515	Steel Protective Coating (113)	ft²	270	240	--	21	9
3420	*Peeling/Bubbling/Cracking*	*ft²*	30	--	--	21	9
113	Steel Stringer (Joists)	ft	110	90	18	2	--
1000	*Corrosion*	*ft*	20	--	18	2	--
515	Steel Protective Coating (113)	ft²	331	291	--	39	1
3420	*Peeling/Bubbling/Cracking*	*ft²*	40	--	--	39	1
313	Fixed Bearing	each	2	--	2	--	--
2210	*Movement*	*each*	2	--	2	--	--
515	Steel Protective Coating (313)	ft²	10	7	--	--	3
3420	*Peeling/Bubbling/Cracking*	*ft²*	3	--	--	--	3
215	Reinforced Concrete Abutment	ft	35	5	27	3	--
1080	*Delamination/Spall/Patched Area*	*ft*	19	--	16	3	--
1120	*Efflorescence/Rust Staining*	*ft*	5	--	5	--	--
1130	*Cracking*	*ft*	6	--	6	--	--
521	Concrete Protective Coating (215)	ft²	700	543	--	135	22
3540	*Effectiveness*	*ft²*	157	--	--	135	22

Table C.4 - Panel 8 "Element Quantity and Condition State Summary" (Current)

Legend
NBEs
BMEs
Defects

Bridge: Sample Bridge
Span: S1
Panel: 8
Length: 16 ft

Element #	Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4
28	Steel Deck with Open Grid	ft^2	345	183	154	8	--
1000	*Corrosion*	*ft^2*	162	--	154	8	--
330	Metal Bridge Railing	ft	32	25	5	2	--
1000	*Corrosion*	*ft*	4	--	4	--	--
1020	*Connection*	*ft*	3	--	1	2	--
515	Steel Protective Coating (330)	ft^2	149	145	--	--	4
3420	*Peeling/Bubbling/Cracking*	*ft^2*	4	--	--	--	4
147	Steel Main Cables	ft	32	20	10	2	--
1000	*Corrosion*	*ft*	11	--	9	2	--
1020	*Connection*	*ft*	1	--	1	--	--
515	Steel Protective Coating (147)	ft^2	63	52	--	9	2
3420	*Peeling/Bubbling/Cracking*	*ft^2*	11	--	--	9	2
148	Secondary Steel Cables	each	2	1	1	--	--
1000	*Corrosion*	*each*	1	--	1	--	--
515	Steel Protective Coating (148)	ft^2	24	24	--	--	--
120	Steel Truss	ft	32	10	14	8	--
1000	*Corrosion*	*ft*	20	--	12	8	--
1900	*Distortion*	*ft*	2	--	2	--	--
515	Steel Protective Coating (120)	ft^2	442	398	--	26	18
3420	*Peeling/Bubbling/Cracking*	*ft^2*	44	--	--	26	18
152	Steel Floorbeam	ft	27	19	5	3	--
1000	*Corrosion*	*ft*	6	--	5	1	--
1020	*Connection*	*ft*	2	--	--	2	--
515	Steel Protective Coating (152)	ft^2	142	131	--	10	1
3420	*Peeling/Bubbling/Cracking*	*ft^2*	11	--	--	10	1
113	Steel Stringer	ft	64	47	7	8	2
1000	*Corrosion*	*ft*	16	--	7	7	2
1020	*Connection*	*ft*	1	--	--	1	--
515	Steel Protective Coating (113)	ft^2	270	255	--	--	15
3420	*Peeling/Bubbling/Cracking*	*ft^2*	15	--	--	--	15
113	Steel Stringer (Joists)	ft	110	99	4	6	1
1000	*Corrosion*	*ft*	9	--	4	4	1
1020	*Connection*	*ft*	2	--	--	2	--
515	Steel Protective Coating (113)	ft^2	331	321	--	--	10
3420	*Peeling/Bubbling/Cracking*	*ft^2*	10	--	--	--	10

Table C.5 - Panel 21 "Element Quantity and Condition State Summary" (Current)

Legend
NBEs
BMEs
Defects

Bridge: Sample Bridge
Span: S1
Panel: 21
Length: 8 ft

Element #	Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4
28	Steel Deck with Open Grid	ft^2	162	65	95	2	--
1000	*Corrosion*	*ft^2*	97	--	95	2	--
330	Metal Bridge Railing	ft	15	13	2	--	--
1000	*Corrosion*	*ft*	2	--	2	--	--
515	Steel Protective Coating (330)	ft^2	70	68	--	--	2
3420	*Peeling/Bubbling/Cracking*	*ft^2*	2	--	--	--	2
147	Steel Main Cables	ft	15	12	3	--	--
1000	*Corrosion*	*ft*	3	--	3	--	--
515	Steel Protective Coating (147)	ft^2	29	27	--	2	--
3420	*Peeling/Bubbling/Cracking*	*ft^2*	2	--	--	2	--
120	Steel Truss	ft	15	7	4	4	--
1000	*Corrosion*	*ft*	6	--	2	4	--
1020	*Connection*	*ft*	1	--	1	--	--
1900	*Distortion*	*ft*	1	--	1	--	--
515	Steel Protective Coating (120)	ft^2	314	295	--	10	9
3420	*Peeling/Bubbling/Cracking*	*ft^2*	19	--	--	10	9
152	Steel Floorbeam	ft	27	13	9	5	--
1000	*Corrosion*	*ft*	13	--	9	4	--
1020	*Connection*	*ft*	1	--	--	1	--
515	Steel Protective Coating (152)	ft^2	142	115	--	24	3
3420	*Peeling/Bubbling/Cracking*	*ft^2*	27	--	--	24	3
113	Steel Stringer	ft	30	20	2	8	--
1000	*Corrosion*	*ft*	10	--	2	8	--
515	Steel Protective Coating (113)	ft^2	127	111	--	7	9
3420	*Peeling/Bubbling/Cracking*	*ft^2*	16	--	--	7	9
113	Steel Stringer (Joists)	ft	110	91	14	5	--
1000	*Corrosion*	*ft*	19	--	14	5	--
515	Steel Protective Coating (113)	ft^2	331	292	--	34	5
3420	*Peeling/Bubbling/Cracking*	*ft^2*	39	--	--	34	5
207	Steel Tower	ft	130	59	51	20	--
1000	*Corrosion*	*ft*	55	--	40	15	--
1010	*Cracking*	*ft*	8	--	6	2	--
1020	*Connection*	*ft*	3	--	--	3	--
1900	*Distortion*	*ft*	5	--	5	--	--
515	Steel Protective Coating (207)	ft^2	9,984	9,718	--	260	6
3420	*Peeling/Bubbling/Cracking*	*ft^2*	266	--	--	260	6
210	Reinforced Concrete Pier Wall	ft	54	29	21	4	--
1080	*Delamination/Spall/Patched Area*	*ft*	20	--	16	4	--
1130	*Cracking*	*ft*	5	--	5	--	--

C.8 Element Quantity and Condition State Summaries (Revised)

Table C.6. - Panel 1 "Element Quantity and Condition State Summary" (Revised) with changes highlighted.

