Final Report
to the
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

on Project 14-23

Practical Bridge Preservation Actions and Investment Strategies

LIMITED USE DOCUMENT

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NOTE CONCERNING THE REPORT

This report for the project and the planned handbook product of the project are submitted as separate items, the handbook outline and reference to the developed sections are provided in the Appendix. The developed section, formatted in AASHTO style is provide as a separate file.

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ABSTRACT

This report describes and documents progress made toward accomplishing the objectives of NCHRP Project 14-23 Practical Bridge Preservation Actions and Investment Strategies.

EXECUTIVE SUMMARY

Many transportation departments have significant practical experience with bridge preservation and have developed conclusions regarding the effectiveness of bridge preservation actions based on those experiences. However, limited efforts have been made to identify, measure, evaluate, and document the short- and long-term performance of specific bridge preservation actions. Bridge preservation consists of actions to deter or correct deterioration of a bridge to extend its useful (service) life and does not entail structural or operational improvements beyond the originally designed strength or capacity of the bridge. Often practitioners apply preservation strategies on the basis of judgment or common sense using available resources. However, it is difficult to translate these strategies into coherent and convincing arguments that will persuade legislatures and agency upper management to support and adequately fund aggressive and well planned programs of bridge preservation. These programs may be inadequately funded due to absence of a creditable, quantitative basis for measuring effectiveness.

The objective of this research was to develop a handbook for possible adoption by AASHTO that will (1) assemble a catalog of bridge element preservation actions; (2) quantify the benefits of bridge preservation actions; (3) provide decision-making tools to optimize bridge preservation actions; and (4) develop a method to determine appropriate levels of funding to achieve bridge agency selected goals and performance measures.

Progress was made toward development of a system for assessing practical bridge preservation actions and investment strategies. This Final Report and the accompanying draft Handbook document this progress. Addenda discussing the surveys conducted and the sources of information and data identified are also provided. The various additional tasks need improved definition for successful completion of the system originally envisioned by the project objectives.

Although agencies have collected bridge condition data under several different systems for years, data collection at the element level varies and is in the process of conversion to a new system based on the 2013 AASHTO Manual for Bridge Element Inspection. This conversion has caused some elements, element defects, and condition descriptions to be a moving target with data for a complete cycle not yet available and certainly historical data not yet accumulated. Quantifying the benefits of bridge preservation actions is problematic without reliable data.

It is clear that some agencies desire a system that will produce optimum recommendations for decision support and accept that life cycle economic analysis is an important tool for decision making. However, during this period of transition, other agencies desire approximate solutions for management until more reliable data is available to justify approaches that might be more optimal.

CHAPTER 1 Background

1.1 Introduction

The bridge community is becoming increasingly aware that preservation of existing bridges is an effective approach to protecting the good condition and extending the service life of bridges at a minimum cost. The term bridge preservation encompasses activities that are variously referred to as routine maintenance, preventive maintenance, repair or rehabilitation. Many different treatments or actions fall under the umbrella concept of bridge preservation and there is a growing need for a straightforward, practical guide to aid in the selection of appropriate preservation actions, treatments and strategies – for individual bridge elements, for groups of bridges and for all bridges across a network. The American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) worked cooperatively to reach consensus on a definition of bridge preservation. The AASHTO Subcommittee on Maintenance (SCOMS) and the Subcommittee on Bridges (SCOBS) accepted the definition at their respective July 2011 meetings. This definition is provided below. Further discussion of the definition can be found in Section 1.5

"Bridge preservation is defined as actions or strategies that prevent, delay or reduce deterioration of bridges or bridge elements, restore the function of existing bridges, keep bridges in good condition and extend their life. Preservation actions may be preventive or condition-driven."

These two organizations recognize the potential economic and life extending benefits of bridge preservation and support its inclusion as a key component of a comprehensive bridge management approach. However, further work is needed to identify and refine the associated strategies, determine the optimal timing of treatment applications and quantify the benefits derived.

Transportation decision makers at all levels of government face extraordinary challenges in meeting the growing backlog of highway infrastructure demands in the wake of declining revenues and increasing customer expectations. While the tragic I-35 W Minneapolis bridge collapse brought instant public awareness of the critical need to ensure bridge safety and reliability, most of the public remains unaware of the growing number of bridges nationwide that have reached or exceeded their planned life expectancy. Many of our nation's bridges to have reached this milestone are candidates for major rehabilitation or replacement.

Over the past several decades significant investments have been made to address structurally deficient bridges, resulting in overall improvement to bridge conditions in many states. Very soon, however, this positive trend will reverse, due to a combination of detrimental factors: the number of aging bridges in various states of deterioration is on the rise; construction and repair costs continue to increase. Ever tightening environmental regulations for new bridges make preservation of existing bridges an even higher priority. As the confluence of these factors conspires to outstrip the capacity for local, state, and federal programs to deal with bridge deterioration, transportation agencies must be guided toward learning and implementing innovative ways to deliver improved levels of service while responding to increasing levels of accountability.

Taken as a whole, the condition of the national bridge inventory has continued to improve because of major rehabilitation efforts and bridge replacement. However, the various processes by

which the condition of the individual elements of a bridge decline over time are still active. Absent specifically directed maintenance and preservation actions, all bridges will inevitably undergo a continuing decline in condition and performance. The pattern and pace of decline for any given bridge element depends on factors which include the construction type and material, the original construction quality, regular service loads, environmental and climatic influences, the effects of natural events such as floods and earthquakes, and any preservation actions employed to correct poor conditions or to prevent or slow its decline. A simple illustration of bridge decline over time is shown in Figure 1.1 showing change in the NBI condition rating over a number of years.

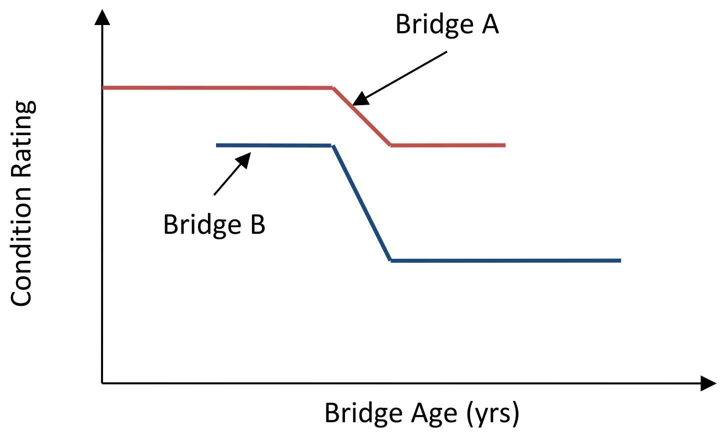

Figure 1.1 Change in bridge condition rating over time.

Figure 1.1 describes the general scenario under which the bridge inventory has declined in condition and performance in the past - bridges in good condition decline to fair condition and bridges in fair condition decline to poor condition. Ultimately, major rehabilitation or complete replacement becomes the only viable option.

A snapshot of the National Bridge Inventory data in Tables 1.1, 1.2, and 1.3, provides some insight into the current condition of the nation's bridges. For simplicity, the condition ratings for deck, superstructure and substructure are collapsed into three broad categories – "Good" (NBI ratings 9, 8 & 7), "Fair" (NBI ratings 6 & 5) , "Poor" (NBI ratings 4) and severe (NBI ratings 3 or below).

Table 1.1 Bridge deck conditions.

Condition Rating	# of Bridges	% of Total Number of Bridges	Deck Area of Bridge Square Meters	% of Total Deck Area of Bridges	Total ADT Vehicles Per Day
Good	99,532	21	61,003,000	18	482,540,000
Fair	341,996	72	259,810,000	77	2,932,430,000
Poor	18,999	4	11,167,993	3	145,921,537
Severe	12,167	3	7,152,007	2	93,448,463
Totals	472,694	100	339,133,000	100	3,654,340,000

Table 1.2 Superstructure conditions.

Condition Rating	# of Bridges	% of Total Number of Bridges	Deck Area of Bridge Square Meters	% of Total Deck Area of Bridges	Total ADT Vehicles Per Day
Good	128,913	27	96,710,000	29	915,080,000
Fair	316,525	67	229,120,000	68	2,640,420,000
Poor	19,007	4	9,295,689	3	68,926,177
Severe	8,249	2	4,034,311	1	29,913,823
Totals	472,694	100	339,160,000	100	3,654,340,000

Table 1.3 Substructure conditions.

Condition Rating	# of Bridges	% of Total Number of Bridges	Deck Area of Bridge Square Meters	% of Total Deck Area of Bridges	Total ADT Vehicles Per Day
Good	102,693	21	68,830,000	20	539,430,000
Fair	336,293	71	257,930,000	76	3,030,880,000
Poor	33,708	7	12,400,000	3	84,030,000
Severe	10,056	2	3,699,252	1	25,068,402
Totals	482,750	100	342,859,252	100	3,679,408,402

The preceding tables show that a very large percentage of the nations' bridges are in "good" or "fair" condition. This is true whether the measure is total number of bridges, total square meters of bridge deck area or the percentage of the traffic volume carried by bridges in "good" and "fair condition. Bridges in "good" or "fair" condition are the best candidates for preservation. Timely intervention with effective bridge preservation actions would prevent or delay their decline to "poor" and ultimately to "severe" condition at which stage actions are usually more costly and may cause lengthy situations where traffic is disrupted by work zones. Thus, these tables illustrate the opportunity as well as the challenge of developing and implementing preservation programs to prevent a large part of the bridge inventory from declining to poor condition and requiring major rehabilitation or replacement. The Moving Ahead for Progress in the 21st Century Act (MAP-21) requires the Secretary of Transportation to establish a definition of "good state of repair". This definition will impact how bridge condition is sorted and viewed in the future.

As noted, these condition assessments of “good”, “fair”, and “poor” are based on NBI ratings provided by bridge inspectors. Due to the nature of the rating scheme these simple tables do not help characterize the deck, superstructure and substructure components of the bridge in terms of how long they have been rated at a certain level of condition. Therefore it is difficult to determine the percentage of the components in each condition category that is near the point where they would fall into the next lowest NBI rating. This parameter would have a significant bearing on the assessment of the suitability of the elements for effective preservation actions.

In addition to undue replacement/rehabilitation costs, owners, highway users and society in general pay a much higher price in terms of disruption and delays in traffic flow, diminished productivity, increased fuel consumption, increased emissions, increased safety concerns, and expenditure of scarce public funds. Clearly, a change must be instituted toward protecting the investment of these critical assets and ensuring the safety of the public and the reliability of our transportation system and away from the traditional “worst first” bridge replacement approach as the principle strategy. A timely and targeted program of intervention in the steady pattern of deterioration that all bridge elements go through would do much to forestall that eventual decline and would help to preserve bridges at a high level of performance with potentially significant cost savings over the life of the typical bridge. In the simple terms of Figure 1, this would mean significantly extending the horizontal portion of the curves by taking actions that preserve the bridge elements in their current condition. These actions would likely be applied more frequently than major rehabilitation or replacement actions, but, each individual project would involve relatively lower cost and would probably result in less disruption to traffic. The growing awareness of the value of the preservation approach is matched by continuing improvements in the practice of bridge preservation – in materials, methodologies, etc. – that provide bridge practitioners with a growing arsenal of bridge preservation options. Although beyond the scope of this study, design of new bridges with greater attention to durability can contribute greatly to preservation of the asset. This includes selection of bridge materials and design features for sustainability and ease of maintenance when needed.

1.2 Problem Statement

Performance and Accountability

In recent years, the aging and degradation of the national transportation system has caused a transformation in the highway investment model from the historical “construct and maintain” to a holistic and strategic methodology focused on maintaining, preserving, operating and renewing transportation assets. The evolution of “Transportation Asset Management” is the direct result of this paradigm shift in strategic methodology and increased expectations from the public. As agencies become more accountable for reporting on the value of their highway assets, they will increasingly rely on asset condition and performance data collected through automated technologies. This data will be combined with fully integrated asset management systems, capable of forecasting network level performance and funding needs analysis to produce optimization techniques over a planning horizon. Many agencies currently report the condition and performance of their infrastructure to the public. And with the passage of the MAP-21 legislation, Congress has created

the National Highway Performance Program which requires adoption of performance measures for bridges on the National Highway System (NHS).

For bridges, meaningful performance measures must be identified to replace or supplement the "percent deficient" measure used by agencies which only serves to perpetuate a doomed "worst first" strategy. Phase I of this project presented an excellent opportunity for the research team to identify best practice transportation agencies that have implemented effective bridge preservation programs and long term strategies combined with meaningful measures to track progress towards agency goals. For example, the Florida Department of Transportation has been recognized as a leader for many years in performance based management of its bridge infrastructure by establishing clearly defined levels of service and performance targets for which agency managers are held accountable. To achieve the established goal (90% of its network bridges in good condition), agency managers directed considerable resources toward maintenance and preservation instead of a replacement only approach. The Florida DOT has surpassed this goal and shared their recipe for success at the AASHTO TSP·2 Southeast Bridge Preservation Partnership meeting held in 2010.

1.3 Research Objective

The objective of this research is to develop a handbook for possible adoption by AASHTO that will (1) assemble a catalog of bridge element preservation actions; (2) quantify the benefits of bridge preservation actions; (3) provide decision-making tools to optimize bridge preservation actions; and (4) develop a method to determine appropriate levels of funding to achieve bridge agency selected goals and performance measures.

Applied Asset Management

The best results will be achieved by agencies that develop and implement preservation programs and network level strategies. A preservation program improves long term performance and extends the life of infrastructure assets. Gary Ridley, Director of the Oklahoma DOT, drove this point home in "Rough Roads Ahead, Fix Them Now or Pay for It Later" [AASHTO (2009)], when he said, "Managing a highway system is like playing chess. You have to look at the whole board, the whole system, not just the next move. Sure we do reactive things, but our best strategy is when we look down the road eight years or more, look at every section of road, and budget to keep those roads in good condition."

Systematically maintaining or replacing bridge deck expansion joints based on an analysis of element level data (deck joints) can preclude damage to bearings and girder ends caused by long term exposure to moisture from leaking joints. This type of planned, preservation strategy is consistent with an asset management approach, and can extend the life of the individual elements and service life of the bridge.

Currently, funding for bridge preservation, major rehabilitation and replacement is always limited. Thus, preservation actions must not only help maintain good conditions but economic analysis needs to be part of the selection process to assure we are getting the "biggest bang for the buck." By extending the process to the network level for similar bridge types, bridges on a particular

route for purposes of contracting and minimizing traffic disruptions, or bridges under a particular maintenance sub-organization, budgets and condition performance tracking can be facilitated.

Applying the Concepts of Asset Management

Driven by increasing traffic, declining revenues and deteriorating highway infrastructure, a growing number of transportation agencies are adopting an Asset Management approach to safeguard their infrastructure investment and satisfy stakeholder expectations. Asset Management is a successful blending of business, economics and engineering that takes a strategic approach to achieve optimum network level performance. This is accomplished by knowing the inventory, collecting data, analyzing the data to model performance and forecast long term economic needs, and developing comprehensive programs for achieving established network goals.

Bridge preservation is clearly consistent with the principles of Asset Management as it represents a proactive approach to maintaining our existing bridges. Bridge preservation enables transportation agencies to reduce the number and scope of costly, time-consuming projects for rehabilitation, reconstruction, or replacement and avoid associated traffic disruptions. Conversely, there will be an increase in the number of short duration projects of a lesser scope to employ preservation treatments. On the whole, the goal of incorporating timely bridge preservation techniques should result in extended bridge longevity while providing the traveling public with improved safety and mobility.

1.4 Scope of Study

Encapsulation

There is a growing awareness that investment of relatively small amounts of money and time in bridge preservation actions can prevent or significantly forestall the need for much larger, much more costly, interventions that may disrupt traffic for lengthy periods of time in later years. This is a reflection of the often used admonishment to “pay me (a little) now or pay me (a lot) later.” The most significant barriers to convincing owners to pay now include difficulty in proving that long term savings accrue from paying now versus paying later and convincing owners to make the smaller investments out of their limited bridge funds when so much major work on seriously deficient bridges is deemed to be a higher priority. The Transportation System Preservation Research, Development, and Implementation Roadmap developed by the FHWA clearly supports this point. Several of the R&D needs statements aim at creating measures and documenting the benefits of pavement and bridge preservation programs and action and then communicating those benefits to the transportation agency decision-makers. Identified needs include:

- Evaluate, analyze and document successful bridge preservation practices;
- Develop deterioration models that account for the performance of preservation actions;
- Quantify the information necessary to guide bridge preservation decisions;
- Determine the economic benefits of bridge preservation strategies;
- Quantify performance and benefits of various bridge preservation treatments; and,
- Determine effective lives of preservation treatments and the associated extensions of life for treated elements.

Development of clear preservation strategies that are supported by realistic data and defined using modern analytical methods will provide bridge owners with the knowledge, tools and confidence to apply the correct action at the correct time. Well-defined metrics by which to measure the effectiveness of the preservation strategies will support the wisdom of the decision to “pay me now.”

The difficulty of presenting a clear and convincing argument in favor of investments in bridge preservation programs is partly a result of:

- Lack of practical tools (e.g., deterioration models) capable of predicting future element condition with and without specific bridge preservation actions;
- Lack of high quality, reliable data on the cost and time required to complete commonly used bridge preservation actions;
- Lack of practical metrics by which to measure the effectiveness and benefits of preservation actions; and,
- Lack of reliable data that is readily available and in a useable format to calculate the values of the performance metrics.

Other barriers to widespread deployment of bridge preservation strategies and treatments include:

- A shortage of well documented success stories on bridge preservation;
- Lack of communication strategies with internal and external customers to show the benefits of preservation;
- Funding constraints and competing priorities.

Each bridge is the sum of its various elements working together as a structural system. There are numerous factors such as traffic and environment that affect the condition and performance of bridge elements and their constituent materials. The impact of these factors on different elements depends on the element and on its level of exposure to these factors. For these reasons, the preservation of bridges must first be addressed at the element level and at the element material level. The inspection process must focus at this level, and evaluation of conditions and selection of appropriate solutions must be specific to the combination of the element and its service environment.