Legend
NBEs
BMEs
Defects

Bridge: Sample Bridge
Span: S1
Panel: 1
Length: 16 ft

Element #	Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4
28	Steel Deck with Open Grid	ft^2	345	114	166	65	--
1000	*Corrosion*	*ft^2*	81	--	81	--	--
XXXX	*Wear*	*ft^2*	150	--	85	65	--
330	Metal Bridge Railing	ft	32	21	10	1	--
1000	*Corrosion*	*ft*	7	--	7	--	--
1020	*Connection*	*ft*	1	--	--	1	--
7000	*Damage*	*ft*	3	--	3	--	--
515	Steel Protective Coating (330)	ft^2	149	142	--	--	7
3420	*Peeling/Bubbling/Cracking*	*ft^2*	5	--	--	--	5
7000	*Damage*	*ft^2*	2	--	--	--	2
305	Assembly Joint without Seal	ft	22	--	--	22	--
2370	*Metal Deterioration or Damage*	*ft*	--	--	--	--	--
XXXX	*Misalignment*	*ft*	22	--	--	22	--
147	Steel Main Cables	ft	32	26	5	1	--
1000	*Corrosion*	*ft*	6	--	5	1	--
515	Steel Protective Coating (147)	ft^2	55	49	--	5	1
3420	*Peeling/Bubbling/Cracking*	*ft^2*	6	--	--	5	1
148	Secondary Steel Cables	each	2	2	--	--	--
1000	*Corrosion*	*each*	--	--	--	--	--
515	Steel Protective Coating (148)	ft^2	9	8	--	--	1
3420	*Peeling/Bubbling/Cracking*	*ft^2*	1	--	--	--	1
163	Steel Main Cable Bands/Splay Castings	each	4	1	2	1	--
1000	*Corrosion*	*each*	3	--	2	1	--
515	Steel Protective Coating (163)	ft^2	12	6	--	5	1
3420	*Peeling/Bubbling/Cracking*	*ft^2*	6	--	--	5	1
164	Steel Main Cable Saddles	each	2	1	1	--	--
1000	*Corrosion*	*each*	1	--	1	--	--
515	Steel Protective Coating (164)	ft^2	40	33	--	5	2
3420	*Peeling/Bubbling/Cracking*	*ft^2*	7	--	--	5	2
165	Steel Cable Anchorage Socket or Assembly	each	10	3	5	2	--
1000	*Corrosion*	*each*	6	--	4	2	--
1020	*Connection*	*each*	1	--	1	--	--
515	Steel Protective Coating (165)	ft^2	200	177	--	20	3
3420	*Peeling/Bubbling/Cracking*	*ft^2*	23	--	--	20	3

Table C.6 (Continued) - Panel 1 "Element Quantity and Condition State Summary" (Revised) with changes highlighted

Legend
NBEs
BMEs
Defects

Bridge: Sample Bridge
Span: S1
Panel: 1
Length: 16 ft

Element #	Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4
120	Steel Truss	ft	32	21	9	2	--
1000	*Corrosion*	*ft*	11	--	9	2	--
515	Steel Protective Coating (120)	ft^2	502	478	--	20	4
3420	*Peeling/Bubbling/Cracking*	*ft^2*	24	--	--	20	4
152	Steel Floorbeam	ft	53	29	21	3	--
1000	*Corrosion*	*ft*	24	--	21	3	--
515	Steel Protective Coating (152)	ft^2	283	225	--	56	2
3420	*Peeling/Bubbling/Cracking*	*ft^2*	58	--	--	56	2
113	Steel Stringer	ft	64	50	6	8	--
1000	*Corrosion*	*ft*	14	--	6	8	--
515	Steel Protective Coating (113)	ft^2	270	240	--	21	9
3420	*Peeling/Bubbling/Cracking*	*ft^2*	30	--	--	21	9
113	Steel Stringer (Joists)	ft	110	90	18	2	--
1000	*Corrosion*	*ft*	20	--	18	2	--
515	Steel Protective Coating (113)	ft^2	331	291	--	39	1
3420	*Peeling/Bubbling/Cracking*	*ft^2*	40	--	--	39	1
313	Fixed Bearing	each	2	--	2	--	--
2210	*Movement*	*each*	2	--	2	--	--
515	Steel Protective Coating (313)	ft^2	10	7	--	--	3
3420	*Peeling/Bubbling/Cracking*	*ft^2*	3	--	--	--	3
215	Reinforced Concrete Abutment	ft	35	5	27	3	--
1080	*Delamination/Spall/Patched Area*	*ft*	19	--	16	3	--
1120	*Efflorescence/Rust Staining*	*ft*	5	--	5	--	--
1130	*Cracking*	*ft*	6	--	6	--	--
521	Concrete Protective Coating (215)	ft^2	700	543	--	135	22
3540	*Effectiveness*	*ft^2*	157	--	--	135	22
221	Concrete Anchorage Chamber	ft	75	25	38	12	--
1080	*Delamination/Spall/Patched Area*	*ft*	11	--	8	3	--
1090	*Exposed Rebar*	*ft*	5	--	--	5	--
1120	*Efflorescence/Rust Staining*	*ft*	27	--	25	2	--
1130	*Cracking*	*ft*	7	--	5	2	--

Table C.7 - Panel 8 "Element Quantity and Condition State Summary" (Revised) with changes highlighted.

Legend
NBEs
BMEs
Defects

Bridge: Sample Bridge
Span: S1
Panel: 8
Length: 16 ft

Element #	Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4
28	Steel Deck with Open Grid	ft^2	345	107	180	58	--
1000	*Corrosion*	*ft^2*	116	--	108	8	--
XXXX	*Wear*	*ft^2*	122	--	72	50	--
330	Metal Bridge Railing	ft	32	25	5	2	--
1000	*Corrosion*	*ft*	4	--	4	--	--
1020	*Connection*	*ft*	3	--	1	2	--
515	Steel Protective Coating (330)	ft^2	149	145	--	--	4
3420	*Peeling/Bubbling/Cracking*	*ft^2*	4	--	--	--	4
147	Steel Main Cables	ft	32	23	9	--	--
1000	*Corrosion*	*ft*	9	--	9	--	--
1020	*Connection*	*ft*	--	--	--	--	--
515	Steel Protective Coating (147)	ft^2	59	48	--	9	2
3420	*Peeling/Bubbling/Cracking*	*ft^2*	11	--	--	9	2
148	Secondary Steel Cables	each	2	2	--	--	--
1000	*Corrosion*	*each*	--	--	--	--	--
515	Steel Protective Coating (148)	ft^2	24	24	--	--	--
163	Steel Main Cable Bands/Splay Castings	each	2	--	1	1	--
1000	*Corrosion*	*each*	1	--	--	1	--
1020	*Connection*	*each*	1	--	1	--	--
515	Steel Protective Coating (163)	ft^2	6	1	--	3	2
3420	*Peeling/Bubbling/Cracking*	*ft^2*	5	--	--	3	2
165	Steel Cable Anchorage Socket or Assembly	each	4	3	1	--	--
1000	*Corrosion*	*each*	1	--	1	--	--
515	Steel Protective Coating (165)	ft^2	4	3	--	--	1
3420	*Peeling/Bubbling/Cracking*	*ft^2*	1	--	--	--	1
120	Steel Truss	ft	32	10	14	8	--
1000	*Corrosion*	*ft*	20	--	12	8	--
1900	*Distortion*	*ft*	2	--	2	--	--
515	Steel Protective Coating (120)	ft^2	442	398	--	26	18
3420	*Peeling/Bubbling/Cracking*	*ft^2*	44	--	--	26	18

Table C.7 (Continued) - Panel 8 "Element Quantity and Condition State Summary" (Revised) with changes highlighted. Note subdivided unit approach for elements of the floor system (refer to Drawing on Page C-18).