The keys to implementing an effective program of bridge preservation are to:

- Identify the elements of a bridge that are most susceptible to deterioration and whose continued deterioration will lead to future costly rehabilitation or replacement (i.e., reduced levels of serviceability and/or reduced service life.
- Adopt uniform methods and terminology for inspecting, rating, evaluating and describing the current condition of the elements. To the extent possible the terminology should serve to correlate the condition of the element with practical feasible actions including preservation actions. Also, to the extent possible, the inspection techniques and the descriptive language should relate to parameters that reveal the optimum timing of preservation actions. As noted below, these feasible actions will often be state specific.
  - NOTE 1: The June 2013 adoption of the AASHTO Manual for Bridge Element Inspection (MBEI) by the Subcommittee on Bridges and Structures provides a uniform, well received template for evaluating bridges at the element level. The adoption of this manual shows that element level inspection is becoming the preferred manner of inspecting bridge elements, reporting condition and evaluating bridge performance.

Additionally, MAP-21 requires the state DOTs to begin reporting element level condition data for all bridges on the NHS. The costs, benefits and feasibility of reporting element level condition data for all bridges not on the NHS are under study and collection of element level data for all bridges in the NBI may be required in the future. The AASHTOWare Bridge Management software (-BrM), previously named Pontis, is currently being updated to reflect the elements in this new guide manual. It makes sense that preservation tools should also be presented with respect to these elements. AASHTO is currently taking steps to ensure the historical value of element level data collected under the previous element definitions and condition state language is preserved by developing tools to migrate previous CoRe format element condition data to the new element definitions and condition state language.

  - Note 2: All DOTs continue to report the condition of the deck, superstructure and substructure according to the requirements of the national bridge inspection standards. The NBI contains an invaluable database of almost 30 years of legacy data on bridge conditions. At least for the near future, many DOTs will continue to use NBI ratings as part of their performance measures including measures of effectiveness of preservation actions. Therefore, while the element descriptions will closely parallel the AASHTO Manual for Bridge Element Inspection, the research team will attempt to relate preservation effectiveness in terms of NBI ratings as well as element level condition state measurements. It is to be noted that FHWA is currently developing a converter using the new element descriptions that will allow "two direction" translation (from NBI rating to element condition states and from element condition states to NBI ratings). The California DOT uses the currently available NBI translator to calculate their deck, superstructure, substructure and culvert ratings from element level condition data using the previous element definitions. Two other state DOTs – Montana and Rhode Island - also use the translator to calculate NBI ratings from element level condition data. On the other hand the Florida DOT does not believe a translator concept is possible. FDOT believes it is very unlikely that a translator can be developed that does not have significant errors. At this point, the usefulness of the proposed NBI converter for the purposes of NCHRP Project 14-23 is uncertain. If that development effort is successful, further evaluation of the use of the converter as an auxiliary tool in the research results should be undertaken.

- Assess element deterioration and impact on the performance of the bridge.
- Identify specific actions – materials, processes, and practices – that when properly applied in a timely manner will prevent or significantly slow the deterioration process of these components. These actions and their effectiveness may differ from region to region and from state to state depending upon local conditions and requirements, bridge types, existing bridge conditions, environment, climate, or other factors.
- Continue or begin to maintain adequate records on bridge preservation actions that will provide uniform descriptions of maintenance activities, bases for measurement of quantities, costs, impacts, performance, and other relevant data for use in cost-benefit analysis, selection of maintenance actions, or other related decisions. Develop practical metrics that allow for evaluation of the optimum timing, effectiveness, durability and cost benefits of the selected preservation actions. There is a need for national standardization of record format for preservation actions that would allow analysis of the data. This is a worthy goal to be reached. The product of NCHRP Project 14-15: Developing a National Database System for Maintenance Actions at Highway Bridges provides the basis for such desirable

standardization of recordkeeping for preservation actions. However, it is unlikely that such a system will be adopted by a significant number of states in the near future.
- Develop damage assessment criteria that will determine urgency and priority of the action as it pertains to modification of the element deterioration rate and condition risk.
- Develop analysis methods to prioritize preventive maintenance actions.
- Incorporate these preservation actions as feasible actions in bridge management systems such as AASHTOWare Bridge Management.

Many states have implemented AASHTOWare Bridge Management as their BMS to varying degrees; others have developed their own systems or are working with software development consultants to develop new systems.

1.5 Review of Literature and Ongoing Bridge Preservation Practices and Programs

Introduction

Bridge preservation is not a new concept – bridge owners have been doing preventive maintenance, restorative maintenance and bridge repairs and rehabilitation ever since bridges were first built. What is new is the growing emphasis on organized programs of bridge preservation actions aimed at extending bridge service life at a minimum cost to the agencies and at minimum cost and disruption to road users. Also new is the emphasis on funding programs to deploy effective bridge preservation strategies and treatments.

The American Association of State Highway & Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) have agreed on a definition of bridge preservation that states that "Bridge preservation is defined as actions or strategies that prevent, delay, or reduce deterioration of bridges, or bridge elements, restore the function of existing bridges, keep bridges in good condition and extend their life. Preservation actions may be preventive or condition-driven." Further guidance on the definition of bridge preservation is contained in the FHWA Bridge Preservation Guide (FHWA). This definition helped define the scope of the review of literature and current practice.

NCHRP Project 14-23 seeks to develop a handbook that will assist state DOTs to make bridge preservation investment decisions for an individual bridge, for a category of bridges with similar characteristics, and at the network level. The handbook should include a decision-making process and associated tools to assist in quantifying the benefits of selecting appropriate bridge preservation actions and investment strategies.

In order to achieve these objectives it is necessary to seek out, evaluate and assimilate the most recent knowledge about bridge preservation from a wide variety of published literature documenting recent and past studies of bridge preservation practices and actions. Additionally, due to the rapidly evolving state of the practice of bridge preservation, it is clear that considerable knowledge will come from information gleaned from examining ongoing bridge preservation activities and from studying recent findings that are only available from unpublished sources. The basis of the information may range from research studies to documentation of field experiences to exercises in expert elicitation.

The state-of-the-knowledge and the state-of-the-practice of bridge preservation are evolving rapidly as bridges owners sponsor research studies, evaluate experiences with preservation actions and strategies, and develop guidelines and best practices for their preservation programs. The purpose of the review of literature and ongoing bridge preservation practices and programs is to elicit the best available knowledge that will provide reliable data and facts for the handbook and data to use in the decision-making processes and associated tools.

One important requirement of NCHRP Project 14-23 is that the handbook and other deliverables should be flexible in order to allow customization based on important factors prevailing in each state. Those prevailing factors may include environment, preferences in bridge types and materials, traffic loadings, cost of implementing bridge preservation practices, preference for using stat DOT and/or contract labor forces, etc. Additional customization will be based on new data and improvements in knowledge gained from continuing experience with bridge preservation practices by various practitioners.

The validity and usefulness of the handbook, decision making processes and the associated tools, will depend partly on knowledge gathered and synthesized from the review of literature and ongoing bridge preservation practices and programs. In particular data and expert opinion are needed to determine:

- Deterioration processes and rates for different bridge elements in different environments
- Types of bridge preservation actions and treatments that are applicable on different bridge elements
- The element condition defects for which each type of action or treatment is effective
- The optimum timing for application of the treatment and/or recommended cycles for application of specific treatments
- The duration over which the treatment is effective in preserving the element
- Costs associated with application of treatments
- Performance metrics which help evaluate the effectiveness of the treatment for results such as:
    - Improvement of condition state of the element
    - Increase in the service life of the element in the post-treatment condition state.

In order to meet these needs for the most recent knowledge and data about bridge preservation, the research team conducted a review of literature from a wide variety of sources and investigated the status and details of ongoing bridge preservation practices and programs from state DOTs in different regions of the country.

The scope of the literature search was guided by the definition of bridge preservation given above. The sources searched for relevant information fall into the categories of highway and highway research organizations at the federal and state levels in the United States, industry organizations representing companies that have interests related to bridge preservation, and similar organizations from outside of the United States. The Table 1.4 lists the organizations identified as possible sources of information and data on bridge preservation technologies and activities:

Table 1.4 Possible Sources of Information and Data on Bridge Preservation

US Agencies & Associations		Industry	International
FHWA	TRB	NACE (Corrosion)	IABSE
AASHTO	NCHRP	SSPC	IABMAS
SCOBridges	SHRP-2	AGA (Galvanizers)	PIARC
SCOMaintenance	NTIS	AWS	Ontario MOT
SCOMaterials	ASCE	NSBA	
TSP2	NACE (County Engrs)	ASBI	
State DOTs		ARTBA	

While the list of possible sources is considerable, most of the relevant and useful information and data is available from a shorter list of sources that includes FHWA, AASHTO and its bridge related committees and activities, TRB committee sponsored activities, NCHRP research reports. Over the course of NCHRP project 14-23 continuing updates will be gleaned from follow-up interviews with individuals from state DOTs, industry companies and universities.

During 2012, two attempts were made to gather information from bridge practitioners at state DOTs. These two surveys were intended to be a one-time events supplemented by follow-up with responders over the next two years as appropriate to gather additional, more detailed input. A summary of the information provided by the respondents can be found in the project Addendum - Bridge Preservation Survey. The state-of-the-knowledge and the state-of-the-practice of bridge preservation is evolving very rapidly. New developments are tracked by active participation with the FHWA Bridge Preservation Expert Task Group (BPETG), the TSP2 bridge preservation partnerships, and relevant committees of AASHTO and TRB as well as by following the research done under the LTBP program. Relevant information can be used to support the research on the following four aspects of the NCHRP 14-23 project:

1. Developing a catalog of bridge elements, the types of deterioration that occurs on those elements and the most common and effective preservation actions applied to those elements (Chapter 2 of this report).

2. Identifying which aspects of bridge service life are positively impacted by bridge preservation actions and evaluating the impacts of the preservation actions identified for study (Chapter 3 of this report).

3. Identifying metrics that can be used to analyze the effectiveness of bridge preservation actions considering when and which action to apply and describe the impacts of applying or delaying an action (Chapter 4 of this report).

4. Developing a proposed method to prioritize the identified metrics for further analysis in Phase II (Chapter 5 of this report).

The discussion provided below represents <u>some examples</u> of information and data available to support the content of the handbook, decision-making processes and the associated tools.

1.5.1 Topic: General Guidance on Bridge Preservation

Defining Bridge Preservation

The scope of work associated with NCHRP Project 14-23 directs the research team to develop a detailed method with examples to prioritize bridge preservation actions according to the metrics previously identified. Examples will consider diverse bridge types, the surrounding environment and the method is to be implemented into decision-making tool(s). In the past, the term bridge preservation was not clearly defined, thus blurring the lines between maintenance and preservation and major rehabilitation to some degree. Under some circumstances, bridge preservation actions are eligible for federal funding.

The recently formed FHWA Bridge Preservation Expert Task Group (BPTEG), with input from the AASHTO Subcommittee on Bridges and Structures (SCOBS) Committee T-9 and the AASHTO Subcommittee on Maintenance (SCOM) Bridge Technical Working Group has developed a definition of bridge preservation that is now accepted by FHWA and AASHTO and is being publicized throughout the bridge community.. The recommended definition and accompanying commentary outlined below will be included in the AASHTO Glossary as well as the AASHTO Maintenance Manual.. FHWA has published a Bridge Preservation Guide which includes the following definition and also provides commentary to further illustrate the definition.

FHWA Bridge Preservation Guide

The Bridge Preservation Guide presents the accepted definition of bridge preservation, presents some key parameters of a bridge preservation program as well as some examples of best bridge preservation practices and promotes the use of common terminology regarding bridge preservation actions and strategies.

<u>Definition</u>

Actions or strategies that prevent, delay or reduce deterioration of bridges or bridge elements, restore the function of existing bridges, keep bridges in good condition and extend their useful life. Preservation actions may be preventive or condition-driven.

<u>Sample c</u>ommentary:

Effective bridge preservation actions are intended to address bridges while they are still in good or fair condition and before the onset of serious deterioration. An effective bridge preservation program:

- Employs long-term network strategies and practices that are aimed to preserve the condition of bridges and extends their useful life;
- Has sustained, adequate funding sources;

- Has adequate tools and processes to ensure that the appropriate treatments are applied at the appropriate time.

An effective bridge preservation program may include, but is not limited to, the following components:

- Qualifying parameters for bridge types and related conditions such as bridge elements or components that are in fair to good condition such as concrete decks, coated steel elements, substructure elements in a marine environment, etc.
- Appropriate treatments such as deck and superstructure cleaning, installation of deck overlays, coating of steel elements, installation of cathodic protection and prevention systems, etc.
- Regular needs assessment to identify, prioritize, and estimate the cost of planned work

Best practices for Bridge Preservation include:

- The method of identification of needs is uniform, specific and repeatable; and based on element level condition data.
- First level national performance measures are used to set program funding levels and second level agency specific performance measures are used to set objectives for the full range of actions (e.g. maintenance, preservation, rehabilitation, replacement) to optimize bridge conditions.
- The prioritization process integrates agency objectives for network condition levels and individual bridge risk.
- Verification and feedback on work is completed.
- A significant portion of resources determined by agency network goals are directed to preservation actions.
- Agency management champions the preservation of assets.

The accepted definition for bridge preservation provided a basic framework for beginning to synthesize the various activities that state DOT's currently have under way in their bridge preservation programs. Recently some different efforts have been undertaken to provide a comprehensive picture of the variety of bridge preservation practices that are currently being employed across the nation. Following are some examples of information that has been gathered in an effort to define the scope of which preservation as it is practiced today.

The TRB joint subcommittee on bridge preservation has developed a matrix of bridge preservation practices. The final results of this effort were published in a paper at the 2013 TRB annual meetings.

One of the prime objectives of this effort was to determine the level of consensus amongst the DOT's with regard to which bridge actions they considered to be operations, maintenance, preservation, rehabilitation, improvements or replacement. However an important side benefit of this study was an identified list of 94 activities that account for the majority of all work that can be performed on a bridge. The activities were categorized by where they are performed on the bridge, not the nature of the activity. Activities were broken down into those performed on decks,

approaches & surface items, the superstructure, the substructure, culvert components, as well as painting and coating, scour mitigation and miscellaneous bridge actions.

In addition to compiling a very comprehensive and useful list of bridge preservation actions the study concluded that:

- Formal definitions of bridge preservation cover actions that are considered maintenance, preservation and rehabilitation by various DOTs
- Definitions of maintenance and preservation are still somewhat ambiguous
- Clear definitions of maintenance and preservation will require classifying specific bridge actions, and
- Actions defined as maintenance more than triple those defined as preservation

Michigan DOT as part of the Midwest Bridge Preservation Partnership (MWBPP) has taken the initiative to survey the MWBPP states and is continuing to develop a detailed matrix of bridge preservation actions employed by the states within that partnership. Similar to the TRB survey, the MWBPP matrix classifies actions according to those performed on decks, approaches & surface items, the superstructure, the substructure, plus all other. Additionally, the actions are grouped as cyclical based activities or condition based activities. Some states have provided commentary on how often activities need to be repeated, providing some expert opinion on longevity of the effectiveness of various bridge preservation actions.

The Western Bridge Preservation Partnership has surveyed all of the states within the partnership together detailed information on the various bridge preservation practices that they currently employ. An example of the replies from those states on bridge preservation activities they currently employ is:

1. **Seal or replace leaking joints or eliminate deck joints.** (Minimizes the deterioration of superstructure and substructure elements beneath the joints.)

   <u>Arizona:</u> We clean and reseal our deck joints (if there is need) when placing bridge deck overlay. We also replace existing deck joints when there is safety concern by using Bridge Preservation fund or Pavement Preservation fund.

   <u>Washington:</u> When we paint steel truss bridges under contract we also have the panel joints cleaned and resealed. As part of our maintenance program we are attempting to initiate a program to clean joints on a five year cycle and reseal and repair them as needed. We will also fill any wheel ruts leading up to the joint to prevent the horizontal impact loading of the tires on any raised joint material. Washington is eliminating joints in the design of new bridges when it is practical to do so. We have not taken out joints in older bridges.

   <u>Utah:</u> We clean and reseal our deck joints when placing bridge deck treatments. We also evaluate opportunities to remove existing joints when possible (this is usually not completed with preservation projects but with a more robust rehabilitation project). When utilizing HMA overlays we also address the joints by including a raised joint detail with the project.

   <u>Colorado:</u> CDOT recognizes seepage through joints to be a leading cause of accelerated deterioration of bridge components beneath the joint. We repair and replace leaking joints

and are currently instigating a washing protocol to stifle the deterioration under joints which have not yet been repaired or replaced. Current backlog of joint repair/replacement is estimated at $36 million to replace 125,000 LF of leaking joints.

California: Caltrans identifies leaking joints through our inspection program and aggressively replaces leaking joints to prevent debris from entering the joint and causing impaction damage and to prevent superstructure deterioration for steel girder bridges. Typical joints used in California include pourable, compression and larger assembly joints.

Montana: MDT maintenance forces do not routinely clean or repair leaking joints. They do fix broken joints that pose a safety hazard. We try to remove, reseal or replace non-functioning deck expansion joints in conjunction with bridge or corridor preservation and rehabilitation projects. Joint replacements can be difficult to accomplish on pavement preservation (corridor) projects due to the different needs for traffic control.

Oregon: Oregon currently replaces leaky joints on a case by case basis. When overlay or deck seal treatments are applied deck joint repair and or replacement is a top priority. At this point Oregon has not developed a program to eliminate deck joints, but it is being considered on a case by case basis.

2. **Deck overlays –** Significantly increases the life of the deck by sealing the deck surface from aggressive solutions and reducing the impact of aging and weathering. Overlay systems include waterproofing membrane with asphaltic concrete overlays, low permeability or high performance concrete overlays, and methyl methacrylate and polymer-system overlays.

   Arizona: We use a variety of different deck treatments depending on the deck condition, location, and long term plan. Arizona typically uses epoxy polymer overlays, and methacrylate deck sealer.

   Washington: We use a membrane with HMA. We also use latex and polymer overlays when the decks are worn or show marked deterioration. We have used thin overlays in the past but did not have good success with them. We have not used the silanes or siloxanes to protect the decks from chlorides.