Legend
NBEs
BMEs
Defects

Bridge: Sample Bridge
Span: S1
Panel: 8
Length: 16 ft

Element #	Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4
152	Steel Floorbeam (Total)	ft	27	19	5	3	--
1000	*Corrosion*	*ft*	6	--	5	1	--
1020	*Connection*	*ft*	2	--	--	2	--
152	Steel Floorbeam **(End 5'-0")**	ft	10	8	--	2	--
1000	*Corrosion*	*ft*	1	--	--	1	--
1020	*Connection*	*ft*	1	--	--	1	--
152	Steel Floorbeam **(Interior 16'-8")**	ft	17	11	5	1	--
1000	*Corrosion*	*ft*	5	--	5	--	--
1020	*Connection*	*ft*	1	--	--	1	--
515	Steel Protective Coating (152)	ft^2	142	131	--	10	1
3420	*Peeling/Bubbling/Cracking*	*ft^2*	11	--	--	10	1
113	Steel Stringer (Total)	ft	64	43	9	10	2
1000	*Corrosion*	*ft*	16	--	7	7	2
1020	*Connection*	*ft*	1	--	--	1	--
XXXX	*Wear*	*ft*	4	--	2	2	--
113	Steel Stringer **(End 2'-0")**	ft	16	11	2	3	--
1000	*Corrosion*	*ft*	1	--	--	1	--
XXXX	*Wear*	*ft*	4	--	2	2	--
113	Steel Stringer **(Fascia, excluding End 2'-0")**	ft	24	16	4	4	--
1000	*Corrosion*	*ft*	8	--	4	4	--
113	Steel Stringer **(Interior, excluding End 2'-0")**	ft	24	18	3	2	1
1000	*Corrosion*	*ft*	6	--	3	2	1
515	Steel Protective Coating (113)	ft^2	270	255	--	--	15
3420	*Peeling/Bubbling/Cracking*	*ft^2*	15	--	--	--	15
113	Steel Stringer (Joists, Total)	ft	110	99	4	6	1
1000	*Corrosion*	*ft*	9	--	4	4	1
1020	*Connection*	*ft*	2	--	--	2	--
113	Steel Stringer **(Joists, End 3'-0")**	ft	30	23	4	3	--
1000	*Corrosion*	*ft*	6	--	4	2	--
1020	*Connection*	*ft*	1	--	--	1	--
113	Steel Stringer **(Joists, Interior 16'-0")**	ft	80	76	--	3	1
1000	*Corrosion*	*ft*	3	--	--	2	1
1020	*Connection*	*ft*	1	--	--	1	--
515	Steel Protective Coating (113)	ft^2	331	321	--	--	10
3420	*Peeling/Bubbling/Cracking*	*ft^2*	10	--	--	--	10
311	Movable Bearing (Stringer Bearings)	each	4	--	2	2	--
XXXX	*Wear*	*each*	4	--	2	2	--
515	Steel Protective Coating (311)	ft^2	8	5	--	--	3
3420	*Peeling/Bubbling/Cracking*	*ft^2*	3	--	--	--	3

Table C.8 - Panel 21 "Element Quantity and Condition State Summary" (Revised) with changes highlighted.

Legend
NBEs
BMEs
Defects

Bridge: Sample Bridge
Span: S1
Panel: 21
Length: 8 ft

Element #	Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4
28	Steel Deck with Open Grid	ft²	162	21	108	33	--
1000	*Corrosion*	*ft²*	58	--	56	2	--
XXXX	*Wear*	*ft²*	83	--	52	31	--
330	Metal Bridge Railing	ft	15	13	2	--	--
1000	*Corrosion*	*ft*	2	--	2	--	--
515	Steel Protective Coating (330)	ft²	70	68	--	--	2
3420	*Peeling/Bubbling/Cracking*	*ft²*	2	--	--	--	2
147	Steel Main Cables	ft	15	12	3	--	--
1000	*Corrosion*	*ft*	3	--	3	--	--
515	Steel Protective Coating (147)	ft²	22	20	--	2	--
3420	*Peeling/Bubbling/Cracking*	*ft²*	2	--	--	2	--
164	Steel Main Cable Saddles	each	2	--	2	--	--
1000	*Corrosion*	*each*	2	--	2	--	--
515	Steel Protective Coating (164)	ft²	40	25	--	9	6
3420	*Peeling/Bubbling/Cracking*	*ft²*	15	--	--	9	6
120	Steel Truss	ft	15	7	4	4	--
1000	*Corrosion*	*ft*	6	--	2	4	--
1020	*Connection*	*ft*	1	--	1	--	--
1900	*Distortion*	*ft*	1	--	1	--	--
515	Steel Protective Coating (120)	ft²	314	295	--	10	9
3420	*Peeling/Bubbling/Cracking*	*ft²*	19	--	--	10	9
152	Steel Floorbeam	ft	27	13	9	5	--
1000	*Corrosion*	*ft*	13	--	9	4	--
1020	*Connection*	*ft*	1	--	--	1	--
515	Steel Protective Coating (152)	ft²	142	115	--	24	3
3420	*Peeling/Bubbling/Cracking*	*ft²*	27	--	--	24	3
113	Steel Stringer	ft	30	20	2	8	--
1000	*Corrosion*	*ft*	10	--	2	8	--
515	Steel Protective Coating (113)	ft²	127	111	--	7	9
3420	*Peeling/Bubbling/Cracking*	*ft²*	16	--	--	7	9
113	Steel Stringer (Joists)	ft	110	91	14	5	--
1000	*Corrosion*	*ft*	19	--	14	5	--
515	Steel Protective Coating (113)	ft²	331	292	--	34	5
3420	*Peeling/Bubbling/Cracking*	*ft²*	39	--	--	34	5
207	Steel Tower	ft	1,040	806	179	55	--
1000	*Corrosion*	*ft*	218	--	168	50	--
1010	*Cracking*	*ft*	8	--	6	2	--
1020	*Connection*	*ft*	3	--	--	3	--
1900	*Distortion*	*ft*	5	--	5	--	--
515	Steel Protective Coating (207)	ft²	9,984	9,718	--	260	6
3420	*Peeling/Bubbling/Cracking*	*ft²*	266	--	--	260	6
210	Reinforced Concrete Pier Wall	ft	54	29	21	4	--
1080	*Delamination/Spall/Patched Area*	*ft*	20	--	16	4	--
1130	*Cracking*	*ft*	5	--	5	--	--

C.9 Notable Changes to Element Quantities and Condition State Summaries

- The "wear" defect category was added which was used to represent the typical section loss in the top surface of the open steel grid deck wearing surface in the wheel-paths which was not previously represented in the element data.
- Stringer bearings are now included in the element analysis whereas only the movable and fixed truss bearings were previously included.
- Numerous stringer bearings of the structure are lacking lubrication and exhibit wear at the sliding surfaces which can be documented in the element data with the addition of the "wear" defect category.
- The "misalignment" defect was added which was most notably used to represent the vertical misalignment measuring up to 1/2" between the sliding plates of the joint at the south abutment which was not previously applicable to the available defect categories.
- Element 221 – Concrete Anchorage Chamber was added which can be used to track the conditions of the reinforced concrete anchorage chambers which were previously not included in the element analysis.
- The steel suspension towers quantity has been increased greatly, totaling the heights of each individual support comprising the tower, rather than a single height quantity for the entire tower. As the Steel Towers at this particular structure are comprised of two legs comprised of four individual built-up column supports (8 column supports for each tower), the quantity for the Steel Tower element was multiplied by eight. This results in a much more accurate representation of the tower by eliminating the distribution of defects at a single support across the entire tower for that given height, decreasing the percentage of the total element quantity in deteriorated condition states.
  - Similarly, the quantity for the Anchorage Bent was revised to count both legs individually, effectively doubling the quantity.
- The main cable sub-elements which were added capture the condition of the saddles, splay castings, anchorage eyebar assemblies, cable bands and suspender rope sockets which were previously only representable through the main cable and secondary cable elements. This allowed differentiation of defects noted at the sub-elements which may be more or less critical than those which may be assumed with a less detailed element summary. Defects noted at the main cable bands, splay castings, and suspender rope sockets which were previously attributed to the main cable or suspender ropes, could instead be attributed to the appropriate sub-element.

- Divided quantities for floor system elements (152 – Steel Floorbeam and 113 – Steel Stringer) at each panel into smaller portions for the ends and interior or exterior members using the ‘subdivided units’ approach which provides a more detailed summary of the floor system elements.

Appendix D – Example Project Planning Spreadsheet

APPENDIX D - EXAMPLE PROJECT PLANNING SPREADSHEET

A distinctive issue with Big Bridges is the need for more detailed data and analysis for project planning. Section 5.2.6 noted that detailed project planning functionality may be of considerably more value to Big Bridges than to average-size structures. Rather than reconfigure its enterprise inspection process and bridge management system to incorporate detailed features such as subdivided unites or enumerated damages, the agency may want to supplement its BMS with a separate but connected spreadsheet analysis that is used only on Big Bridges, keeping all other bridges in a simpler framework.