   Utah: We use a variety of different deck treatments depending upon the age, location, and long term plan. Utah typically uses polymer overlays, healer sealer treatments, and waterproofing membranes with an asphalt overlay. We are evaluating the use of polyester concrete overlays along with demolition with HPC or latex modified concrete. We prescribe polymer overlays on new bridge decks and are evaluating other strategies other than the waterproofing membrane with an AC overlay to extend the bridge life.

   Colorado: Waterproofing membranes and deck sealing is a top maintenance priority for CDOT given our extreme climate and aggressive use of deicing solutions. Silane sealant are used on all new bare decks, waterproofing membranes to be installed on all deck with asphalt wearing surfaces, beginning to use thin bonded overlays on decks without asphalt wearing surfaces. Deck sealing and installation of water proofing membranes correspond to a backlog of $42 million to treat 11 million SQF of deck.

Alaska: Install and replace timber running planks to protect timber decks from rutting (section loss).

California: Caltrans has numerous bridges with polyester and asphalt overlays. A much lesser number of multi-layer epoxy or other more exotic overlays have been used. In general we do not apply asphalt to bridge that do not have an existing asphalt overlay. Polyester is our wearing surface of choice.

Montana: MDT generally specifies thick or rigid concrete overlays. For the last couple decades we primarily specified latex modified concrete. In the last couple of years we switched to giving the contractor the choice of latex or silica fume modified concrete. We tried thin overlays 15-20 years ago but did not have good success with them; many de-bonded and came off in sheets. However, some are still working well today. We do see trying them again, as we believe our application knowledge has improved. We prefer not to use asphalt overlays but have on occasions used them without membranes to address short term ride-ability (pot holes) issues. This is done when we know the bridge is being programmed for replacement. Otherwise asphalt overlays are only used with membranes in combination with precast deck elements in accelerated construction.

Oregon: We have not had good results from waterproof membranes. Adhesion to the deck has been an issue. There is currently only one spray on membrane on our qualified products list, it has been recently used and the results have been good. We have used silanes on decks in the past; one particular bridge had superstructure treatment in 1985 and is showing evidence of preventing chloride penetration. Silane treatments appear to last a long time as long as they are not used under conditions where traction tire and devices are used.

Collectively these 3 efforts begin to provide a comprehensive picture of all the various bridge preservation practices that are currently being used in the US.

1.5.2 Topic: Bridge Preservation Actions and Treatments

The following example element sources provide useful, relevant information and data on types of bridge preservation actions and treatments including when/where they are most effective (on different bridge elements, in different condition states, in different environments etc.), how long the treatment will be effective and how often it should be repeated. The sources include published research reports as well as guidelines from individual DOTs developed through elicitation of expert opinion.

The FHWA Bridge Preservation Guide provides guidance on what is considered a Systematic Preventive Maintenance (SPM) program. The AASHTO Subcommittee on Maintenance's definition of "preventive maintenance" includes the phrase "a planned strategy of cost-effective treatments." An SPM program is based on a planned strategy that is equivalent to having a systematic process that defines the strategy, how it is planned, and how activities are determined to be cost effective. An SPM program for bridges can be defined as a planned strategy of cost-effective treatments to existing bridges that are intended to maintain or preserve the structural integrity and functionality of

elements and/or components, and retard future deterioration, thus maintaining or extending the useful life of the bridge.

Many state DOTs have developed an SPM program or are in the process of doing so. One example of the many is that of the New Jersey DOT. See Survey Addendum for the full description of the NJ DOT SPM program. The Bridge Preventive Maintenance Program is intended to extend the life of bridges in good-standing condition by applying cost-effective preventive maintenance treatments. Preventive Maintenance will be performed at the optimal time or specified intervals to help preserve bridge conditions throughout its service life or to extend the service life of the bridges. In addition to defining the expectations of the SPM program and establishing a project selection process, the NJ DOT program establishes a preferred list of bridge preservation actions and provides their expectation of the effectiveness of various actions in terms of when and how often they should be employed. Table 1.5 provides an illustration.

Table 1.5 Example NJDOT preservation actions, criteria and cycle.

Activity	Selection Criteria	Cycle
Bridge Cleaning/Washing	All functional structures, with priority given to highway over highway bridges	Every two years
Repair/Replace Joints	Decks coded “5” or higher, condition state “2” or lower	Every ten years
Repair Concrete Deck/Sidewalk	Decks coded “5” or higher, condition state “4” or lower	Every ten years
Seal Concrete Deck	Decks coded “5” or higher, Condition State “2” or lower	Every five years
Seal Cracks on Wearing Surface– asphalt overlay	Decks coded “5” or higher, Condition State “2” or lower	Every two years
Seal Cracks on Deck	Decks coded “5” or higher, Deck Cracking Smartflag is“2” or lower – bare concrete	Every two years
Seal Cracks on Substructure	Substructure rated “5” or higher, Condition State “3” or lower	Every five years
Substructure Concrete Repair	Substructure rated “5” or higher, Condition State “3” or lower	Every ten years
Corrosion Inhibitor	All functional structures, with priority given to highway over highway bridges	Every five years
Lubricate Bearings	As needed, applied only if other work is being performed on structure	Every four years
Seal Substructure Concrete	As needed, applied only if other work is being performed on structure	As needed
Repair Approach Slabs	As needed, applied only if other work is being performed on structure	As needed
Repair Erosion/Scour	As needed, applied only if other work is being performed on structure	As needed
Safety Improvements	As needed, applied only if other work is being performed on structure	As needed

Other state DOTs have SPM programs that provide to guidance on bridge preservation actions that will help define the consensus expert opinion on effectiveness and longevity of bridge preservation actions.

Other sources of information on effectiveness and longevity of bridge preservation actions are provided in matrices developed by DOTs to quantify the approach to decision-making. Several of these are devoted to preservation of decks such as the following:

NYSDOT Bridge Deck Treatment Matrix (currently in draft status):

For different types of overlays as well as penetrating sealers and crack fillers this guide provides estimated unit costs for the work as well as an estimated service life for some of the treatments.

Michigan DOT Bridge Deck Preservation Matrix:

- Decks with Uncoated “Black” Rebar
- Decks With Epoxy Coated Rebar (ECR)

These guides provide recommended repair options based on deck NBI rating, extent of deficiencies on top and bottom surfaces of the deck; the guides also project expected improvements to the deck rating as well as expected service life of the treatment.

Washington DOT Deck Preservation Matrix:

Similar to the Michigan matrices, this guide provides recommended repair options based on deck NBI rating, extent of deficiencies on top and bottom surfaces of the deck; optional criteria based on exposure of rebar, load rating, age, and ADT are also provided for reaching a decision on the most appropriate treatment. The guide also project expected improvements to the deck rating as well as expected service life of the treatment. The type of guidance provided is shown in Table 1.6.

These and other guides like them are an excellent source of expert opinion on applicability, effectiveness and longevity of bridge deck preservation treatments.

Other useful sources of information and data on bridge preservation treatments include:

NCHRP SYNTHESIS 425 Waterproofing Membranes for Concrete Bridge Deck:

The objective of this synthesis study was to update NCHRP Synthesis of Highway Practice 220: Waterproofing Membranes for Concrete Bridge Decks, a report on the same topic published in 1995. This synthesis documents information on materials, specification requirements, design details, application methods, system performance, and costs of waterproofing membranes used on new and existing bridge decks since 1995.

Some additional information sources include can be found in additional research studies listed in project Addendum - Reference Sources Identified for Possible Relevant Content .

Table 1.6 Washington DOT deck preservation matrix.

Deck Type	Deck Condition State			Optional Criteria				Repair Options	Potential Result to NBI	Next Anticipated Evaluation
	NBI Rating	Deck Deficiency	Deck Underside (Soffit)	Exposed Rebar	Load Rating	Age	Lane ADT			
Concrete Deck	6 or 7	< 1%						Deck Patch	No Change	2 years
								Crack Seal	No Change	
			0%			> 60	Low	HMA w/o mem	No Change	10 – 30 years
	5	1% to 2%						Deck Patch	No Change	2 years
			>0%			< 40	Low	HMA w/ mem	No Change	10 – 30 years
			<0.5%	>0%	Low	< 40	High	Concrete Overlay	NBI 7	15 – 30 years
	4	2% to 5%	>1%			> 60		Deck Patch	No Change	2 years
			0%				Low	HMA w/ mem	No Change	7 – 12 years
			<0.5%	>0%	Low	< 40	High	Concrete Overlay	NBI 7	10 – 20 years
	3	>5%						Deck Patch	No Change	2 years
			>0%					Concrete Overlay	NBI 7	20 – 40 years
			>5%					Replace Deck	NBI 7	40 – 60 years
Slab/Girder Deck	6 or 7	< 1%						Deck Patch	No Change	2 years
								Crack Seal	No Change	
							Low	HMA w/ mem	No Change	10 – 30 years
	5	1% to 2%						Deck Patch	No Change	2 years
			0%			< 40	Low	HMA w/ mem	No Change	10 – 30 years
			<0.5%	>0%	Low	< 40	High	Concrete Overlay	NBI 7	15 – 30 years
	4	2% to 5%	>1%			> 60		Deck Patch	No Change	2 years
			0%				Low	HMA w/ mem	No Change	10 – 30 years
			<0.5%	>0%	Low	< 40	High	Concrete Overlay	NBI 7	15 – 30 years
	3	>5%						Deck Patch	No Change	15 – 30 years
			>0%					Concrete Overlay	No Change	20 – 40 years
			>5%					Replace Deck	NBI 7	40 – 60 years

1.5.3 Topic: Costs of Bridge Preservation Actions

The usefulness of the handbook, decision-making processes and the associated tools will depend on having reliable cost data to plug into calculations. This traditionally has been a weak point in the ability to calculate life cycle costs, run optimization methodologies, etc. Across the various states, recordkeeping systems for costs vary widely. A recent development done under NCHRP Project 14-23 provides some promise for producing realistic cost figures for preservation activities. NCHRP 14-15 developed a Framework for a National Database System for Maintenance Actions on Highway Bridges (NCHRP Report 668). This database provides a means for establishing a record of actions that includes uniform descriptions of maintenance activities, bases of measurement, costs, impacts, performance and other relevant data for use in cost-benefit analysis, selection of maintenance actions or other related decisions. Over time, this database could become a valuable

tool to evaluate the effectiveness of bridge preservation actions. The 14-15 project also surveyed agencies and tabulated costs of bridge maintenance actions of significant expected value in this project. The NCHRP Project 14-23 research team has this data available for analysis in developing realistic costs for bridge preservation actions.

It is also well recognized that the costs of any bridge preservation action will vary considerably from one state to another. Thus it will be important to supplement the data from project 14-23 with input from other sources. One example is the table below that provides estimated costs for typical actions employed by NC DOT in their bridge preservation program.

Based on the data in NCHRP 14-23 and costs tables collected from states such as North Carolina (see Table 1.7), the handbook and tools will be demonstrated using a set of costs that are deemed reasonable for national averages. As mentioned previously, the handbook and tools will be flexible for the individual states to substitute data that is more in line with costs as experienced in their state.

Table 1.7 NCDOT typical bridge preservation activity unit costs.

Preservation Activities	Cycle (years)	Condition Grade	Unit Cost * ($/SF Deck Area)
Deck Joints	10	5-8	$5
Deck Overlays (Latex Modified Concrete)	20	3-4	$20
Deck overlays (Epoxy)	20	5-6	$10
Deck Sealers	4	6-8	$2
Deck Chloride Extractors	8	6-8	$1
Deck Washing	As needed	3-8	$1
Structural Steel Painting	30	3-4 Complete 5-6 Partial 7-8 Washing	$17 $10 $1
Structural Steel Repairs (in conjunction with painting)	30	3-6	$10
Concrete Girders	20	3-4 Spall Repair 5 Spall Repair 6-8 Sealing	$8 $5 $2
Concrete Substructure	20	3-4 Spall Repair 5 Spall Repair 6-8 Sealing	$8 $4 $2
Bearing Cleaning and Recoating	10	3-5	$5
Bent/Endbent Rehabilitation and Sealing	20	3-5	$5
Bearing Replacements (Steel with elastromeric)	As needed	3-5	$30

* to raise to acceptable LOS

The NYSDOT Bridge Deck Treatment Matrix (currently in draft status) is another example of a source for costs associated with bridge preservation treatments.

1.5.5 Topic: Tools for Bridge Program Decision-making

Some documents that present the results of previous research on pavement preservation but that have some significant application to bridge preservation are also reviewed.

Title: NCHRP REPORT 523 Optimal Timing of Pavement Preventive Maintenance Treatment Applications
Author(s): D.G. Peshkin, T.E. Hoerner, K.A. Zimmerman
Agency: Transportation Research Board
Year Published: 2004
Abstract/Key Points:

This report describes a methodology for determining the optimal timing for the application of preventive maintenance treatments to flexible and rigid pavements. The methodology is also presented in the form of a macro-driven Microsoft® Excel Visual Basic Application—designated OPTime—available to users by accessing the NCHRP website (http://trb.org/news/blurb_detail.asp?id=4306). The methodology is based on the analysis of performance and cost data and applies to any of the treatments and application methods that are used by highway agencies. A plan for constructing and monitoring experimental test sections is also provided to assist highway agencies in collecting the necessary data if such data are not readily available. The report is a useful resource for state and local highway agency personnel and others involved in pavement maintenance and preservation.

The computer algorithms in OPTime will play an essential role in the decision-making tools developed as part of this project.

Additional resources associated with this report include

Appendixes A, B, C, and E submitted by the research agency are not published herein. Titles of available appendixes are as follows:
APPENDIX A Summary of Agency Experiences
APPENDIX B Historical Optimization-Based Approaches Used for Transportation-Related Problems
APPENDIX C User's Guide for the Optimal Preventive Maintenance Timing Analytical Tool (OPTime)
APPENDIX D Plan for Constructing and Monitoring Preventive Maintenance Test Sections
APPENDIX E Example Illustrating the Inclusion of Different Cost Types

Title: NCHRP Web Document 45 (Project 10-50A): Contractor's Final Report, A Process for Selecting Strategies for Rehabilitation of Rigid Pavements
Author(s): S. Anderson, G. Ullman, B. Blaschke
Agency: Transportation Research Board
Year Published: 2004
Abstract/Key Points:

The document describes a process that while it is explicitly focused on pavements addresses some fundamentals that have direct application to bridges:

- A probable Maintenance, Repair, and Rehabilitation (MRR) strategy should be identified early in project development, and preferably prior to the establishment of project funding. The strategy

ideally will dictate funding, rather than the funding dictating strategy.

- The early and continuing involvement of many agency professionals in the selection process is desirable. Materials, design, traffic, construction, maintenance, and contract organizations should have input to support the pavement design effort.
- The probable cause of pavement distress should be determined and the MRR strategy selected should correct the cause, not just treat the symptoms.
- After selecting potential MRR strategies for further study, it is desirable to screen the strategies to eliminate those that are not practical or economically feasible. The remaining strategies would then be studied in greater detail.
- In high volume traffic conditions, the disruption of traffic, even for short time periods, can result in extensive road user costs. Hence, selecting pavement treatments, materials, traffic management approaches, and contracting methods that will accelerate the work and minimize traffic disruption becomes a critical consideration. Nonetheless, the process emphasizes that these considerations should not, where possible, be allowed to dictate strategy selections that do not correctly address the actual causes of the pavement distress.
- In high volume traffic conditions, selecting MRR strategies requires construction knowledge and experience to insure that each strategy is constructible, cost effective, minimizes traffic delays, and provides a safe environment for workers and the traveling public.

The following factors and constraints play a major role in decision-making when selecting MRR strategies. A key attraction of the proposed process is that most of the time these factors can be modified to fit the project objectives, if addressed in the early stages of design.

- Availability of Funds - increments on allocated funds for the project may be required to select appropriate and cost-effective strategies.
- Safety (motorist and workers) - development of traffic and construction management approaches that maximize a safe environment during MRR activities.
- Traffic congestion - development of traffic and construction management approaches that minimize the amount of congestion created, the duration of the congestion, and the degree of driver dissatisfaction with the SHA about how traffic is accommodated.
- Public opinion - information campaigns to obtain public involvement in the early stages of the project. This may help avoid conflicts and delays due to public opposition. This may also create public acceptance for delays if the project is completed in a timely way.
- SHA policies - assessment of policies and formal procedures. Possible modifications to written and unwritten policies may have to be submitted for approval.

CHAPTER 2 Bridge Elements and Preservation Actions

2.1 Bridge Element Preservation

The research in this task is to create a catalog of bridge elements with the corresponding types of deterioration common to those elements and the preservation actions that are commonly applied to those elements. Hereinafter, for brevity, this catalog will be referred to as the “Catalog of Actions” or simply “the catalog”. For each element and type of deterioration, one or more feasible preservation actions will be identified. To the extent possible, the effort is to match each feasible preservation action with data on anticipated life of the treatment/action and unit costs.

The knowledge for this task is developed from a combination of the literature search, the expertise of the experienced team members, and contacts made with bridge preservation experts identified from a selection of states that will ensure diversity of environment, bridge types and current preservation practices.

The AASHTO Manual for Bridge Element Inspection (MBEI) was adopted by SCOBS in June 2013. It replaces the previous AASHTO Guide Manual for Element Level Inspection. This manual will become the fundamental guide for bridge element level inspection, and ultimately serve as the basis for Federal element condition reporting standards. Recognizing the importance of this standard, the content and terminology included in the Catalog of Actions will be as consistent as possible with the bridge elements and types of deterioration used in the MBEI. The types of deterioration identified will be described with levels of deterioration that relate as closely as possible to its formally defined element level condition states.