NCHRP Project 12-67 (Patidar et al 2007) developed this type of spreadsheet. While the main goal of that study was to develop a network level optimization procedure, the project also produced a spreadsheet module to perform a project development analysis to generate inputs to the network optimization. The spreadsheet can be obtained from the Transportation Research Board web site at http://www.trb.org/Main/Public/Blurbs/159292.aspx. Included in the Excel model are worksheets to:

- Perform life cycle cost analysis for an individual element, which can be a part of a subdivided structure unit if desired (Table D1). This would be used for selecting a preservation treatment based on minimization of long-term cost.
- Analyze safety and mobility deficiencies to quantify the impact on road users and the potential benefit if deficiencies are corrected. (Table D2).
- Combine all the element preservation actions and functional improvements on a bridge into a work candidate (Table D3).
- Prepare a long-term life cycle activity profile projecting the future projects likely to be needed on the bridge (Table D4).
- Present a digital dashboard that brings together a set of alternatives of scope and timing to aid in developing a project plan for the bridge (Table D5).

With a spreadsheet-based approach each bridge can be stored in a separate file, and configured to fit the needs of the structure. For an example where maintenance of traffic flow is a concern, the preservation portion of the analysis can be separately performed for each structure unit to help in dividing a project into phases; or the agency may choose to focus on the needs above the deck in a separate project from needs below the deck. Big Bridges tend to have unit costs and indirect costs that significantly differ from most of an agency's inventory, so the flexibility of a spreadsheet model can allow the agency to tailor these planning metrics to fit the specific bridge under consideration. Separate alternative concepts of a project can be saved in separate files for later refinement and evaluation.

When the element level analysis is performed for separate subdivided units of a bridge, the combined scoping worksheet in Table D3 and the digital dashboard in Table D5 can act as a network-level analysis that treats each bridge as a network of structure units. It then becomes a tool for prioritizing investments and for grouping them into projects in a way that minimizes life cycle costs while providing the ability to visualize the accomplishment of transportation service performance objectives.

Relying on spreadsheets for Big Bridge analysis requires some Excel development skill and time to be devoted to each individual bridge, but may be justified by ensuring that a project definition is an exact fit to the needs of the agency and the bridge.

Table D1. Element Life Cycle Cost Analysis Worksheet

Bridge Level | Dashboard | Menu | Roadway | Element | Scoping | Performance | LCAP

Computation Detail for Bridge-Level Analysis

Element Performance of Bridge 15 0015L - HUNTERS CREEK

This worksheet is not intended to be edited and should not be referenced by formulas.

Auto MRRI (2 of 3) 2011 (5 of 20)

Element 38/2 - Bare Concrete Slab (1 of 5)

Inputs

Field	Value	Description
BaseYear	2007	First year of program
RestYears	7	Rest period after intervention
Quantity	330	Element quantity (sq.m.)
StateCnt	5	Number of condition states
HealthWt	806.59	Health index weight
FailCost	806.59	Failure unit cost ($/sq.m.)
FailProb	3.56	Failure probability (%)
TEV	266173	Total element value (for health ix)

Deterioration model

States	To 1	2	3	4	5
From 1	97.47	2.53	0.00	0.00	0.00
2	0.00	95.92	4.08	0.00	0.00
3	0.00	0.00	96.44	3.56	0.00
4	0.00	0.00	0.00	96.44	3.56
5	0.00	0.00	0.00	0.00	96.44

Percent making transition from each state to each state in one year

Long-term actions

State	Action	LT unit cost	End cond	LTC
1	0 - DN	5.05	42.93	716
2	0 - DN	15.01	28.78	1426
3	0 - DN	33.37	18.81	2071
4	0 - DN	80.10	7.05	1864
5	1 - Repair&Pro	192.31	2.43	1540
Sum			100.00	7617

LT unit cost = Pontis long term unit cost ($/sq.m.)
Selected actions have lowest LT unit cost for each state
End cond = Condition at end of program horizon (from table below)
LTC = Long-term preservation cost ($)

Scope items affecting this element

Action type	State/Action	ActPct	Effectiveness 1	2	3	4	5

ActPct = Of quantity in this state, the percent that was treated
Effectiveness = Probability of each state immediately after the action (beginning of year)

Condition forecast

	Year	Condition states 1	2	3	4	5	Health Index CEV	Health	Economic failure FailPct	FailRisk
	State weight	1	0.75	0.5	0.25	0				
Insp	1997	100.00	0.00	0.00	0.00	0.00	266173	100		
	2007	77.39	18.71	3.53	0.35	0.02	248278	93	0.0008	2
	2008	75.44	19.91	4.16	0.46	0.04	246376	93	0.0013	3
	2009	73.53	21.00	4.83	0.59	0.05	244456	92	0.0018	5
	2010	71.67	22.01	5.51	0.74	0.07	242519	91	0.0026	7
	2011	69.85	22.92	6.21	0.91	0.10	240567	90	0.0035	9
	2012	68.09	23.75	6.93	1.10	0.13	238600	90	0.0047	12
	2013	66.36	24.51	7.65	1.31	0.17	236619	89	0.0061	16
	2014	64.69	25.19	8.38	1.53	0.22	234624	88	0.0077	21
	2015	63.05	25.79	9.11	1.78	0.27	232616	87	0.0097	26
	2016	61.45	26.34	9.84	2.04	0.34	230597	87	0.0119	32
	2017	59.90	26.82	10.56	2.32	0.41	228566	86	0.0145	39
	2018	58.38	27.24	11.28	2.61	0.49	226524	85	0.0175	46
	2019	56.91	27.60	11.99	2.92	0.58	224473	84	0.0208	55
	2020	55.47	27.92	12.69	3.24	0.69	222412	84	0.0245	65
	2021	54.06	28.18	13.38	3.58	0.80	220343	83	0.0286	76
	2022	52.70	28.40	14.05	3.93	0.93	218266	82	0.0331	88
	2023	51.36	28.57	14.71	4.29	1.07	216182	81	0.0381	101
	2024	50.06	28.71	15.35	4.66	1.22	214092	80	0.0435	116
	2025	48.80	28.80	15.97	5.04	1.39	211995	80	0.0494	132
	2026	47.56	28.86	16.58	5.43	1.57	209894	79	0.0558	149
Rest	2027	46.36	28.89	17.17	5.82	1.76	207788	78	0.0627	167

Deterioration - percent by condition state

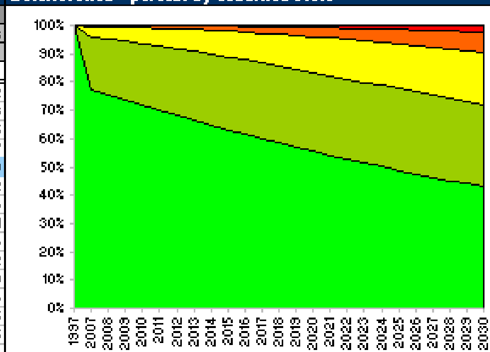
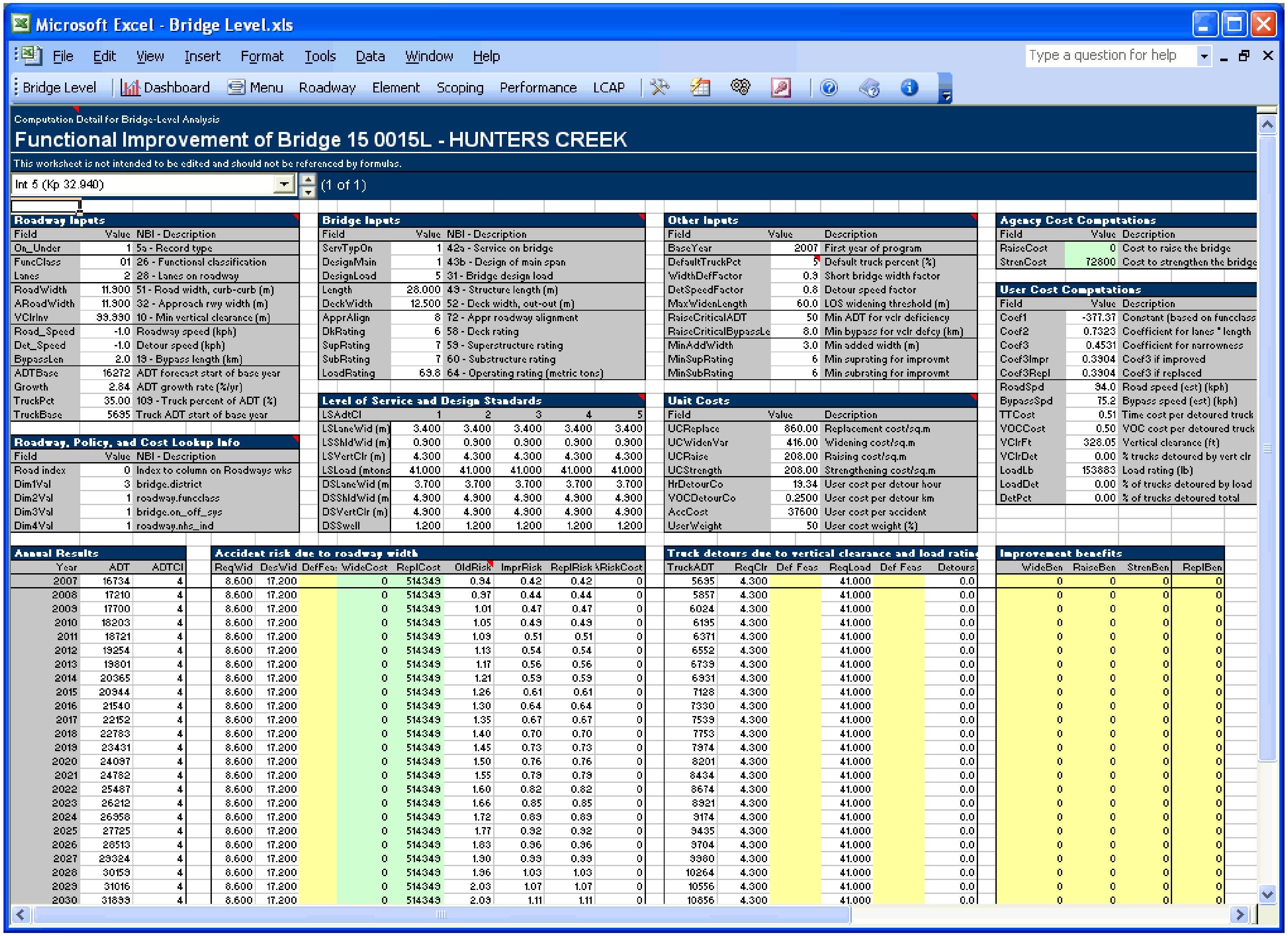


Table D2. Functional Needs Analysis Worksheet



Microsoft Excel - Bridge Level.xls

Computation Detail for Bridge-Level Analysis

Functional Improvement of Bridge 15 0015L - HUNTERS CREEK

This worksheet is not intended to be edited and should not be referenced by formulas.

Int 5 (Kp 32.940) (1 of 1)

Roadway Inputs

Field	Value	NBI - Description
On_Under	1	5a - Record type
FuncClass	01	26 - Functional classification
Lanes	2	28 - Lanes on roadway
RoadWidth	11.900	51 - Road width, curb-curb (m)
ARoadWidth	11.900	32 - Approach rwy width (m)
VClrInv	99.990	10 - Min vertical clearance (m)
Road_Speed	-1.0	Roadway speed (kph)
Det_Speed	-1.0	Detour speed (kph)
BypassLen	2.0	19 - Bypass length (km)
ADTBase	16272	ADT forecast start of base year
Growth	2.84	ADT growth rate (%/yr)
TruckPct	35.00	109 - Truck percent of ADT (%)
TruckBase	5695	Truck ADT start of base year

Roadway, Policy, and Cost Lookup Info

Field	Value	NBI - Description
Road index	0	Index to column on Roadways wks
Dim1Val	3	bridge.district
Dim2Val	1	roadway.funcclass
Dim3Val	1	bridge.on_off_sys
Dim4Val	1	roadway.nhs_ind

Bridge Inputs

Field	Value	NBI - Description
ServTypOn	1	42a - Service on bridge
DesignMain	1	43b - Design of main span
DesignLoad	5	31 - Bridge design load
Length	28.000	49 - Structure length (m)
DeckWidth	12.500	52 - Deck width, out-out (m)
ApprAlign	8	72 - Appr roadway alignment
DkRating	6	58 - Deck rating
SupRating	7	59 - Superstructure rating
SubRating	7	60 - Substructure rating
LoadRating	69.8	64 - Operating rating (metric tons)

Level of Service and Design Standards

LSAdtCl	1	2	3	4	5
LSLaneWid (m)	3.400	3.400	3.400	3.400	3.400
LSShldWid (m)	0.900	0.900	0.900	0.900	0.900
LSVertClr (m)	4.300	4.300	4.300	4.300	4.300
LSLoad (mtons	41.000	41.000	41.000	41.000	41.000
DSLaneWid (m	3.700	3.700	3.700	3.700	3.700
DSShldWid (m	4.900	4.900	4.900	4.900	4.900
DSVertClr (m)	4.900	4.900	4.900	4.900	4.900
DSSwell	1.200	1.200	1.200	1.200	1.200

Other Inputs

Field	Value	Description
BaseYear	2007	First year of program
DefaultTruckPct	5	Default truck percent (%)
WidthDefFactor	0.9	Short bridge width factor
DetSpeedFactor	0.8	Detour speed factor
MaxWidenLength	60.0	LOS widening threshold (m)
RaiseCriticalADT	50	Min ADT for vclr deficiency
RaiseCriticalBypassLe	8.0	Min bypass for vclr defcy (km)
MinAddWidth	3.0	Min added width (m)
MinSupRating	6	Min suprating for improvmt
MinSubRating	6	Min subrating for improvmt

Unit Costs

Field	Value	Description
UCReplace	860.00	Replacement cost/sq.m
UCWidenVar	416.00	Widening cost/sq.m
UCRaise	208.00	Raising cost/sq.m
UCStrength	208.00	Strengthening cost/sq.m
HrDetourCo	19.34	User cost per detour hour
VOCDetourCo	0.2500	User cost per detour km
AccCost	37600	User cost per accident
UserWeight	50	User cost weight (%)

Agency Cost Computations

Field	Value	Description
RaiseCost	0	Cost to raise the bridge
StrenCost	72800	Cost to strengthen the bridge

User Cost Computations

Field	Value	Description
Coef1	-377.37	Constant (based on funcclass
Coef2	0.7323	Coefficient for lanes * length
Coef3	0.4531	Coefficient for narrowness
Coef3Impr	0.3904	Coef3 if improved
Coef3Repl	0.3904	Coef3 if replaced
RoadSpd	94.0	Road speed (est) (kph)
BypassSpd	75.2	Bypass speed (est) (kph)
TTCost	0.51	Time cost per detoured truck
VOCCost	0.50	VOC cost per detoured truck
VClrFt	328.05	Vertical clearance (ft)
VClrDet	0.00	% trucks detoured by vert clr
LoadLb	153883	Load rating (lb)
LoadDet	0.00	% of trucks detoured by load
DetPct	0.00	% of trucks detoured total