Several formats have been explored to mirror the format of the Manual for Bridge Element Inspection in the catalog. In an example (Fig. 2.1), each element is listed and described as in the Inspection Manual and follows with a matrix of possible actions that may improve the condition of the element and will extend the life of the element. Where reliable information is available, the matrix can be augmented with more detailed information on evaluation of the condition and/or specific qualities of the element that will help in further refining the selection of the best preservation action to take. Examples of this refined knowledge include the NCHRP 20-07, Task 34 report. Chapter 1.5 describes other potential sources of knowledge and data for the catalog content. Additional sources are listed in project Addendum - Reference Sources Identified for Possible Relevant Content. The matrix will also outline the expected added life and improved condition in terms of element level condition states (as well as NBI ratings if deemed feasible) that will be anticipated from each action. Later in the project, available cost information was added to this matrix as well. Another aspect of the catalog will be descriptions of the actions that have shown to be successful for each National Bridge Element and Bridge Management Element. Discussions on the actions themselves, as well as areas and climates where they work best and the best time to apply treatments will be included within the catalog of actions.

Selection of actions for consideration will depend on the mix of existing condition states. It is likely that decision trees defining triggers levels of condition will facilitate selections. Where there are multiple options, the final selection can be made based on comparison of life-cycle costs for the element’s preservation.

Element #: 12 — Reinforced Concrete Deck

Description: This element defines all reinforced concrete bridge decks regardless of the wearing surface or protection systems used.

Defect: Cracking

State	Condition Description	Activity Category	Action	Resulting Condition State		Cost of Action ($)	Units	Service Condition (SC)							
								SC1		SC2		SC3		SC4	
								Action Cycle (yrs)	Element Added Life (yrs)	Action Cycle (yrs)	Element Added Life (yrs)	Action Cycle (yrs)	Element Added Life (yrs)	Action Cycle (yrs)	Element Added Life (yrs)
1	Width less than 0.012 in. or spacing greater than 3.0 ft.	Do Nothing	--	1	None	0.00	SQ FT	50	0	42	0	35	0	25	0
		Cyclical	Clean and Wash	1	No change – sustains current conditions	0.50	SQ FT	50	0	5	0.5	2	0.5	1	0.5
		Preserve	Seal Cracks	1	No change – sustains current conditions	2.00	SQ FT	10	3.8	8	2.5	6	1.8	4	1
		Preserve	Wearing Surface Overlay	1	No change – sustains current conditions	10.00	SQ FT	25		20		15		12	
2	Width 0.012–0.05 in. or spacing of 1.0–3.0 ft.	Do Nothing	--	2	None	0.00	SQ FT	50	0	42	0	35	0	25	0
		Cyclical	Wash	2	No change – sustains current conditions	0.50	SQ FT	50	0	5	0.5	2	0.5	1	0.5
		Preserve	Seal Cracks	2	No change – sustains current conditions	2.50	SQ FT	10	3.8	8	2.5	6	1.8	4	1

Figure 2.1 Sample Catalog Format – Element 12 Decks / Slabs with Cracking

State	Condition Description	Activity Category	Action	Resulting Condition State		Cost of Action ($)	Units	Service Condition (SC)							
								SC1		SC2		SC3		SC4	
								Action Cycle (yrs)	Element Added Life (yrs)	Action Cycle (yrs)	Element Added Life (yrs)	Action Cycle (yrs)	Element Added Life (yrs)	Action Cycle (yrs)	Element Added Life (yrs)
3	Width greater than 0.05 in. or spacing of less than 1 ft	Do Nothing	--	3	No Change	0.00	SQ FT	50	0	42	0	35	0	25	0
		Preserve	Seal Cracks	2	sustains current conditions	3.00	SQ FT	10	3.8	8	2.5	6	1.8	4	1
		Rehab	Overlay	2	Reset to Condition 2	20.00	SQ FT	20							
4	Warrants structural review	Do Nothing	--	4	None	0.00	SQ FT	50	0	42	0	35	0	25	0
		Rehab	Overlay	2	Reset to Condition 2	20.00	SQ FT	20							
		Replace	Remove / Replace	1	Reset to Condition 1	60.00	SQ FT	50							

Note: Estimated costs only include direct cost; indirect costs such maintenance of traffic, engineering and other miscellaneous are not included.

Figure 2.1 Sample Catalog Format – Element 12 Decks / Slabs with Cracking (continued)

2.2 Catalog of Bridge Element Preservation Actions

The universe of possible preservation actions has been evolving and expanding over time. The discussion of actions in the manuals used for element level inspection has typically been very general. For example, the descriptions of actions included in the AASHTO Guide for Commonly Recognized (CoRe) Structural Elements – December 1997, were:

- Do Nothing – Let the element deteriorate to a point where the action was most effective
- Preemptive actions – The element is treated prior to the start of any deterioration processes with prevent or forestall the initiation of deterioration.
- Clean and Restore – Process to remove the deterioration of the protective system and replace the removed material. This process is primarily for paint systems.
- Repair – Fix the issue that is causing the condition to be less than "new". Repairs were never considered a resolution to the issue. These actions were considered for discrete areas. Depending on the nature of the repair, the duration of the effectiveness of the repair action may differ (i.e., be shorter or longer) than that of the rehabilitation or replacement actions.
  Rehabilitate – Work that is done to restore the structural integrity of the element. The rehabilitation process restores the element to near new. Some of the issues still remain such as age and material limitations.
- Replace – Removal and replacement in-kind of the element is completed. The element is restored to new.

The descriptions of these actions were too general and the cost for taking the action was not tied to any one possible specific action. The cost used for the management system was an average of all of the possible costs for that category of action.

Preservation actions have evolved into specific actions and activities. The development of preservation project included individual actions and grouping of actions that are required for economy of scale.

Preservation activities can be grouped into the primary components of deck, superstructure, substructure and culvert. Some of the activities will fall into more than one group based on material type and structural design. Below are typical activities that are taken on structures. Table 2.1 groups activities by structural component and by material for actions. These actions can be grouped together to create a comprehensive preservation network program and scope of work for individual projects.

Table 2.1 Identification of bridge element maintenance and preservation actions

Component	***Action***	***Result of Treatment***	***Action Type***
Deck	Waterproofing Sealant	Resist water and chloride penetration. Applied when deck shows no to minimum distress.	Cyclical Preservation
	Deck Washing	Chloride remove	Cyclical Preservation
	Concrete Crack Sealing	Fill crack voids with material to resist water and chloride ponding and penetration. Applied when deck shows signs of small to moderate cracking.	Preservation (Preventive Maintenance / Rehabilitation)
	Deck Patching – Full Depth and Partial Depth	Riding Surface Restoration	Repair, Preservation When Attached to Other Activities
	Repair/infilling of wheel ruts	Riding Surface Restoration; additional protection for rebars	Repair
	Epoxy/Polymer Overlays	Waterproofing – applied with low to no surface defects	Preservation (Preventive Maintenance / Rehabilitation)
	Hot Mix Asphalt Overlay with Waterproofing Membrane	Waterproofing, sacrificial wearing surface	Preservation – allows riding surface restoration in conjunction with roadway activities
	Hot Mix Asphalt Overlay with No Membrane	Riding Surface Restoration	Repair
	Shallow Concrete (2” And Less) Overlay – Silica Fume/Latex Modified Concrete	Waterproofing and ride restoration	Preservation (Preventive Maintenance / Rehabilitation)
	A Deep Concrete (Over 2”) Overlay – Low Slump Concrete	Ride Restoration and chloride concrete removal	Preservation (Preventive Maintenance / Rehabilitation)

Component	*Action*	*Result of Treatment*	*Action Type*
	Add Protective System (Cathodic)	Sacrificial elements for Chloride resistance	Preservation
	Maintenance of Protective System (Cathodic)	Replace/Repair the Cathodic system	Repair
	Replace Riding Surface (Sacrificial riding surface) on Timber or Corrugated Metal Deck	Riding Surface Restoration and deck material protection	Repair
	Deck Rehabilitation (without Traffic Capacity Change)	Repair and update major defects of the deck. Activities could include the combination of several activates	Preservation if no increase in traffic capacity.
	Deck Replacement (without Traffic Capacity Change)	Remove and replace-in-kind	Preservation if no increase in traffic capacity or change in design
Traffic Barriers	Repair – Traffic Impact	Restore to safety requirement	Repair
	Repair – Deterioration	Restore to safety requirement	Preservation (Preventive Maintenance / Rehabilitation)
	Seal Concrete in splash zones	Waterproofing	Preservation (Preventive Maintenance / Rehabilitation)
	Clean and Spot Recoating (includes paint, galvanization)	Maintaining Waterproofing	Preservation (Preventive Maintenance / Rehabilitation)
	Rehabilitation	Remove Defects and Restore Safety Requirement	Preservation (Preventive Maintenance / Rehabilitation)
	Traffic Barrier Upgrade/Retrofit - Replacement	Update to Current Standards	Preservation (Preventive Maintenance / Rehabilitation)

Component	***Action***	***Result of Treatment***	***Action Type***
	Replacement	Restore Safety and Remove All Defects	Preservation (Preventive Maintenance / Rehabilitation)
Deck Joints	Joint Repair (open and other joints that do not fit the joint systems)	Restore functionality	Repair
	Joint Replacement (open and other joints that do not fit the joint systems or replace not-in-kind)	Removes all defects	Preservation (Preventive Maintenance / Rehabilitation)
	Joint Removal (Update to Joint less Deck)	Remove maintenance Requirement – protection for superstructure elements for exposure to deck contaminates	Preservation (Preventive Maintenance / Rehabilitation)
	Clean Joint	Remove debris from joint	Annual Maintenance
	Strip Seal Joint Repair	Localized seal repair	Repair
	Strip Seal Joint Rehabilitation	Replacement of the Seal Material and repair of headers	Preservation (Preventive Maintenance / Rehabilitation)
	Strip Seal Joint Replacement	Restore to New	Preservation (Preventive Maintenance / Rehabilitation)
	Pourable Joint Seal Repair	Localized seal repair	Repair
	Pourable Joint Seal Rehabilitation	Replacement of the Seal Material and repair of headers and anchor system	Preservation (Preventive Maintenance / Rehabilitation)
	Pourable Joint Seal Replacement	Replace Seal Material and Anchor System	Preservation (Preventive Maintenance / Rehabilitation)
	Compression Joint Seal Repair	Localized seal repair	Repair

Component	***Action***	***Result of Treatment***	***Action Type***
	Compression Joint Seal Rehabilitation	Replacement of the Seal Material and repair of headers and anchor system	Preservation (Preventive Maintenance / Rehabilitation)
	Compression Joint Seal Replacement	Replace Seal Material and Anchor System	Preservation (Preventive Maintenance / Rehabilitation)
	Repair of Assembly Joint Seals (Modular)	Localized seal repair	Repair
	Rehabilitation of Assembly Joint Seals (Modular)	Replacement of the Seal Material; repair of headers and anchor system; Align modular sections	Preservation (Preventive Maintenance / Rehabilitation)
	Replacement of Assembly Joint Seals (Modular)	Replace Seal Material and Anchor System	Preservation (Preventive Maintenance / Rehabilitation)
	Repair of Steel Armor Expansion Joint (with and without Seal)	Localized plate repair, clean and repair drainage systems	Repair
	Rehabilitation of Steel Armor Expansion Joint (with and without Seal)	Replacement of the broken and missing armor plates; repair of headers and anchor system; Align modular sections; clean and repair drainage systems	Preservation (Preventive Maintenance / Rehabilitation)
	Replacement of Steel Armor Expansion Joint (with and without Seal)	Replace assembly plates; Anchor System and drainage system	Preservation (Preventive Maintenance / Rehabilitation)
	Repair of Polymer Block Out Expansion Joints	Localized polymer repair	Repair
	Replace Polymer Block Out Expansion Joint	Replace polymer block, bridging plate and backer rod	Preservation (Preventive Maintenance / Rehabilitation)

Component	***Action***	***Result of Treatment***	***Action Type***
Superstructure (Does not include Widening, Increased Strength or Raising for Clearance)	Superstructure Washing	Remove contaminates such as chlorides and other environmental contaminates	Cyclical Preservation
	Repair Collision Damage	Restore to as-built design strength and standards	Repair
	Repair of ancillary bridge items (sign attachment assemblies, luminaries, bird netting, catwalks, etc.)	Localized repair of system	Repair
	Rehabilitate of ancillary bridge items (sign attachment assemblies, luminaries, bird netting, catwalks, etc.)	Restore the system to the original working condition	Preservation (Preventive Maintenance / Rehabilitation)
	Replace of ancillary bridge items (sign attachment assemblies, luminaries, bird netting, catwalks, etc.)	Replace-in-kind	Preservation (Preventive Maintenance / Rehabilitation)
	Pin & Hanger Maintenance	Grease pin connection for movement	Operations
	Pin & Hanger	Install catch system	Preservation (Preventive Maintenance / Rehabilitation)
	Pin & Hanger Replacement	Restore to New Condition	Preservation (Preventive Maintenance / Rehabilitation)
	Epoxy Inject Concrete Superstructure Cracks	Reduce/Prevent corrosion of reinforcement and/or prestressing steel	Preservation (Preventive Maintenance

Component	***Action***	***Result of Treatment***	***Action Type***
	FRP Reinforcement for Concrete Superstructure Cracks	Restore strength (not increase)	Preservation (Rehabilitation)
	Concrete Superstructure Sealing	Reduce/Prevent Chloride Contamination in Splash Zones	Preservation (Preventive Maintenance / Rehabilitation)
	Steel Beam End Repair	Restoration of steel beams to capacity (includes any location that has exposure to deck runoff)	Repair / Preservation
	Steel Fatigue Crack Arrestment	Stopping of localize fatigue crack	Repair / Preservation
	Steel Section Loss Repair	Remove / Replace Section with Corrosion that compromises strength; Restore to design strength	Repair / Preservation
	Superstructure Repair	Covers other bridge repairs that could be done. This covers timber beam stitching for crack or severely checked beams.	Repair
	Superstructure Rehabilitation (without change in traffic volume capacity)	Restore all of the superstructure elements to near new condition	Preservation (Preventive Maintenance / Rehabilitation)
	Superstructure Replacement (without increase in traffic volume capacity)	Replace superstructure elements with new elements	Preservation (Preventive Maintenance / Rehabilitation)
	Seismic retrofit	Update to Current Standards	(Preventive Maintenance / Rehabilitation)
Substructure (Does not include Widening, Increased Strength or Raising for Clearance)	Epoxy Inject/FRP Enforce Concrete Superstructure Cracks	Restore Strength (not increase)	Preservation (Preventive Maintenance / Rehabilitation)

Component	***Action***	***Result of Treatment***	***Action Type***
	Substructure Washing	Remove contaminates such as chlorides and other environmental contaminates	Cyclical Preservation
	Concrete Substructure Sealing	Chloride Contamination in Splash Zones	Preservation (Preventive Maintenance / Rehabilitation)
	Repair Collision Damage	Restore to as-built design strength and standards	Repair
	Steel Section Loss Repair	Remove / Replace Section with Corrosion that compromises strength; Restore to design strength	Repair / Preservation
	Element Surface Coating	Weatherproofing against corrosion; For Steel, Concrete and Timber	Preservation (Preventive Maintenance / Rehabilitation)
	Timber Pest Control	Protection on section loss from insect infestation	Operation
	Add Protective System (Cathodic)	Sacrificial elements for Chloride resistance	Preservation (Preventive Maintenance / Rehabilitation)
	Installation of Pile Jackets W/ CP Systems	Sacrificial elements for Chloride resistance	Preservation (Preventive Maintenance / Rehabilitation)
	Maintenance of Protective System (Cathodic)	Replace/Repair the Cathodic system	Repair
	Scour Counter Measures (other than Rip Rap)	Protect Erosion Activity	Preservation (Preventive Maintenance / Rehabilitation0
	Install Rip Rap	Protect Erosion Activity	Preservation (Preventive Maintenance / Rehabilitation)

Component	***Action***	***Result of Treatment***	***Action Type***
	Remove Channel Debris Around Substructure Units	Protect Erosion Activity	Preservation (Preventive Maintenance)
	Repair Pier Protection (both navigational and/or debris)	Repair existing pier protection systems	Preservation (Preventive Maintenance / Rehabilitation)
	Install Pier Protection (both navigational and/or debris)	Install protection system on outset of external scour activities; change in navigation activities	Preservation (Preventive Maintenance / Rehabilitation)
	Repair of Bearing Seat	Restore strength capacity of bearing seat for proper bearing operation	Preservation (Preventive Maintenance / Rehabilitation
	Partial Substructure Replacement	Replace discrete substructure elements with new elements (caps, piles; primary for timber and steel)	Preservation (Preventive Maintenance / Rehabilitation)
	Substructure Repair	Other activities not specified	Preservation (Preventive Maintenance / Rehabilitation)
	Substructure Rehabilitation (without change in traffic volume capacity)	Restore all of the substructure elements to near new condition	Preservation (Preventive Maintenance / Rehabilitation)
Bearings	Clean Bearing and Seat	Remove Debris for proper movement	Preservation
	Reset Bearings	Set proper alignment	Preservation
	Maintenance Mechanical Bearings (Rocker and Roller)	Grease and reset for proper movement	Preservation
	Upgrade Bearings	Allow better movement with less maintenance	Preservation (Preventive Maintenance / Rehabilitation)

Component	***Action***	***Result of Treatment***	***Action Type***
	Rehabilitation of Bearing	Restore to proper working order	Preservation (Preventive Maintenance / Rehabilitation)
	Replace Bearing	Replace failed bearing; restore to proper operation	Preservation (Preventive Maintenance / Rehabilitation)
	Seismic retrofit	Update to Current Standards	(Preventive Maintenance / Rehabilitation)
Coating System; Primary Paint	Spot Painting	Target at localize system Failure	Preservation (Preventive Maintenance / Rehabilitation)
	Zone Painting	Cleaning and Painting areas of high paint deterioration	Preservation (Preventive Maintenance / Rehabilitation)
	Compete Painting	Clean and arrest corrosion; Apply new paint system	Preservation (Preventive Maintenance / Rehabilitation)
Culverts	Reset barrels	Erosion and under mining	Preservation (Preventive Maintenance / Rehabilitation)
	Cleaning of Sediment	Reset to proper Hydraulic characteristics	Preservation
	Repair Erosion control Devices (headwalls, flared end sections and outlet flow control)	Repair to working order to control undermining and scour	Preservation (Preventive Maintenance / Rehabilitation)
	Rehabilitation of culvert	Remove and Replace Deteriorated Sections	Preservation (Preventive Maintenance / Rehabilitation)

Component	*Action*	*Result of Treatment*	*Action Type*
	Relining of Culvert Barrel	Improve culvert structural properties; reset to proper Hydraulic characteristics	Repair

The research in this task identified the bridge elements to be covered in the catalog and how the types of deterioration that commonly occur and the preservation options available can be presented. The types of deterioration each have defined condition states. For each element and type of deterioration, there are preservation options. The intent is for the catalog to be compatible with the 2013 AASHTO *Manual for Bridge Element Inspection*.