Annual Results / **Accident risk due to roadway width**

Year	ADT	ADTCl	ReqWid	DesWid	DefFeas	WideCost	ReplCost	OldRisk	ImprRisk	ReplRisk	∆RiskCost
2007	16734	4	8.600	17.200		0	514349	0.94	0.42	0.42	0
2008	17210	4	8.600	17.200		0	514349	0.97	0.44	0.44	0
2009	17700	4	8.600	17.200		0	514349	1.01	0.47	0.47	0
2010	18203	4	8.600	17.200		0	514349	1.05	0.49	0.49	0
2011	18721	4	8.600	17.200		0	514349	1.09	0.51	0.51	0
2012	19254	4	8.600	17.200		0	514349	1.13	0.54	0.54	0
2013	19801	4	8.600	17.200		0	514349	1.17	0.56	0.56	0
2014	20365	4	8.600	17.200		0	514349	1.21	0.59	0.59	0
2015	20944	4	8.600	17.200		0	514349	1.26	0.61	0.61	0
2016	21540	4	8.600	17.200		0	514349	1.30	0.64	0.64	0
2017	22152	4	8.600	17.200		0	514349	1.35	0.67	0.67	0
2018	22783	4	8.600	17.200		0	514349	1.40	0.70	0.70	0
2019	23431	4	8.600	17.200		0	514349	1.45	0.73	0.73	0
2020	24097	4	8.600	17.200		0	514349	1.50	0.76	0.76	0
2021	24782	4	8.600	17.200		0	514349	1.55	0.79	0.79	0
2022	25487	4	8.600	17.200		0	514349	1.60	0.82	0.82	0
2023	26212	4	8.600	17.200		0	514349	1.66	0.85	0.85	0
2024	26958	4	8.600	17.200		0	514349	1.72	0.89	0.89	0
2025	27725	4	8.600	17.200		0	514349	1.77	0.92	0.92	0
2026	28513	4	8.600	17.200		0	514349	1.83	0.96	0.96	0
2027	29324	4	8.600	17.200		0	514349	1.90	0.99	0.99	0
2028	30159	4	8.600	17.200		0	514349	1.96	1.03	1.03	0
2029	31016	4	8.600	17.200		0	514349	2.03	1.07	1.07	0
2030	31899	4	8.600	17.200		0	514349	2.09	1.11	1.11	0

Truck detours due to vertical clearance and load rating / **Improvement benefits**

Year	TruckADT	ReqClr	Def Feas	ReqLoad	Def Feas	Detours	WideBen	RaiseBen	StrenBen	ReplBen
2007	5695	4.300		41.000		0.0	0	0	0	0
2008	5857	4.300		41.000		0.0	0	0	0	0
2009	6024	4.300		41.000		0.0	0	0	0	0
2010	6195	4.300		41.000		0.0	0	0	0	0
2011	6371	4.300		41.000		0.0	0	0	0	0
2012	6552	4.300		41.000		0.0	0	0	0	0
2013	6739	4.300		41.000		0.0	0	0	0	0
2014	6931	4.300		41.000		0.0	0	0	0	0
2015	7128	4.300		41.000		0.0	0	0	0	0
2016	7330	4.300		41.000		0.0	0	0	0	0
2017	7539	4.300		41.000		0.0	0	0	0	0
2018	7753	4.300		41.000		0.0	0	0	0	0
2019	7974	4.300		41.000		0.0	0	0	0	0
2020	8201	4.300		41.000		0.0	0	0	0	0
2021	8434	4.300		41.000		0.0	0	0	0	0
2022	8674	4.300		41.000		0.0	0	0	0	0
2023	8921	4.300		41.000		0.0	0	0	0	0
2024	9174	4.300		41.000		0.0	0	0	0	0
2025	9435	4.300		41.000		0.0	0	0	0	0
2026	9704	4.300		41.000		0.0	0	0	0	0
2027	9980	4.300		41.000		0.0	0	0	0	0
2028	10264	4.300		41.000		0.0	0	0	0	0
2029	10556	4.300		41.000		0.0	0	0	0	0
2030	10856	4.300		41.000		0.0	0	0	0	0

Table D3. Project Scoping Worksheet

Bridge Level | Dashboard | Menu | Roadway | Element | Scoping | Performance | LCAP

Computation Detail for Bridge-Level Analysis

Scoping of Bridge 15 0015L - HUNTERS CREEK

This worksheet is not intended to be edited and should not be referenced by formulas.

Auto MRRI (1 of 1) 2011 (5 of 20)

Average do-nothing long-term cost (DNLTC) / **Maximum MRR costs**

Element/Environment	Condition at start of intervention year 1	2	3	4	5	Do-nothing full long term unit cost (DNLTC) 1	2	3	4	5	Average DNLTC	State/ Action	Quantity	Units	Variable Unit Cost	Maximum Cost
38/2 - Bare Concrete Slab	69.85	22.92	6.21	0.91	0.10	5.05	15.01	33.37	80.10	204.01	9.98	5/2	330	sq.m.	330.84	109178
215/2 - R/Conc Abutment	75.15	21.69	2.85	0.31		54.72	189.80	658.38	2097.75		107.61	4/2	85	m.	2027.15	172308
227/2 - R/C Submerged Pile	100.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		0.00	4/2	22	ea.	2053.15	45169
301/2 - Pourable Joint Seal	12.46	16.43	71.11			157.39	254.29	449.72			381.20	3/1	50	m.	167.38	8369
333/2 - Other Bridge Railing	51.65	30.32	18.04			55.28	115.09	224.40			103.92	3/2	232	m.	292.28	67809

MRR Actions implied by scope items / **B/C Computation**

Action Type	Element/Environment	State/Action	Quantity	Units	VarUnitCo	FixUnitCo	VarCost	LTCost	VarLTC	DNLTC	NetBen	B/C	Included
TSR Superstructure	38/2 - Bare Concrete Slab	5/2 - Replace	330.00	sq.m.	330.84	178.15	109178	513.80	335.66	9.98	-107474	-0.984	100.0
TSR Superstructure	301/2 - Pourable Joint Seal	3/1 - Patch&Rsl	50.00	m.	167.38	90.13	8369	409.00	318.87	381.20	3116	0.372	100.0
TSR Superstructure	333/2 - Other Bridge Railing	3/2 - Replace	232.00	m.	292.28	157.38	67809	502.32	344.94	103.92	-55917	-0.825	100.0
TSR Deck Structure	38/2 - Bare Concrete Slab	5/2 - Replace	330.00	sq.m.	330.84	178.15	109178	513.80	335.66	9.98	-107474	-0.984	100.0
TSR Deck Structure	301/2 - Pourable Joint Seal	3/1 - Patch&Rsl	50.00	m.	167.38	90.13	8369	409.00	318.87	381.20	3116	0.372	100.0
TSR Deck Structure	333/2 - Other Bridge Railing	3/2 - Replace	232.00	m.	292.28	157.38	67809	502.32	344.94	103.92	-55917	-0.825	100.0
TSR Wearing Surface	38/2 - Bare Concrete Slab	5/1 - Repair&Pro	330.00	sq.m.	121.88	65.63	40219	192.31	126.69	9.98	-38515	-0.958	100.0
TSR Expansion Joints	301/2 - Pourable Joint Seal	3/1 - Patch&Rsl	50.00	m.	167.38	90.13	8369	409.00	318.87	381.20	3116	0.372	100.0
TSR Railings	333/2 - Other Bridge Railing	3/2 - Replace	232.00	m.	292.28	157.38	67809	502.32	344.94	103.92	-55917	-0.825	100.0
MRR Deck Elements	38/2 - Bare Concrete Slab	2/1 - Repair	75.64	sq.m.	51.71	27.84	3911	85.31	57.47	15.01	-3211	-0.821	100.0
MRR Deck Elements	38/2 - Bare Concrete Slab	3/2 - Repr&Prot	20.51	sq.m.	76.67	41.29	1572	122.77	81.49	33.37	-987	-0.628	100.0
MRR Deck Elements	38/2 - Bare Concrete Slab	4/1 - Repair	3.01	sq.m.	103.41	55.68	311	174.70	119.02	80.10	-117	-0.376	100.0
MRR Deck Elements	38/2 - Bare Concrete Slab	5/1 - Repair&Pro	0.33	sq.m.	121.88	65.63	40	192.31	126.69	204.01	25	0.634	100.0
MRR Concrete Elem	215/2 - R/Conc Abutment	2/1 - Seal&Patch	18.44	m.	261.94	87.31	4829	407.80	320.49	189.80	-2409	-0.499	0.0
MRR Concrete Elem	215/2 - R/Conc Abutment	3/1 - Cln&Patch	2.42	m.	607.81	202.60	1471	903.62	701.02	658.38	-103	-0.070	0.0
MRR Concrete Elem	215/2 - R/Conc Abutment	4/1 - Rehab	0.27	m.	1346.07	448.69	359	1956.10	1507.41	2097.75	157	0.439	100.0
MRR Concrete Elem	227/2 - R/C Submerged Pile	2/1 - Seal&Patch	0.00	ea.	2053.15	684.38	0	2737.53	2053.15	0.00	0	---	0.0
MRR Concrete Elem	227/2 - R/C Submerged Pile	3/1 - Cln&Patch	0.00	ea.	2053.15	684.38	0	2737.53	2053.15	0.00	0	---	0.0
MRR Concrete Elem	227/2 - R/C Submerged Pile	4/1 - Rehab	0.00	ea.	2053.15	684.38	0	2737.53	2053.15	0.00	0	---	0.0
MRR Expansion Joints	301/2 - Pourable Joint Seal	2/1 - Cln&Reseal	8.22	m.	57.82	31.13	475	240.45	209.31	254.29	370	0.778	100.0
MRR Expansion Joints	301/2 - Pourable Joint Seal	3/1 - Patch&Rsl	35.56	m.	167.38	90.13	5951	409.00	318.87	449.72	4653	0.782	100.0
MRR Railings	333/2 - Other Bridge Railing	2/1 - Rehab	70.34	m.	59.53	32.06	4187	161.34	129.28	115.09	-998	-0.238	0.0
MRR Railings	333/2 - Other Bridge Railing	3/1 - Rehab	41.84	m.	82.26	44.30	3442	200.37	156.07	224.40	2859	0.831	100.0

VarUnitCo = Variable unit cost; LTCost = BMS long-term cost; NetBen = Net life cycle benefit of including the action
FixUnitCo = Fixed unit cost; VarLTC = Variable long-term cost; B/C = Benefit/cost ratio
VarCost = Total variable cost; DNLTC = Do-nothing long-term cost; Included = Percent of action included in scope item

Scope Item scale feasibility and performance

Action Type	VarCost	MRRI	MaxCost	Scale	MinScale	ScaleFeas	NetBen	B/C	Included
IMP Widen	0	0	514349	0.0	15	No	0	---	No
IMP Raise	0	0	514349	0.0	15	No	0	---	No
IMP Strengthen	0	0	514349	0.0	15	No	0	---	No
IMP Scour Mitigation	0	0	514349	0.0	5	No	0	---	No
IMP Seismic Retrofit	0	0	514349	0.0	5	No	0	---	No
IMP Fatigue Mitigate	0	0	514349	0.0	5	No	0	---	No
IMP Other Mitigation	0	0	514349	0.0	5	No	0	---	No
TSR Superstructure	185356	19890	185356	10.7	30	No	-160275	-0.865	No
TSR Deck Structure	185356	19890	185356	10.7	30	No	-160275	-0.865	No
TSR Wearing Surface	40219	5834	109178	5.3	15	No	-38515	-0.958	No
TSR Expansion Joints	8369	6426	8369	76.8	30	Yes	3116	0.372	Yes
TSR Railings	67809	7630	67809	11.3	30	No	-55917	-0.825	No
MRR Deck Elements	5834	5834	109178	5.3	5	Yes	-4290	-0.735	No
MRR Concrete Elem	359	359	217477	0.2	5	No	157	0.439	No
MRR Expansion Joints	6426	6426	8369	76.8	5	Yes	5022	0.782	No
MRR Railings	3442	3442	67809	5.1	5	Yes	2859	0.831	Yes

VarCost = Variable cost; Scale Feas = Indicator of whether the need is large enough
MRRI = MRR and improvement needs; Net Ben = Net life cycle benefit
MaxCost = Maximum deteriorated cost; B/C = Benefit/cost ratio
Scale = Relative extent of needs; Included = Indocator of whether the Scope Item is selected
MinScale = Minimum needs threshold

Indirect and total cost computation

MobFix	5000	Fixed cost of mobilization
MOTFix	5000	Fixed cost of maint of traffic
MobVar	0.1	Variable mob as % of direct cost
MOTVar	0.1	Variable MOT as % of direct cost
DesignMai	1	43b - Design type main span
TopLanes	2	Total lanes on structure
BotLanes	0	Total lanes under structure

Direct costs of:	Top	Bottom
Functional improvements	0	0
Substructure elements	0	0
Superstructure elements	0	0
Deck elements	11811	0
Total cost basis	11811	0

Des & Engi	591	Design and engineering cost
Mobilzn	6181	Mobilization cost
MOT	12362	Maintenance of traffic cost
Indirect	19134	Total indirect cost
IMP	0	Direct cost of improvements
TSR	8369	Direct cost of TSR actions
MRR	3442	Direct cost of MRR actions
Total	30945	Total intervention cost

Table D4. Life Cycle Activity Profile Worksheet

Bridge Level | Dashboard | Menu | Roadway | Element | Scoping | Performance | LCAP

Computation Detail for Bridge-Level Analysis

Life Cycle Activity Profile of Bridge 15 0015L - HUNTERS CREEK

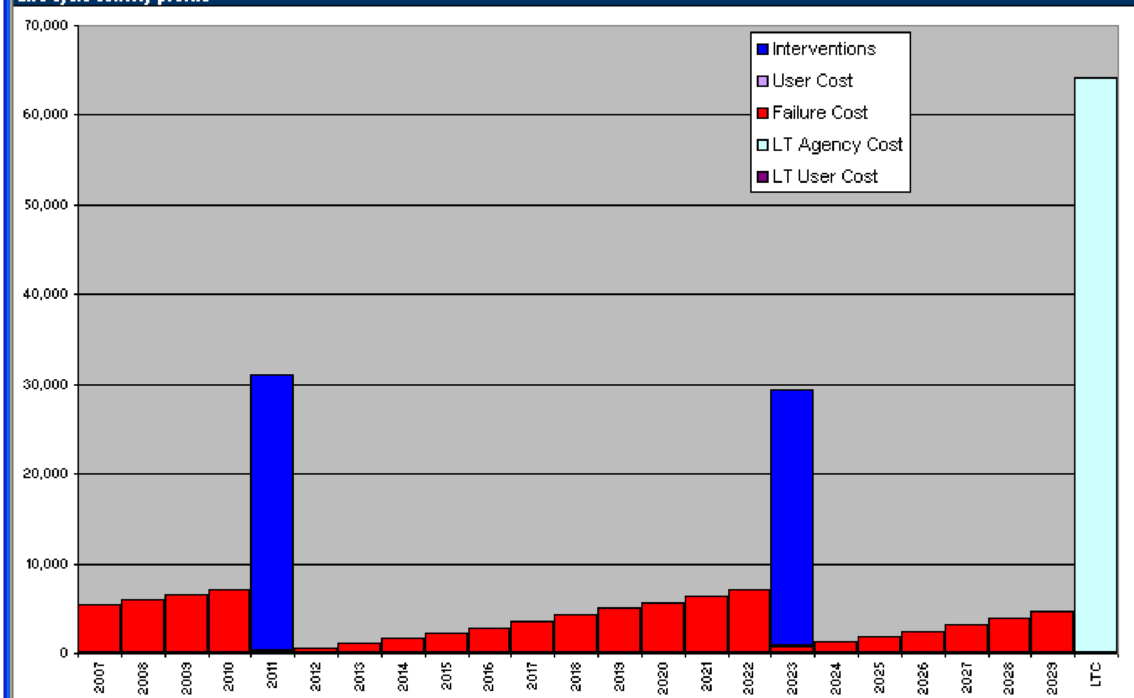
This worksheet is not intended to be edited and should not be referenced by formulas.