Efforts to improve the format of the Catalog have continued during Phase II. This has included improving compatibility with the new AASHTO Manual and incorporation of the element service environment. An example of the catalog format for actions by element, defect, and condition is illustrated in Appendix II of this Progress Report. Many other tables for the catalog have also been formatted. Finding reliable data remains a problem to be resolved with ongoing research.

During the continued development of the catalog in Phase II, it has become apparent that the content should concentrate on the elements where preservation activity and data is more prevalent. Bridge element maintenance and preservation needs often reflect the Pareto Principle, also known as the 80-20 rule. Under this principle, it can be expected that 80% of the needs will occur in 20% of the elements. The needs of the remaining 80% of the elements can be expected to be more specialized, more random, and less predictable. Since 80% of the costs can be expected in 20% of the elements, it is appropriate at this stage of development of the catalog, methodology and tool to focus on the elements that tend to generate the most costs. In the future, if the project results prove helpful to users, the catalog and tool capacity could be expanded. As proposed herein, about 40% of the AASHTO MBEI elements are recommended for inclusion in the catalog at this stage.

The elements and types proposed to be covered are summarized in Table 1.2. A similar summary in the format of the pending AASHTO Manual for Bridge Element Inspection is provided in Appendix II.

Table 2.2 Summary of bridge elements covered

Component	Element	Type or Material	Element No.
Deck	Wearing Surface	Overlay	510
	Deck/Slabs	Reinf. Concrete	12, 16, 38
		P/S Concrete	13, 15
		Timber	31, 54
	Deck Joints	Strip Seal	300
		Pourable Seal	301
		Compression Seal	302
		Assembly w/Seal	303
		Open	304
		Assembly w/o Seal	305
Superstructure	Stringers and beams	Reinf. Concrete	110, 116, 155
		P/S Concrete	109, 115, 154
		Steel	107, 113, 152
		Timber	111, 117, 156
	Bearings	Elastomeric	310
		Movable	311
		Fixed	313
	Coatings	Steel Protective Coating	515
Substructure	Caps	Reinf. Concrete	234
		P/S Concrete	233
		Timber	235
	Piers	Reinf. Concrete	205
		P/S Concrete	204
		Timber	206
	Abutments	Reinf. Concrete	215
		Timber	216
		Masonry	217

Another aspect of the handbook will be descriptions of the actions that have shown to be successful for each National Bridge Element and Bridge Management Element. Discussions on the actions themselves and condition states for which the action may be effective will be indicated within the catalog of actions. Actions being considered include, but are not limited to the following:

Decks/Wearing Surfaces

- Washing
- Concrete Crack Sealing
- Concrete Deck Sealing
- Deck Patching
- Polymer overlays
- Hot Mix Asphalt overlay with waterproofing membrane
- Hot Mix Asphalt cap with no membrane
- Shallow Concrete overlay
- A Deep Concrete Overlay
- Barrier patching
- Deck replacement

Deck Joints

- Strip Seal Joint Repair
- Strip Seal Joint Replacement
- Pourable Joint Seal Repair
- Pourable Joint Seal Replacement
- Compression Joint Seal Repair
- Compression Joint Seal Replacement
- Replacement of Assembly Joint Seals (Modular)
- Replacement of Steel Armor Expansion Joints
- Repair of Polymer Block Out Expansion Joints

Superstructure

- Washing
- Concrete Surface Coating
- Pin & Hanger Replacement
- Beam End Repair
- Superstructure Replacement
- Bearing repair & Replacement

Steel Protective Coatings

- Spot Painting
- Zone Painting
- Painting: Over Coating and Remove & Replace

Concrete Protective Coatings

- Concrete Surface Coating

Substructure

- Washing
- Concrete Sealing

- Concrete Surface Coating
- Substructure Concrete Patching and Repair
- Composite Wraps
- Scour Countermeasures
- Substructure Replacement or Partial Substructure Replacement (such as pier cap).
- Cathodic Protection

Table 2.3 presents the spreadsheet layout of an example portion of the catalog of preservation actions. In some cases, similar bridge elements have been consolidated by material type where the action options and costs are similar. The elements each have several possible defects defined by Defect Codes listed in the AASHTO Bridge Element Inspection Manual. Defects due to settlement and collision damage are not considered since the incidences vary widely in severity and cannot be predicted. Defects associated with scour are considered to be better managed by other in-place bridge programs. For each material, defect, and condition state, preservation actions are listed along with the costs and units of measure. Because some unit costs vary with the size of a bridge (e.g. bearings are in units of each but vary in cost with span length), the costs are based on a bridge of average width, 50 ft. and average individual span length of about 100 ft. Unit costs are order of magnitude based on review of available data, interpolation, and extrapolation. It will be necessary for the user to supply better cost data based on their own experiences and the effects of inflation at that time. The unit costs include labor, materials, and equipment normally associated with the actions. No distinction is made between agency performed actions and contracted actions. Costs of maintenance of traffic and contract administration are not included.

An additional general class of preservation action is considered to include actions such as cleaning, washing, sealing of concrete surfaces, lubricating, and installation of overlays which may be done after other actions addressing specific defects or may be done generally to a material to extend its life. Examples of these general actions are grouped immediately after the actions to address defects. Examples are found in the tables of Appendix E. An example is in lines 176-193 of Tables E-1.4a-c where washing, sealing, and installation of new overlays are listed for concrete R/C and P/S decks. By implication, these general actions may be done after actions on defects are completed and the condition state possibly increased by those actions on defects.

Table 2.3 Example catalog table of preservation actions: Joints - sealed

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2			Defect			Deck		Superstructure		Substructure		
3	Material	Defect	Code	Condition	Preservation Action	Elements	Cost ($)	Elements	Cost ($)	Elements	Cost ($)	Units
4	Joints - sealed	Leakage	2310	1	Do nothing	300, 301, 302,	0.00	na	na	na	na	ft.
5	Joints - sealed	Leakage	2310	2	Reseal	300, 301, 302,	10.00	na	na	na	na	ft.
6	Joints - sealed	Leakage	2310	3	Reseal	300, 301, 302,	15.00	na	na	na	na	ft.
7	Joints - sealed	Leakage	2310	4	Replace seal	300, 301, 302,	25.00	na	na	na	na	ft.
8	Joints - sealed	Adhesion	2320	1	Do nothing	300, 301, 302,	0.00	na	na	na	na	ft.
9	Joints - sealed	Adhesion	2320	2	Reseal	300, 301, 302,	8.00	na	na	na	na	ft.
10	Joints - sealed	Adhesion	2320	3	Reseal	300, 301, 302,	12.00	na	na	na	na	ft.
11	Joints - sealed	Adhesion	2320	4	Replace seal	300, 301, 302,	25.00	na	na	na	na	ft.
12	Joints - sealed	Damage	2330	1	Do nothing	300, 301, 302,	0.00	na	na	na	na	ft.
13	Joints - sealed	Damage	2330	2	Do nothing	300, 301, 302,	0.00	na	na	na	na	ft.
14	Joints - sealed	Damage	2330	3	Replace seal	300, 301, 302,	25.00	na	na	na	na	ft.
15	Joints - sealed	Damage	2330	4	Replace seal	300, 301, 302,	25.00	na	na	na	na	ft.
16	Joints - sealed	Cracking	2340	1	Do nothing	300, 301, 302,	0.00	na	na	na	na	ft.
17	Joints - sealed	Cracking	2340	2	Do nothing	300, 301, 302,	0.00	na	na	na	na	ft.
18	Joints - sealed	Cracking	2340	3	Repair	300, 301, 302,	15.00	na	na	na	na	ft.
19	Joints - sealed	Cracking	2340	4	Replace seal	300, 301, 302,	25.00	na	na	na	na	ft.
20	Joints - sealed	Debris	2350	1	Clean	300, 301, 302,	0.50	na	na	na	na	ft.
21	Joints - sealed	Debris	2350	2	Clean	300, 301, 302,	1.00	na	na	na	na	ft.
22	Joints - sealed	Debris	2350	3	Clean	300, 301, 302,	1.00	na	na	na	na	ft.
23	Joints - sealed	Debris	2350	4	Clean	300, 301, 302,	1.50	na	na	na	na	ft.
24	Joints - sealed	DeckDet	2360	1	Do nothing	300, 301, 302,	0.00	na	na	na	na	ft.
25	Joints - sealed	DeckDet	2360	2	Patch	300, 301, 302,	25.00	na	na	na	na	ft.
26	Joints - sealed	DeckDet	2360	3	Patch	300, 301, 302,	25.00	na	na	na	na	ft.
27	Joints - sealed	DeckDet	2360	4	Repair and replace	300, 301, 302,	145.00	na	na	na	na	ft.
28	Joints - asm w/s	Leakage	2310	1	Do nothing	303	0.00	na	na	na	na	ft.
29	Joints - asm w/s	Leakage	2310	2	Do nothing	303	0.00	na	na	na	na	ft.
30	Joints - asm w/s	Leakage	2310	3	Repair	303	50.00	na	na	na	na	ft.
31	Joints - asm w/s	Leakage	2310	4	Replace	303	100.00	na	na	na	na	ft.
32	Joints - asm w/s	Adhesion	2320	1	Do nothing	303	0.00	na	na	na	na	ft.
33	Joints - asm w/s	Adhesion	2320	2	Repair	303	35.00	na	na	na	na	ft.
34	Joints - asm w/s	Adhesion	2320	3	Repair	303	50.00	na	na	na	na	ft.
35	Joints - asm w/s	Adhesion	2320	4	Replace	303	100.00	na	na	na	na	ft.
36	Joints - asm w/s	Damage	2330	1	Do nothing	303	0.00	na	na	na	na	ft.
37	Joints - asm w/s	Damage	2330	2	Do nothing	303	0.00	na	na	na	na	ft.
38	Joints - asm w/s	Damage	2330	3	Repair	303	100.00	na	na	na	na	ft.
39	Joints - asm w/s	Damage	2330	4	Replace	303	260.00	na	na	na	na	ft.
40	Joints - asm w/s	Cracking	2340	1	Do nothing	303	0.00	na	na	na	na	ft.
41	Joints - asm w/s	Cracking	2340	2	Do nothing	303	0.00	na	na	na	na	ft.
42	Joints - asm w/s	Cracking	2340	3	Repair	303	50.00	na	na	na	na	ft.
43	Joints - asm w/s	Cracking	2340	4	Replace	303	100.00	na	na	na	na	ft.
44	Joints - asm w/s	Debris	2350	1	Clean	303	0.50	na	na	na	na	ft.
45	Joints - asm w/s	Debris	2350	2	Clean	303	1.00	na	na	na	na	ft.
46	Joints - asm w/s	Debris	2350	3	Clean	303	1.00	na	na	na	na	ft.
47	Joints - asm w/s	Debris	2350	4	Clean	303	1.50	na	na	na	na	ft.
48	Joints - asm w/s	DeckDet	2360	1	Do nothing	303	0.00	na	na	na	na	ft.
49	Joints - asm w/s	DeckDet	2360	2	Patch	303	25.00	na	na	na	na	ft.
50	Joints - asm w/s	DeckDet	2360	3	Patch	303	25.00	na	na	na	na	ft.
51	Joints - asm w/s	DeckDet	2360	4	Replace	303	120.00	na	na	na	na	ft.
52	Joints - asm w/s	MetalDet	2370	1	Do nothing	303	0.00	na	na	na	na	ft.
53	Joints - asm w/s	MetalDet	2370	2	Do nothing	303	0.00	na	na	na	na	ft.
54	Joints - asm w/s	MetalDet	2370	3	Repair	303	100.00	na	na	na	na	ft.
55	Joints - asm w/s	MetalDet	2370	4	Replace	303	260.00	na	na	na	na	ft.

CHAPTER 3 Preservation Impacts on Aspects of Bridge Service Life

3.1 Assessing the Impacts of Bridge Preservation Actions

The process of identifying which aspects of bridge service life are positively impacted by bridge preservation actions begins with the knowledge gleaned from the literature search. This body of knowledge is being supplemented by contacts with DOT personnel who have direct experience in the subject area and by the knowledge of experienced members of the research team. In order to ensure adequate coverage of the many factors that govern bridge performance and determine bridge service life, the group contacted is being selected to provide the maximum feasible coverage of knowledge about:

- Bridges of different span types and main construction materials (e.g. steel, concrete, and timber);
- The effects of different service environments exposures related to – traffic, freezing, deicing, water, marine exposure, etc.;
- Different historical practices in design, construction, preservation, and maintenance;
- Experience with bridge management practices or systems that attempt to optimize investments at the individual bridge level as well as at the network level; and,
- Different levels of investment in preservation and maintenance.
- Different approaches to keeping data on bridge preservation actions – type, cost, date, etc.

3.2 Impacts of Bridge Preservation Actions

Preservation actions may have both direct and indirect impacts. Efforts to preserve joints have a direct impact upon the joint itself by improving its condition or extending the time during which it remains in its current condition. Either impact extends the life of the joint itself. However, efforts to preserve joints also have an indirect impact on the girder ends, bearings and bent caps below the joint by reducing their rate of deterioration. The indirect benefit may reduce overall long term costs more than the direct benefit. A similar relationship of impacts exists for paint and other coatings in regard to the substrate they protect. Examples are listed in Table 3.1. Understanding prioritization of the actions requires quantifying metrics for the impacts.

Table 3.1 Example impacts of preservation actions

Element	Preservation Action	Direct Impact	Indirect Impact
Bearings	Clean and lubricate	Increase bearing condition state Extend bearing life	Reduce potential damage to caps Prevent/Reduce potential damage to girder ends
Steel materials	Spot painting	Increase coating condition state Extend life of existing coating by inhibiting adjacent deterioration	Prevent/Reduce steel section loss
Steel materials	Complete painting	Increase coating condition state	Prevent/Reduce steel section loss
Concrete Decks	Overlay	Improve riding quality, delay penetration of chlorides	Prevent/forestall rebar corrosion and subsequent deck deterioration
Concrete Decks	Sealing with penetrating sealer	Prevent/forestall penetration of chlorides	Prevent/forestall rebar corrosion and subsequent deck deterioration
Joints	Sealing, replacement of damaged parts	Proper functioning of joint during expansion and contraction	Prevent/forestall rebar corrosion and subsequent deterioration of beam ends, abutment seats and pier caps
Drainage inlets and pipes	Clean out and repair	Minimize ponding and hazards to traffic	Prevent/forestall rebar corrosion and subsequent deck deterioration by removal of chlorides from deck

Table 3.2 presents the impacts of each preservation action. The row numbers of Table 3.2 match the listing of preservation actions in Table 2.2. The primary impact is the impact on the element itself. Secondary impacts on up to three protected elements are listed in subsequent columns. For example in line 7, a joint that is normally intended to be sealed has defect 2310, leakage, and is in condition state 4. The indicated preservation action is to replace the seal. This action will have a direct impact on the primary element of increasing its condition state. By sealing the joint during the replacement, the action will also have secondary impacts - extending the life of three secondary elements: bearings, beam ends, and pier caps.

Although load capacity improvements may occasionally occur, they are comparatively rare, highly variable and dependent on original design issues or other elements that are not readily known. Thus, the potential of a load capacity increase is not considered.

Table 3.2 Example catalog table of preservation action impacts: Joints - sealed

	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2			Defect			Primary Element		Secondary Element No. 1		Secondary Element No. 2		Secondary Element No. 3	
3	Material	Defect	Code	Condition	Preservation Action	Element	Direct Impact	Element	Indirect Impact	Element	Indirect Impact	Element	Indirect Impact
4	Joints - sealed	Leakage	2310	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
5	Joints - sealed	Leakage	2310	2	Reseal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
6	Joints - sealed	Leakage	2310	3	Reseal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
7	Joints - sealed	Leakage	2310	4	Replace seal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
8	Joints - sealed	Adhesion	2320	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
9	Joints - sealed	Adhesion	2320	2	Reseal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
10	Joints - sealed	Adhesion	2320	3	Reseal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
11	Joints - sealed	Adhesion	2320	4	Replace seal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
12	Joints - sealed	Damage	2330	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
13	Joints - sealed	Damage	2330	2	Do nothing	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
14	Joints - sealed	Damage	2330	3	Replace seal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
15	Joints - sealed	Damage	2330	4	Replace seal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
16	Joints - sealed	Cracking	2340	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
17	Joints - sealed	Cracking	2340	2	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
18	Joints - sealed	Cracking	2340	3	Repair	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
19	Joints - sealed	Cracking	2340	4	Replace seal	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
20	Joints - sealed	Debris	2350	1	Clean	Joints	Extend life	Bearings	None	Beam ends	None	Pier caps	None
21	Joints - sealed	Debris	2350	2	Clean	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
22	Joints - sealed	Debris	2350	3	Clean	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
23	Joints - sealed	Debris	2350	4	Clean	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
24	Joints - sealed	DeckDet	2360	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
25	Joints - sealed	DeckDet	2360	2	Patch	Joints	Increase condition state	Bearings	None	Beam ends	None	Pier caps	None
26	Joints - sealed	DeckDet	2360	3	Patch	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
27	Joints - sealed	DeckDet	2360	4	Repair and replace	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
28	Joints - asm w/s	Leakage	2310	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
29	Joints - asm w/s	Leakage	2310	2	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
30	Joints - asm w/s	Leakage	2310	3	Repair	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
31	Joints - asm w/s	Leakage	2310	4	Replace	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
32	Joints - asm w/s	Adhesion	2320	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
33	Joints - asm w/s	Adhesion	2320	2	Repair	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
34	Joints - asm w/s	Adhesion	2320	3	Repair	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
35	Joints - asm w/s	Adhesion	2320	4	Replace	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
36	Joints - asm w/s	Damage	2330	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
37	Joints - asm w/s	Damage	2330	2	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
38	Joints - asm w/s	Damage	2330	3	Repair	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
39	Joints - asm w/s	Damage	2330	4	Replace	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
40	Joints - asm w/s	Cracking	2340	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
41	Joints - asm w/s	Cracking	2340	2	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
42	Joints - asm w/s	Cracking	2340	3	Repair	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
43	Joints - asm w/s	Cracking	2340	4	Replace	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
44	Joints - asm w/s	Debris	2350	1	Clean	Joints	Extend life	Bearings	None	Beam ends	None	Pier caps	None
45	Joints - asm w/s	Debris	2350	2	Clean	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
46	Joints - asm w/s	Debris	2350	3	Clean	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
47	Joints - asm w/s	Debris	2350	4	Clean	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
48	Joints - asm w/s	DeckDet	2360	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
49	Joints - asm w/s	DeckDet	2360	2	Patch	Joints	Increase condition state	Bearings	None	Beam ends	None	Pier caps	None
50	Joints - asm w/s	DeckDet	2360	3	Patch	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
51	Joints - asm w/s	DeckDet	2360	4	Replace	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
52	Joints - asm w/s	MetalDet	2370	1	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
53	Joints - asm w/s	MetalDet	2370	2	Do nothing	Joints	None	Bearings	None	Beam ends	None	Pier caps	None
54	Joints - asm w/s	MetalDet	2370	3	Repair	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life
55	Joints - asm w/s	MetalDet	2370	4	Replace	Joints	Increase condition state	Bearings	Extend life	Beam ends	Extend life	Pier caps	Extend life

CHAPTER 4 Metrics for Analysis of Bridge Preservation Action Effectiveness

4.1 Background

Since the methodology for prioritizing preservation actions is separate from the larger scope of a BMS, it is assumed that either the bridges under consideration are not structurally deficient or functionally obsolete, where user costs are critical to rehabilitation and replacement decisions, or that preservation is desired in spite of those inadequacies. Theoretically, preservation actions can be applied to any bridge. However, by definition, preservation actions do not generally remove functional problems (load capacity, lane width, clearance deficiencies). An exception would be complete replacement of deck rated structurally deficient since this falls within the currently accepted definition of bridge preservation. It is envisioned that the BMS or other decision methods used by the agency should identify whether a bridge should be replaced, rehabilitated, or remain in service. Bridges to remain in service become candidates for preservation action decision-making to be covered by the catalog, methodologies, examples, and support tool being developed in this study.

Methods of prioritizing among alternatives have evolved over the past 50 years, but the basic intent of bridge decision makers has probably been consistent: to make the best use of the limited funds available. Prior to 1970, information on each bridge was limited and formal methods of evaluation were lacking. Thus, decisions were often subjective and made without consideration of the needs of other bridges or the needs of the bridge network as a whole. Due to the complexity of the problem, a simple utility function, the Sufficiency Rating, was developed as a somewhat subjective, but consistently applied, means of providing a general evaluation of a bridge's adequacy. Furthermore, the Sufficiency Rating became an important factor in eligibility for federal bridge funds. For many years, although highly subjective, the Sufficiency Rating continued to have the support of most states for funding eligibility, perhaps because of the view that the devil you know is better than the devil you don't know. As a part of MAP-21, other performance measures will be put in place and the Sufficiency Rating, modified to include risk, will be an optional reference measure but not a criteria for funding.

North Carolina DOT, an early advocate for bridge management systems, focused on the following user needs in prioritizing bridges for limited funding:

- Does the bridge have adequate load capacity for the users of the bridge to avoid detours?
- Does the bridge have adequate width and lanes for the traffic volume to avoid accidents and allow for an acceptable level of traffic service?
- Does the bridge have adequate vertical over/under clearance to avoid detours and avoid collisions?
- Does the condition of the components indicate a short remaining life

Researchers at North Carolina State University envisioned a system based on life cycle cost modeling, but in 1981 the fundamental understanding of the cost relationships was not available. Thus, a utility function was subjectively developed emphasizing deficiencies in load capacity, clear deck width, over/under clearance and remaining life (Johnston and Zia, 1984). This

deficiency point system was adapted as a feature by several states such as Pennsylvania and Kansas, in early BMS development. In parallel, Hyman and Hughes (1983) were developing life cycle cost models based on agency costs only and unconstrained funding for Wisconsin.

Chen and Johnston (1987), continuing development for NCDOT, combined deterministic models of component deterioration, user and agency costs, and varying minimum levels of service for different roadway classifications to create a computer program based in life cycle cost analysis to determine optimum actions and timing under unlimited budgets. O'Connor and Hyman (1989) in FHWA Demonstration Project 71, summarized progress on BMS development by the states and encouraged further development of comprehensive systems.

Al-Subhi, Johnston and Farid (1989, 1990a, 1990b) extended the system for NCDOT to create OpBridge which added the capability to do bridge-by-bridge optimization of replacement, rehabilitation, and repair decisions under constrained budgets and predict the performance of individual bridges and the network over a selected horizon of years, 20 for example. The large scale knap-sack optimization required a high-speed mainframe for solution under constrained budgets when considering the 15,000 bridges in the NCDOT inventory. OpBridge and associated NCDOT programs became the first BMS approved by FHWA to meet its BMS requirements. Developers of the original Pontis software incorporated these user cost relationships but utilized Markov probabilistic models for deterioration. The original Pontis program, based initially on a 325 PC platform, necessitated a simplified optimization of rolled up condition needs at the system level rather than a bridge-by-bridge optimization.

The various states began to adopt or develop elements of bridge management systems to assist in the process of decision making for bridge replacement, rehabilitation, repair and preservation. Advances in electronic recording of inspection data, computing capacity, computing interfaces for the system users, and expanded databases on inspection information have all contributed to improved bridge management.

The application of life-cycle cost evaluation to the problem of bridge element preservation provides a similar opportunity for enhancing the decisions needed to extend life through proper preservation strategy. A bridge is a capital investment. Extending the life of critical elements can extend bridge life [Farid, Johnston, Chen, Laverde, and Rihani, (1988)].

4.2 Data and Metric Identification Process

Three factors have been considered when evaluating the possible data and metrics needed. First, what is essential data for use in a practical analytical model? Second, what is reasonable to expect might be available as basic bridge data from the inspection process and what can be reasonably distilled by agencies (such as costs and impacts) from their records or from their subject matter experts? Finally, what are the metrics that indicate impacts of preservation actions on the bridge elements?

The literature search and the interactions with bridge preservation specialists and state DOT bridge maintenance experts have identified metrics that have been used in the past or are being currently used to assess performance of bridges and performance of actions applied to individual elements. The contacts were derived from a master list of State Bridge Engineers, members of

the AASHTO TSP·2 Regional Bridge Preservation Partnerships, and State Bridge Maintenance Engineers developed from work on a previous project.

Potential variations on the identified metrics that might improve their effectiveness and applicability continue to be evaluated**.** Each of these metrics is being assessed in order to determine:

- What information is necessary to support calculation of the metric,
- How that information is or could be collected and the costs associated with collection,
- How that information is or could be stored and accessed for analysis,
- Availability of historical records of that information,
- The method of calculating the metric,
- Relative granularity of the data- for example the NBI condition rating of 6 for a superstructure as compared to the assessment of superstructure girders using element level condition data for several condition states, as compared to data collected from specific test procedures such half-cell potential readings
- Potential for direct or indirect correlation of the metric to bridge preservation actions
- The rate at which the data changes as a function of time and typical degradation processes that affect bridge components,
- Potential for use of the information as a trigger for optimum deployment timing of the preservation action,
- Potential for use of the information to predict/measure the life of preservation action before return to original condition state prior to performing the action, and
- Potential for use of the information to predict/measure the life cycle cost effectiveness of preservation and maintenance action.

Weaknesses in the existing data for use in validation of the considered metrics and bridge preservation actions are being considered. Example weaknesses include:

a. Inadequacy of records about what types of bridge preservation actions were taken, how many units (e.g. square feet) of the actions were applied, what the unit cost or total cost of the actions were, the before and after condition of the elements, how long the actions were effective before a repeat action was justified, etc.
b. The weaknesses of the 0 to 9 NBI rating system including subjectivity of the rating system, known disparities in ratings from one inspector to another, and the inability to relate the NBI rating to a specific element or problem.
c. Lack of precision in element level condition ratings.
d. The reliance of the definitions for structurally deficient and functional obsolete bridges on arbitrary breakpoints (e.g. NBI rating of deck of 4 or less = structurally deficient) compounded by the subjective nature of the NBI ratings.

The long term nature of most degradation processes that affect bridge components significantly magnifies the difficulties of establishing practical metrics to analyze the effectiveness of bridge preservation actions, to help determine when and which action to apply ("the right action, on the right bridge element, at the right time"), and to describe and quantify the impacts of applying or delaying an action. This issue is only compounded by the general lack of detailed data on application and performance of different preservation treatments. At the

same time, the assessment of element condition is undergoing another evolution with the implementation of the ASSHTO Manual for Bridge Element Inspection (2013). This change and the intent of this project to be consistent with that data structure make availability of current data and impact relationships problematic. This and all of the issues stated above are being considered in the effort to identify the metrics with the most potential for application.

In prioritizing the identified metrics, the highest priorities are given to metrics that are practical and effective, that would be simple to incorporate in the agency's bridge management programs. Some features that weigh most heavily in the priorities are:

- The relative ease by which the metric can be implemented by agencies;
- The degree to which data (NBI ratings, element level condition state data, etc.) that is currently collected can be used to calculate the metric;
- Any additional costs of using the metric such as personnel, training, inspection technology, data collection costs and IT costs for data management; and,
- The clarity of the connection between the metric and an extension of service life.

4.3 Identified Data and Metrics

The following is an outline of bridge data envisioned as essential for the analysis and solution process.

- Bridge environment factors: frequency of freeze-thaw cycles, deicing treatment, deicing salt spray, water exposure, marine conditions and ADTT; sensitivity will vary by element
- Element identification
- Element material or type
- Quantity of element (each, linear ft., sq. ft.)
- Element proportion in each condition state (quantity or percent)
- Preservation options for each condition state
- Cost of each preservation option feasible for each condition state ($/each, $/lin. ft., $/sq. ft.)
- Improvement in element condition state and/or extension of element life.

The following is an outline of bridge metrics envisioned as having potential for tracking the impacts of bridge preservation actions.

- Impact of each preservation option:
    - Increase in element condition state
    - Prolonged time in element condition state
    - Service life estimate of preservation treatment
- Impact of actions on bridge condition:
    - Increase in bridge average element condition state
    - Increase in bridge weighted average condition state
    - Increase in bridge health index
- Impact of actions on a selected network of bridges:

- Increase in bridge network average condition states of elements
- Increase in bridge network average element condition state
- Increase in bridge network weighted average condition state
- Increase in bridge network health index

Table 4.1 presents the metrics for each preservation action. The row numbers of Table 4.1 match the listing of preservation actions in Table 2.2 and indications of impacts in Table 3.2. The primary metrics are for the element itself. Metrics for up to three secondary protected elements are listed in subsequent columns.

The actions are driven by the element condition state, indicated as "condition before action" and the effect on primary element is indicated as "condition after action." Some actions are of the type that an average cycle time can be projected and some are of the type that are initiated only in response to specific conditions. Cycle time will vary depending on the service environment. The service environments used are the same as those defined by the AASHTO Manual of Bridge Element Inspection. However, cycle time, and element added life from the actions are assumed to be the same for Service Environments 2 and 3, and the column heading for the combined case is indicated as SE23.

The condition state of the secondary protected elements does not change, but they have added life in their condition state as a result of the action. However, the added life will also vary with their service environment. The condition state improvements and the added element life resulting from the preservation actions will vary depending upon past practices, materials of original construction, and actual variations in environment. Thus, agencies should update the data to reflect their experiences. A time to condition state is provided to allow a system of integrating deterioration expectations as a function of service environment.

Table 4.1 Example table of metrics for preservation actions: Joints - sealed

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1													Primary Element				Seconday Element No. 1				Seconday Element No. 2				Seconday Element No. 3			
2	Material	Defect	Defect	Condition before action	Time to Condition (yrs)			Preservation Action	Preservation Action Cycle (yrs)			Element	Condition after action	Element Added Life (yrs)			Element No. 1	Element Added Life (yrs)			Element No. 2	Element Added Life (yrs)			Element No. 3	Element Added Life (yrs)		
3	Service Environ.		Code		SE1	SE23	SE4		SE1	SE23	SE4			SE1	SE23	SE4		SE1	SE23	SE4		SE1	SE23	SE4		SE1	SE23	SE4
4	Joints - sealed	Leakage	2310	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
5	Joints - sealed	Leakage	2310	2				Reseal	na	na	na	Joints	1	12	10	8	Bearing	0	1	3	Beam Ends	0	1	3	Pier Caps	0	1	3
6	Joints - sealed	Leakage	2310	3				Reseal	na	na	na	Joints	1	10	8	5	Bearing	2	5	8	Beam Ends	2	5	8	Pier Caps	4	7	10
7	Joints - sealed	Leakage	2310	4				Replace seal	na	na	na	Joints	1	35	28	20	Bearing	8	12	15	Beam Ends	12	16	20	Pier Caps	10	18	25
8	Joints - sealed	Adhesion	2320	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
9	Joints - sealed	Adhesion	2320	2				Reseal	na	na	na	Joints	2	12	10	8	Bearing	0	1	2	Beam Ends	0	1	2	Pier Caps	0	1	2
10	Joints - sealed	Adhesion	2320	3				Reseal	na	na	na	Joints	2	10	8	5	Bearing	1	2	3	Beam Ends	1	2	3	Pier Caps	1	2	3
11	Joints - sealed	Adhesion	2320	4				Replace seal	na	na	na	Joints	1	35	28	20	Bearing	3	9	12	Beam Ends	3	10	15	Pier Caps	12	16	20
12	Joints - sealed	Damage	2330	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
13	Joints - sealed	Damage	2330	2				Do nothing	na	na	na	Joints	2	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
14	Joints - sealed	Damage	2330	3				Replace seal	na	na	na	Joints	1	35	28	20	Bearing	5	8	12	Beam Ends	8	12	15	Pier Caps	12	16	20
15	Joints - sealed	Damage	2330	4				Replace seal	na	na	na	Joints	1	35	28	20	Bearing	5	8	12	Beam Ends	8	12	15	Pier Caps	12	16	20
16	Joints - sealed	Cracking	2340	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
17	Joints - sealed	Cracking	2340	2				Do nothing	na	na	na	Joints	2	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
18	Joints - sealed	Cracking	2340	3				Repair	na	na	na	Joints	2	10	8	5	Bearing	2	5	8	Beam Ends	2	5	8	Pier Caps	4	7	10
19	Joints - sealed	Cracking	2340	4				Replace seal	na	na	na	Joints	1	35	28	20	Bearing	4	8	12	Beam Ends	10	14	18	Pier Caps	11	16	22
20	Joints - sealed	Debris	2350	1				Clean	6	4	2	Joints	1	3	2	1	Bearing	0	0	0.5	Beam Ends	0	0	0.5	Pier Caps	0	0	0.5
21	Joints - sealed	Debris	2350	2				Clean	6	4	2	Joints	1	3	2	1	Bearing	1	2	3	Beam Ends	1	2	3	Pier Caps	1	2	3
22	Joints - sealed	Debris	2350	3				Clean	6	4	2	Joints	1	3	2	1	Bearing	4	6	8	Beam Ends	4	6	8	Pier Caps	4	6	8
23	Joints - sealed	Debris	2350	4				Clean	6	4	2	Joints	1	3	2	1	Bearing	8	12	15	Beam Ends	12	16	20	Pier Caps	12	18	25
24	Joints - sealed	DeckDet	2360	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
25	Joints - sealed	DeckDet	2360	2				Patch	na	na	na	Joints	1	12	10	8	Bearing	1	2	3	Beam Ends	1	2	3	Pier Caps	1	2	3
26	Joints - sealed	DeckDet	2360	3				Patch	na	na	na	Joints	1	10	8	6	Bearing	2	5	7	Beam Ends	2	5	7	Pier Caps	2	5	7
27	Joints - sealed	DeckDet	2360	4				Repair and replace	na	na	na	Joints	1	35	28	20	Bearing	4	8	12	Beam Ends	10	14	18	Pier Caps	11	16	22
28	Joints - asm w/s	Leakage	2310	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
29	Joints - asm w/s	Leakage	2310	2				Do nothing	na	na	na	Joints	2	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
30	Joints - asm w/s	Leakage	2310	3				Repair	na	na	na	Joints	2	10	8	5	Bearing	2	5	8	Beam Ends	2	5	8	Pier Caps	4	7	10
31	Joints - asm w/s	Leakage	2310	4				Replace	na	na	na	Joints	1	40	35	30	Bearing	8	12	15	Beam Ends	12	16	20	Pier Caps	10	18	25
32	Joints - asm w/s	Adhesion	2320	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
33	Joints - asm w/s	Adhesion	2320	2				Repair	na	na	na	Joints	1	12	10	8	Bearing	1	2	3	Beam Ends	1	2	3	Pier Caps	1	2	3
34	Joints - asm w/s	Adhesion	2320	3				Repair	na	na	na	Joints	2	10	8	5	Bearing	2	5	7	Beam Ends	2	5	7	Pier Caps	2	5	7
35	Joints - asm w/s	Adhesion	2320	4				Replace	na	na	na	Joints	1	40	35	30	Bearing	4	8	12	Beam Ends	10	14	17	Pier Caps	8	16	20
36	Joints - asm w/s	Damage	2330	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
37	Joints - asm w/s	Damage	2330	2				Do nothing	na	na	na	Joints	2	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
38	Joints - asm w/s	Damage	2330	3				Repair	na	na	na	Joints	1	20	18	15	Bearing	2	5	8	Beam Ends	2	5	8	Pier Caps	4	7	10
39	Joints - asm w/s	Damage	2330	4				Replace	na	na	na	Joints	1	40	35	30	Bearing	3	6	10	Beam Ends	4	8	12	Pier Caps	3	6	10
40	Joints - asm w/s	Cracking	2340	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
41	Joints - asm w/s	Cracking	2340	2				Do nothing	na	na	na	Joints	2	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
42	Joints - asm w/s	Cracking	2340	3				Repair	na	na	na	Joints	2	10	8	5	Bearing	3	7	11	Beam Ends	4	9	13	Pier Caps	3	7	11
43	Joints - asm w/s	Cracking	2340	4				Replace	na	na	na	Joints	1	40	35	30	Bearing	4	8	12	Beam Ends	10	14	17	Pier Caps	8	16	20
44	Joints - asm w/s	Debris	2350	1				Clean	6	4	2	Joints	1	3	2	1	Bearing	0	0	0.5	Beam Ends	0	0	0.5	Pier Caps	0	0	0.5
45	Joints - asm w/s	Debris	2350	2				Clean	6	4	2	Joints	1	3	2	1	Bearing	1	2	3	Beam Ends	1	2	3	Pier Caps	1	2	3
46	Joints - asm w/s	Debris	2350	3				Clean	6	4	2	Joints	1	3	2	1	Bearing	4	6	8	Beam Ends	4	6	8	Pier Caps	4	6	8
47	Joints - asm w/s	Debris	2350	4				Clean	6	4	2	Joints	1	3	2	1	Bearing	8	12	15	Beam Ends	12	16	20	Pier Caps	12	18	25
48	Joints - asm w/s	DeckDet	2360	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
49	Joints - asm w/s	DeckDet	2360	2				Patch	na	na	na	Joints	1	12	10	8	Bearing	1	2	3	Beam Ends	1	2	3	Pier Caps	1	2	3
50	Joints - asm w/s	DeckDet	2360	3				Patch	na	na	na	Joints	2	10	8	6	Bearing	2	5	7	Beam Ends	2	5	7	Pier Caps	2	5	7
51	Joints - asm w/s	DeckDet	2360	4				Replace	na	na	na	Joints	1	40	35	30	Bearing	4	8	12	Beam Ends	10	14	18	Pier Caps	11	16	22
52	Joints - asm w/s	MetalDet	2370	1				Do nothing	na	na	na	Joints	1	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
53	Joints - asm w/s	MetalDet	2370	2				Do nothing	na	na	na	Joints	2	0	0	0	Bearing	0	0	0	Beam Ends	0	0	0	Pier Caps	0	0	0
54	Joints - asm w/s	MetalDet	2370	3				Repair	na	na	na	Joints	2	10	8	6	Bearing	2	4	6	Beam Ends	5	7	9	Pier Caps	5	8	11
55	Joints - asm w/s	MetalDet	2370	4				Replace	na	na	na	Joints	1	40	35	30	Bearing	4	8	12	Beam Ends	10	14	18	Pier Caps	11	16	22