Auto MRRI (2 of 3) 2011 (5 of 20)

Input data

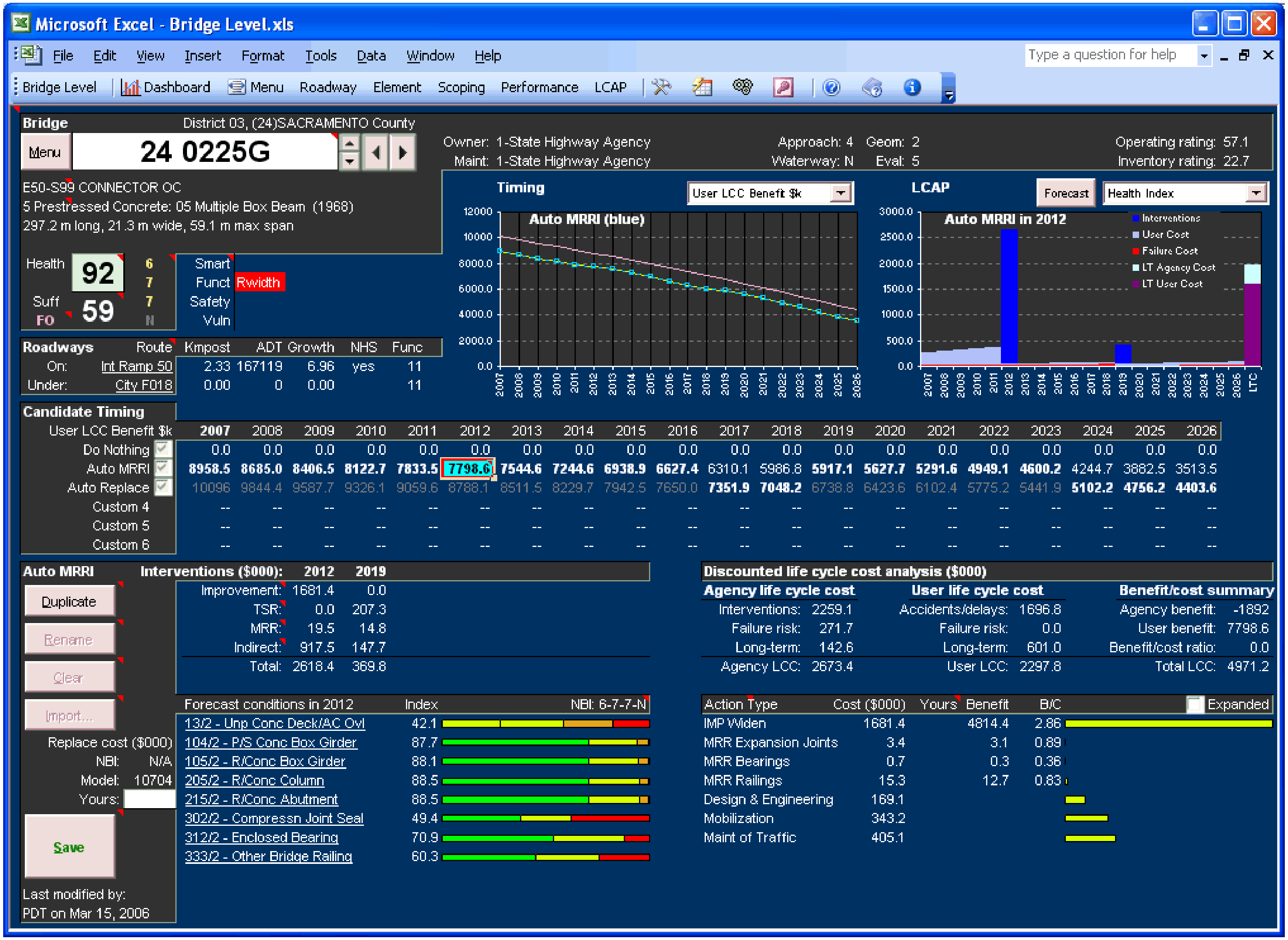
BaseYear	2007	First year of program
RestYears	7	Rest period after intervention
DiscFactor	0.9525	Discount factor
DiscRate	0.0499	Discount rate
ReplCost	514349	Replacement cost (long-term)

Life cycle activity profile



Programmed life cycle costs								Unprogrammed life cycle costs					Present value		
Year	REPL	IMP	TSR	MRR	Indirect	Custom	Subtotal	UserCost	Failure	LTAgcy	LTUser	Subtotal	Total	Discount	TotalNPV
2007							0	0	5483			5483	5483	1.0000	5483
2008							0	0	6005			6005	6005	0.9525	5720
2009							0	0	6519			6519	6519	0.9073	5914
2010							0	0	7023			7023	7023	0.8642	6069
2011	0	0	8369	3442	19134	0	30945	0	213			213	31158	0.8231	25646
2012							0	0	586			586	586	0.7840	460
2013							0	0	1065			1065	1065	0.7468	796
2014							0	0	1623			1623	1623	0.7113	1155
2015							0	0	2240			2240	2240	0.6775	1517
2016							0	0	2896			2896	2896	0.6453	1869
2017							0	0	3580			3580	3580	0.6147	2201
2018							0	0	4280			4280	4280	0.5855	2506
2019							0	0	4987			4987	4987	0.5577	2781
2020							0	0	5694			5694	5694	0.5312	3025
2021							0	0	6396			6396	6396	0.5060	3236
2022							0	0	7089			7089	7089	0.4819	3416
2023	0	0	0	10108	18538	0	28646	0	759			759	29405	0.4590	13498
2024							0	0	1229			1229	1229	0.4372	537
2025							0	0	1800			1800	1800	0.4165	749
2026							0	0	2446			2446	2446	0.3967	970
2027							0	0	3145			3145	3145	0.3778	1188
2028							0	0	3882			3882	3882	0.3599	1397
2029							0	0	4642			4642	4642	0.3428	1591
LTC										64210	0	64210	64210	0.3265	20965
Total	0	0	8369	13550	37672	0	59591	0	83582	64210	0	147793	207383		112690

Table D5. Digital Dashboard to Compare Scoping and Timing Alternatives



Appendix E – Bridge Health Index Calculation

APPENDIX E - BRIDGE HELTH INDEX CALCULATION

One of the challenges of communicating bridge conditions is the need to digest the very detailed information in an element condition report into a simpler measure suitable for communication, especially for showing bridge-level trends, forecasts, and targets to non-technical personnel. The Health Index is a type of weighted average, on a scale of 0 (worst) to 100 (best) summarizing all the elements and condition states for a bridge or any subset of an inventory. The weights give emphasis to elements that have the biggest economic or structural impact on bridge functionality.

Health Index is a consistent way to reduce the voluminous data in an element inspection into a simpler quantity that can be compared across bridges and over time. It is computed as follows:

Health index
$$HI = \frac{CEV}{TEV} \times 100$$

Current element value
$$CEV = \sum_e W_e \left(P_{e1} + \frac{2}{3}P_{e2} + \frac{1}{3}P_{e3}\right)$$

Total element value
$$TEV = \sum_e W_e$$

where W_e is the health index weight for element *e*
P_{ei} is the fraction of element *e* in condition state *i*

The health index weights can be based on replacement cost, life cycle cost, or determined by a panel of bridge management experts. AASHTOWare Bridge Management contains a set of suggested weights produced by a Technical Review Team composed of such experts. Once the weights are established they do not change, and are applied uniformly to every bridge in the inventory.

This index can be computed for an individual element, for a group of elements, a whole bridge, or any group of bridges. It is common practice, for example, for agencies to use a deck health index or paint health index to communicate performance on those maintenance-intensive components of a bridge.

Sections 5.5 and 5.6 show examples where the health index provides an appropriate level of detail for communicating time-series condition data. A benefit of using the health index in this way is that the index is mathematically derived from element condition state data, with no application of judgment involved, and no considerations other than condition. So it is consistent over time and compatible with element deterioration and action effectiveness forecasting models.

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