Chapter 5 Element Condition Deterioration and Impact of Preservation

5.1 Condition Deterioration

There are several deterioration scenarios as illustrated in Figure 5.1. Physical deterioration of an element is a gradual process as illustrated by the curve A-B. Timely application of preservation actions, perhaps even shortly after the element is put into service, can extend the life of some elements as illustrated by the curve A-C. If preservation action occurs after some deterioration as indicated by curve A-D, improvement in condition may occur (D-E) followed by subsequent deterioration as illustrated by E-F. It is often possible to apply multiple cycles of preservation action in extending the life of an element, timely painting and subsequent repainting of steel being a good example.

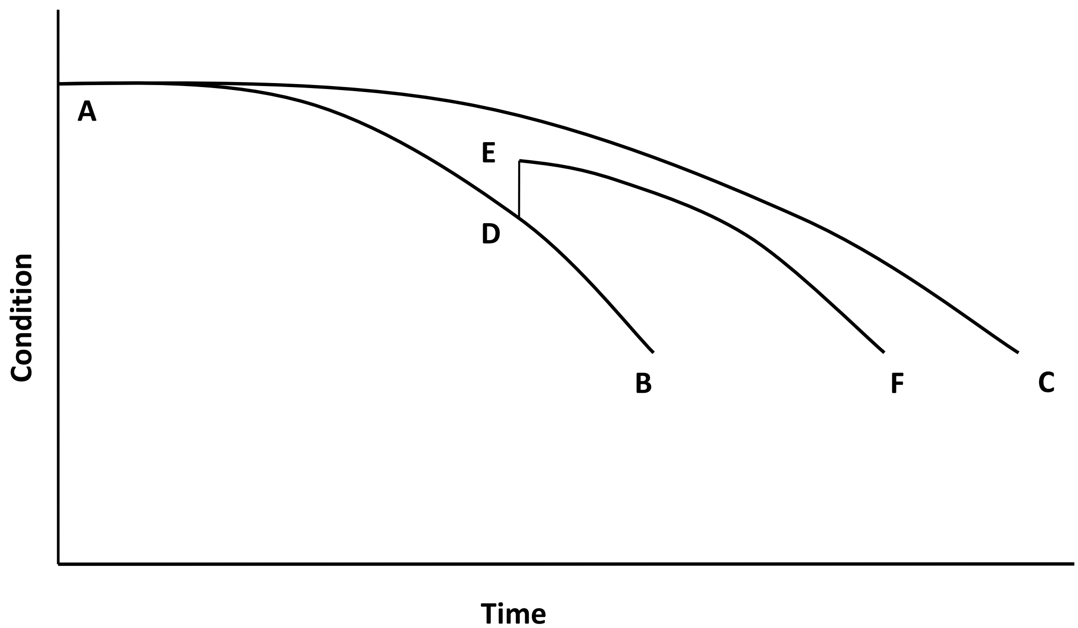

Figure 5.1 Effect of preservation on idealized condition over time.

Deterioration models based on condition inspection data have a different visual form. If the number of possible condition states is large the model is stepped but closer to the physical model. If the number of states is small, the steps are larger and offer less definition of the gradual process.   Whatever the chosen system, the actual shape of the model for each element is determined by the definition of the triggers for each condition state and time involved in moving from one state to another as shown in Figure 5.2. Various investigators have approached the problem of modeling deterioration [examples: Abed-Al-Rahim and Johnston, (1995), Morcous, G. (2011)] or estimating deterioration rates [example: Agrawal, A.K. and Kawaguchi, A. (2009)].

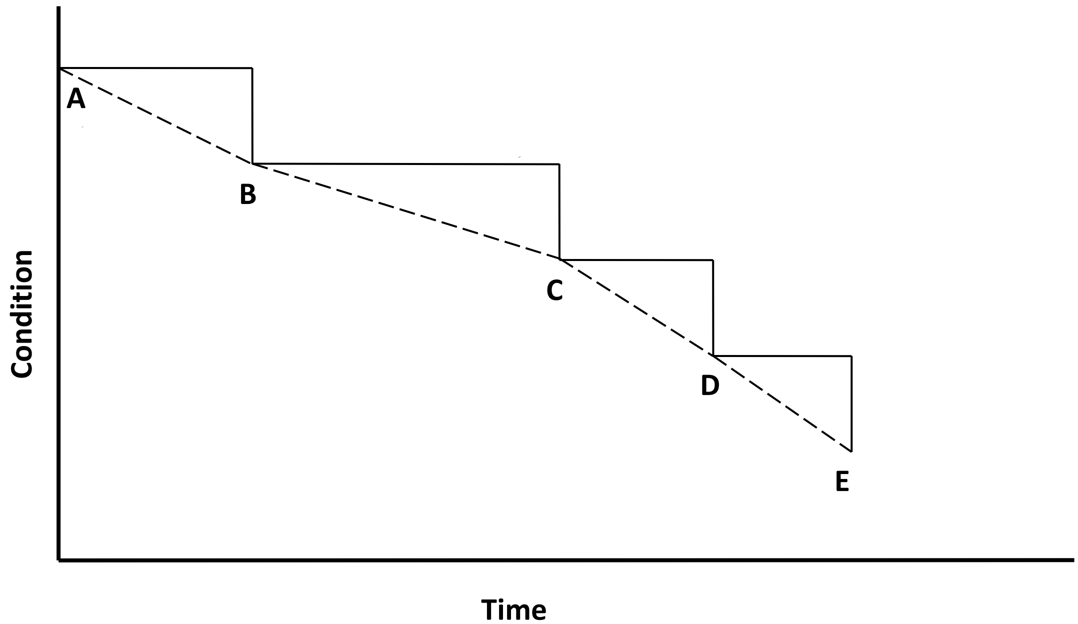

Figure 5.2 Example condition state deterioration model.

Regardless of the shape of the model, the effects of preservation actions are similar. The life of the element may be extended as a result of the preservation action by extending the time at each condition state or the life can be extended by elevating the condition state from a declined state.

Essential to this project is developing information and methodologies to help states and local governments make better decisions and investments in bridge preservation. Key parameters are:

- Bridge elements,
- Modes of deterioration and causative factors,
- Environment and climate factors,
- Condition state system,
- Preservation options,
- Element life extension,
- Element condition state improvement or partial improvement,
- Estimated costs for preservation actions and other feasible actions,
- Assessment of benefits and
- Methodology for analysis.

For the purposes of this study, the analysis is will be based on the life-cycle cost analysis at the element level. Applications of life-cycle methods to bridge improvement have been presented in various publications such as Farid, Johnston, Chen, Laverde, Rihani (1988), and

Abed-Al-Rahim and Johnston (1991). However, ultimately it will be important for agencies to integrate this knowledge into BMS analysis, so that in considering possible preservation actions for each bridge, the functional characteristics are also analyzed to allow optimum decisions [Patidar, Labi, Sinha, and Thompson (2007)] at the individual bridge level and at the system level.

The element life extension and the cost are key metrics in the analysis but other metrics are likely to be involved. There may be more than one preservation option. There are likely to be different options at different condition states. Some options will maintain condition state, others may improve condition state. There will always be the do-nothing option for comparison. While extension of life and cost appear to be items that are not well defined, other considerations in developing the methodology are no less daunting and will need significant thought. Is it adequate to consider the element in a stand-alone analysis? Should specific maintenance levels-of-service [Nash and Johnston (1985)] be targeted? How are other elements that might control life of the bridge to be considered? How is the benefit of the bridge life extension as a whole, a span, or a subsystem to be considered? What are determining factors for bridge by bridge analysis? When can the results be applied to groups of similar bridges?

The development of solutions to this problem is not entirely new. Following the development of the OPBRIDGE BMS in 1988, which was aimed at decision making for deficient and obsolete bridges, NCDOT desired a decision support system for actions that were focused at maintenance of bridge elements. NCDOT had begun collecting element condition data in the late 1970's in a database far beyond the normal NBI requirements. This data was first used in a study by Morrow and Johnston (1993) in developing a Maintenance Management System for bridge maintenance level of service optimization. The MAINTBRG analysis program considered 21 bridge elements for which deterioration was modeled using the NCDOT 0-9 element condition assessment scale. Unit costs and impact of actions on condition were determined from NCDOT work records and staff input. Methodology was included to determine the backlog of needs. Optimization was based on the Algorithm for Selection of Optimum Policy (ASOP) with considerations of safety and preservation of investment. The output provided the optimum set of condition state triggers for maintenance resulting from the budget allocated.

Subsequently, Jabreen and Johnston (1995) converted the methodology to include life-cycle cost methods applied to the maintenance actions based on the ratio of incremental benefits to the incremental costs. Optimization through integer programming was used to arrive at the set of condition states that triggered maintenance actions under a given budget allocation with options to impose a time period to overcome a backlog of needs.

5.2 Bridge Preservation Elements and Condition State Systems

The following sections will describe the steps taken in order to perform an economic evaluation of the different preservation alternatives on each preservation element. A preservation element is a physical part of a bridge that requires a substantial preservation effort and whose condition and preservation cost can be obtained. The inspection and rating system divides bridges into three major components: deck, superstructure and substructure. This classification is too broad and ignores many bridge elements that have unique characteristics including the manner and rate at which they deteriorate. Bridge owners must have expanded databases which

include various bridge elements that are not included in the NBI. Various states and software systems, such as AASHTOWare Bridge Management, have element databases with condition state information.

5.3 Defining the Condition of an Element

The current national standard in the United States is based on the NBI coding guide published by FHWA. The condition rating scale is based on the safety of the bridge and has a high level description of the safety characteristics. These “condition” descriptions are tied to the four major components of the bridge

- Deck – Item 58,
- Superstructure – Item 59,
- Substructure – Item 60 and,
- Culvert – Item 62

The evaluation of each component is based on a 0 through 9 scale where 0 is bridge closure and 9 in new condition. A condition of 3 or under is usually an unacceptable condition that requires immediate action. Table 5.1 shows the description of these condition ratings and general action recommendation. These four components share the same assessment descriptions. The “General Action Recommendations” listed came from an earlier version of the FHWA *Bridge Preservation Guide*.

Table 5.1 Description of NBI Condition Ratings.

Code*	Description of the Defect*	General Action Recommendation
N	Not Applicable – component not on the structure	
9	Excellent Condition	New or Near New, No Action Required
8	Very Good Condition	No Defects or Damage Noted, No Action Required
7	Good Condition - some minor problems.	Defects or damage exists, potential exists for minor maintenance.
6	Satisfactory Condition - structural elements show some minor deterioration.	Defects or damage exists; potential exists for major maintenance or preservation action.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.	Defects or damage exists; preservation actions are feasible with a potential for minor rehabilitation.
4	POOR CONDITION - advanced section loss, deterioration, spalling or scour.	Defects or damage exists; preservation actions will have low impact on the condition of the bridge; potential exists for major rehabilitation
3	SERIOUS CONDITION - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.	Defects exists and require action, repair or rehabilitation required immediately
2	CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.	Defects exist and require action, the need for repair, preservation or rehabilitation is urgent; bridge replacement feasibility is considered.
1	"IMMINENT" FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.	Study should determine the feasibility of taking corrective action to restore the bridge to full service; bridge replacement feasibility is considered.
0	FAILED CONDITION - out of service - beyond corrective action.	Defects or damage is beyond repair or restoration; bridge replacement feasibility is considered.

* From FHWA's Recording and Coding Guide for Structure Inventory and Appraisal of the Nation's Bridges, Report No. FHWA-PD-96-001.

All states must report bridge condition data to the FHWA for Items 58, 59, 60 and 62. For elements, some states use the NBI 0 to 9 scale with the NBI definition; other states use definitions of the condition which are modified to more closely reflect the unique features

of the elements. One state uses a condition scale from 0 to 7, rates each bridge on a span-by-span basis and then calculates NBI 0 to 9 ratings for Items 58, 59, 60 and 62. At least one state uses the NBI translator to calculate NBI ratings from element level condition data collected according to the AASHTO Guide. Many states conduct dual inspections during which they collect NBI ratings and also capture element level condition data collected according to the AASHTO Guide. The original AASHTO CoRe element definitions had 3, 4 or 5 condition states. The new AASHTO Manual for Bridge Element Inspection (2013) has adopted a 1 to 4 scale for all element condition state identification. Table 5.2 provides a typical definition of condition state language.

Table 5.2 Typical element condition state language.

Element	**Reinforced Concrete Deck Delamination/Spall/Patched Area**
Condition State 1	None.
Condition State 2	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.
Condition State 3	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area that is unsound or showing distress. Does not warrant structural review.
Condition State 4	Warrants structural review.

Figure 5.3 is a typical diagram illustrating deterioration of a point on an element with time where the condition state changes one point after a period of years. The time between two consecutive drops is the average time that portion of the element stays at that condition. Figure 5.4 illustrates how the portions of an element gradually evolve in condition state through time.

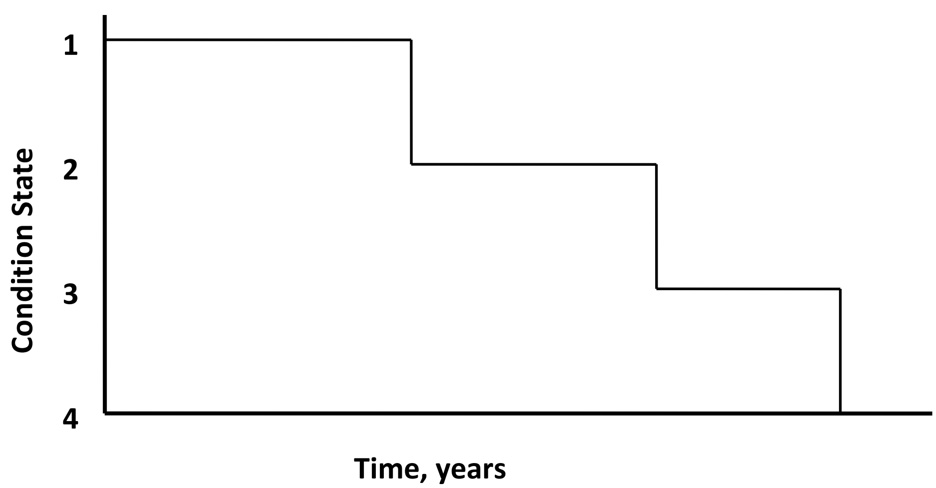

Figure 5.3 Condition deterioration with time.

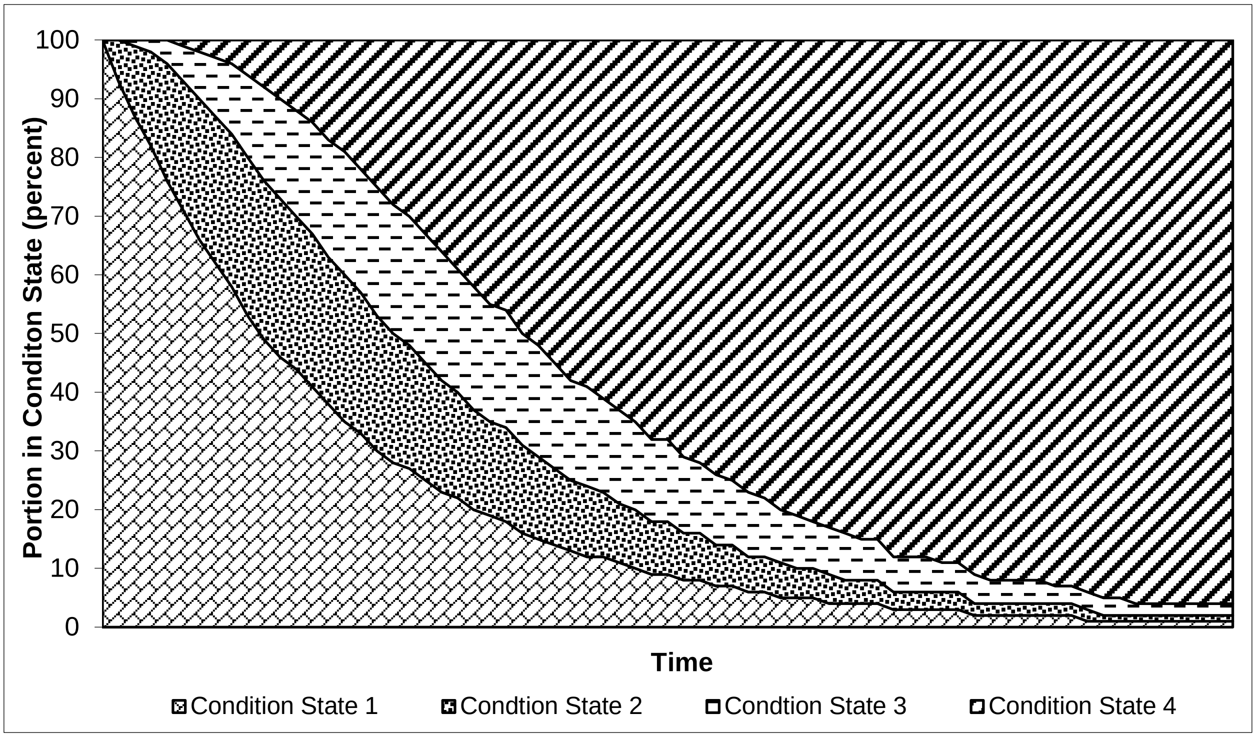

Figure 5.4 Element condition deterioration with time.

5.4 Element Service Life

For each element, e, in the system, certain parameters should be defined. Element deterioration behaviour is the first of these parameters. Bridge elements deteriorate with time and it is important to know the deterioration rates for the various elements at various condition states in different service environments. Abed-Al-Rahim and Johnston (1991) developed a methodology to estimate deterioration rates of various elements by examining bridge inspection and condition data. The result is a deterioration rate table showing the average time (in years) an element will stay at each condition state. This can be represented by the variable $DTR_{(e,c)}$ where e is the element and c is the condition state. In addition, the useful service life of an element is another important parameter. Service life is the time span that a bridge element can serve its purpose before it needs replacement. The maintenance policy employed by the agency can affect the useful life of an element. If maintenance policy requires the replacement of an element at a higher condition, the useful service life will be shortened. If maintenance objectives include preservation, the life of the element can be extended, perhaps indefinitely. However, it may be more economical to replace an element before it reaches the end of its useful life if the life cycle cost of the replacement option is less than that of the maintenance option.

The service life of an element can be estimated as the number of years it takes an element to deteriorate from a new condition state, n, to the minimum acceptable condition state, m. The average service life can be computed as:

$$SL_e = \sum_{c=n}^{m} DTR_{(e,c)} \tag{5-1}$$

where:

$DTR_{(e,c)}$ = The average time (in years) an element, e, will stay in condition state, c, before deteriorating to next lower condition state;

Complicating the estimate of service life is the fact that different portions of the same element may deteriorate at different rates as shown in Figure 5.4. Element condition state data is typically collected in a manner that defines the portion of each element type in each condition state. Various agencies have attempted to analyse their data and estimate deterioration rates. However, the analysis is complicated by the history of past work which has been done on a bridge and which may not be recorded or may have been incorrectly recorded. While the relative durations may appear reasonable the magnitude of the durations in a particular condition state are often unreasonably long. This is usually due to effects of prior maintenance and rehabilitation that is often not considered in the time and condition data. Experienced bridge maintenance personnel sometimes have better expert opinions when solicited by a Delphi process (Chen and Johnston, 1987) than is often derived from the data. Abed-Al Rahim and Johnston (1995) used statistical techniques to improve deterioration estimates. With improved records of maintenance, Sobanjo and Thompson (2011) carefully isolated elements without prior maintenance activity in order to improve analysis of deterioration. Agrawal and Kawaguchi (2009) and Sobanjo and Thompson (2011) have suggested that a Weibull deterioration model is more accurate than a pure Markovian model, particularly in the early stages of an elements life or after major maintenance.

Although a Markov or Weibull probabilistic process could be considered for deterioration, the benefits gained in view of the uncertainty of the transition probabilities and the added analysis complication may make such an approach presently impractical. A practical approach would be to:

1. Accept that a probabilistic process has resulted in the set of condition states and associated quantities that exist.
2. Predict the future deterioration of the quantity in each condition state with deterministic models for each element and factors to adjust for element service environment.

Each element and element material type needs to have a defined deterioration pattern. Typically, the pattern is described as the average time in years that the element will stay at each condition state with only routine maintenance but without preservation or repair actions. Multiple tables or sets of adjustment factors would be needed to reflect variations in environment.

The average condition state, ACS_e, of an element could be defined as the weighted average of the quantities of the element in the various condition state options.

$$ACS_e = \frac{\sum_{i=1}^{k} iQ_{ei}}{\sum_{i=1}^{k} Q_{ei}} \tag{5.2}$$

where:

i = condition state value;

k = number of condition states;

Q_{ei} = quantity of element e in condition state i.

If based on the AASHTO Manual for Bridge Element Inspection (2013), k equals 4 condition states. The average condition state can be considered as a measure of the health of an individual element. For example, assume a multi-span bridge has compression seal joints with 120 ft in State 1, 30 ft. in State 2, 10 ft. in State 3 and 5 ft, in State 4. The ACS would be (120 + 2*30 + 3*10 + 4*5) / (120 +30+10+5) or 1.4 (condition is between 1 and 2).

Various methods have been used to relate the condition of the bridge. The NBI rating for deck, superstructure, and substructure components are an effort to represent the condition of groups of elements. Various health indices have been suggested as improved methods to relate bridge overall condition, some weighting individual element condition by relative importance measures of the various elements. Bridge owning agencies may adopt or develop measures of overall health for tracking purposes. One possibility for the analysis tool is to provide predictions of the changes in element condition resulting from the preservation actions and provide a default tracking index. Agencies desiring to compute their own preferred index for tracking could extract the condition data for that purpose.

5.5 Estimating Deterioration

Due to the time required to implement the 2013 AASHTO Manual for Bridge Element Inspection, it is expected to be some time before good deterioration data for elements is available. Sources of deterioration relationships might include AASHTOWare Bridge Management based on a Markov model, or a hybrid model combining Weibull and Markov representations. In the short term, a polynomial relationship or a piecewise segmental relationship could be developed based on input from subject matter experts.

Expert elicitation through a Delphi process has be used both to derive temporary models and to temper analytical models from NBI condition data. Excel, the base for the analytical tool, has the capability to generate multiple regression models. For example, assume a group of experienced bridge maintenance practitioners have estimated the time from new or newly replaced to the Weighted Average Condition State of an element are as follows:

Condition State	Age (years)
1.0	0
1.5	15
2.0	23
2.5	30
3.0	35
3.5	40
4.0	50

This or similar data can be used to create a 3rd or 4th order polynomial equation providing a relationship between condition and time as shown in Figure 5.5. It can be noted that if sufficient data points are developed, a piecewise liner representation of deterioration could be a simple and possibly satisfactory alternate. Ultimately, the accuracy depends as much on the quality of the data as on the model.

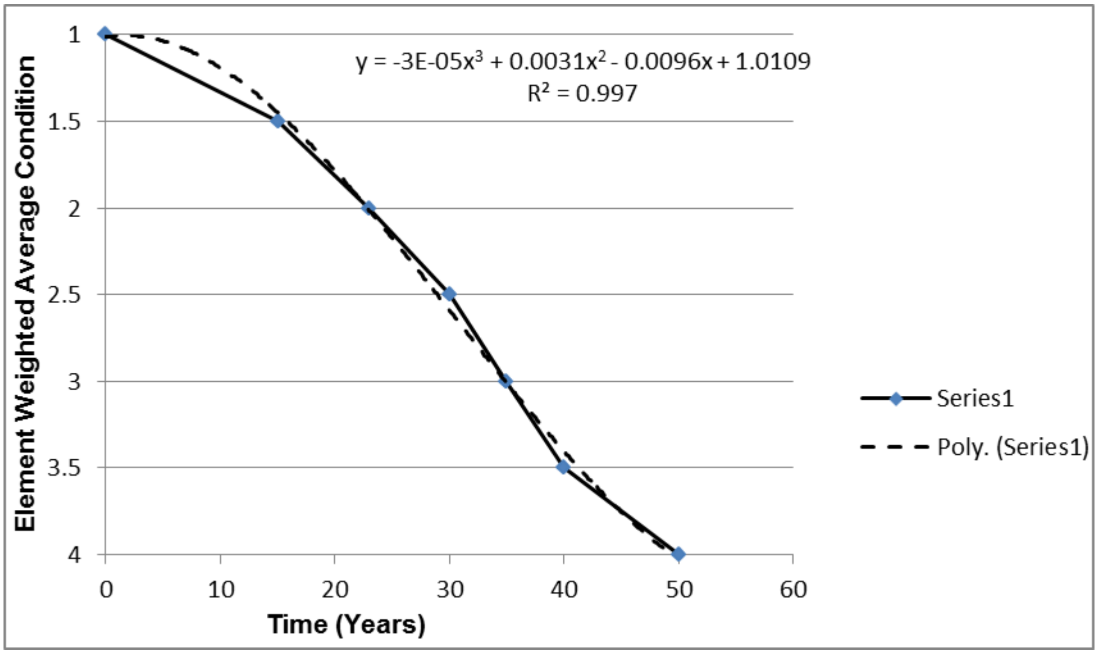

Figure 5.5 Polynomial regression and piecewise linear representations of deterioration.

5.6 Identifying Preservation Actions

There will often be several preservation action alternatives at each element Condition State (CS). Some elements may have only one or two feasible actions especially the elements in the very high (good) or the very low condition states. The scope of these actions may involve preservation, repair, rehabilitation or replacement of the element. These actions can contribute to the preservation of the bridge. For each preservation action (PA), the following information should be defined:

a. The cost of performing this preservation action [$PACST_{(e,c,k)}$]

   The main source for obtaining preservation costs is historical data. A list of example elements and actions is provided in Table 2.1. An element action function code identifier can be assigned to each element action. The identifier can be selected to suit the agency preferences. The function codes should each describe a certain type of work item that can be generally related to a particular bridge element. The unit cost of each preservation action can be estimated by analyzing the preservation costs and quantities' data available in history files. Abed-Al-Rahim and Johnston (1991) performed an analysis of maintenance costs for NCDOT and obtained a unit cost for each function code which was linked to a maintenance element and represented by $PACST_{(e,c,k)}$ where e is the element, c is the condition before maintenance and k was the condition after the action. For a given element, a triangular matrix of preservation unit costs can be developed as shown in Figure 5.6. Similar cost matrices related to bridge maintenance have been developed by Chen and Johnston (1987), Morrow and Johnston (1993) and Hearn, et al (NCHRP Report 668, 2010).

b. The effect of preservation action on the condition of element.

It is assumed that each action will either improve the condition of the element and, therefore, extend its service life or extend its service in the same condition state. Either case defers the need for replacement. An improvement can be represented by an increase in the element condition state after preservation. Figure 5.5 presents a unit cost matrix to achieve condition state improvement from c to k. A condition state can remain the same or improve with maintenance. The cost of maintenance action will be higher for the actions that increase the condition to a higher state. The increase in condition state will translate into an extension in the service life of the element that can be calculated as:

$$EX_{(e,c,k)} = \sum_{c=c+1}^{k} DTR_{(e.c)} \tag{5-3}$$

Figure 5.7 shows how a preservation action may result in an element condition improvement and extend the element service life. Figure 5.8 shows how a preservation action may result in an extension of the current condition state and extend the element service life. Timely repeated preservation actions can extend the service life of many elements indefinitely but this would be discontinued when conditions of other elements are terminal.

In some instances there will be no increase in condition state after performing a preservation action. Therefore, the extension in service life may be less than the average time an element stays at a condition state or any other fraction depending on the extent of the preservation action. Example costs for these actions are represented by the main diagonal cells of the matrix such as PACST(i,2,2,m). Each of these actions also has an associated extension of life of the element.

<table>
<tr><th colspan="2" rowspan="2">Element i Description</th><th colspan="4">Condition after action</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td rowspan="4">Condition before action</td><td>1</td><td>PACST(i,1,1,m)</td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>PACST(i,2,1,m)</td><td>PACST(i,2,2,m)</td><td></td><td></td></tr>
<tr><td>3</td><td>PACST(i,3,1,m)</td><td>PACST(i,3,2,m)</td><td>PACST(i,3,3,m)</td><td></td></tr>
<tr><td>4</td><td>PACST(i,4,1,m)</td><td>PACST(i,4,2,m)</td><td>PACST(i,4,3,m)</td><td>PACST(i,4,4,m)</td></tr>
</table>

Figure 5.6 Preservation action unit costs for element i and option m.

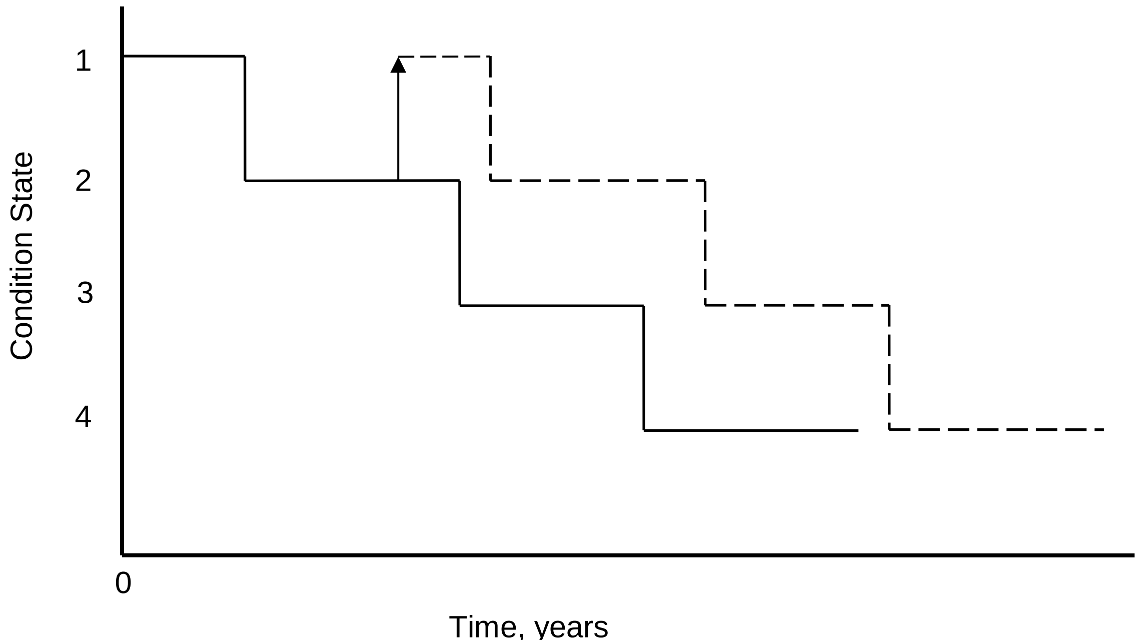

Figure 5.7 Extension of life resulting from improvement in condition state.

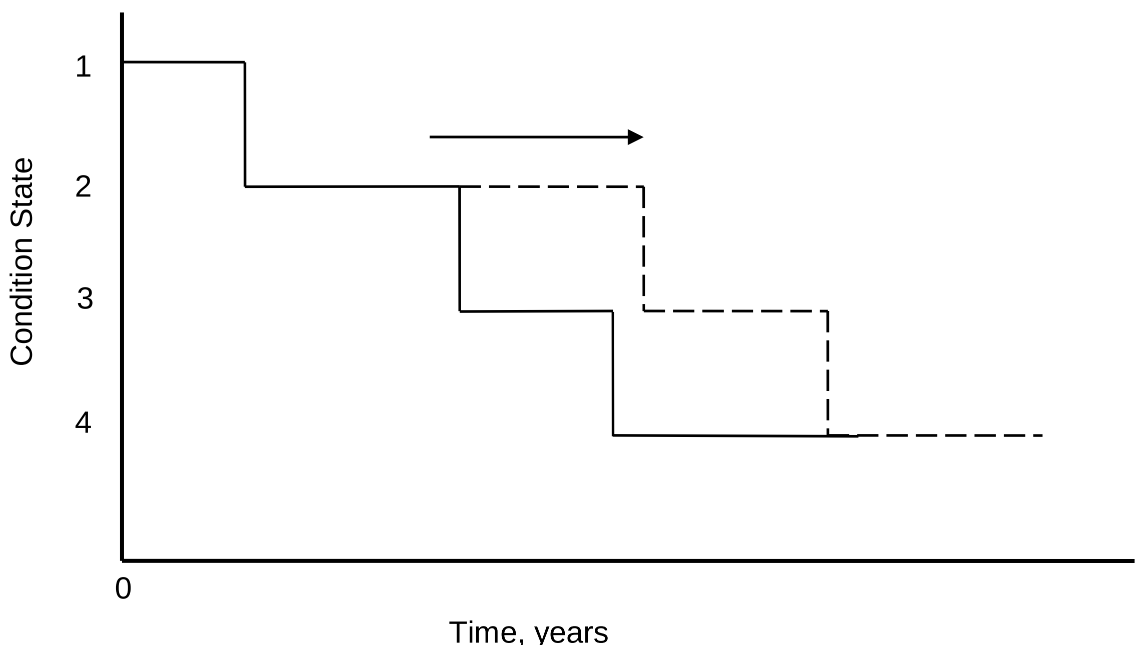

Figure 5.8 Extension of life resulting from extension of time in condition state.

Figure 5.9 schematically illustrates the effect of a repeated deck preservation action. In this case, a healer-sealer might be applied three times. Initially, the sealer reduces the rate of deck deterioration. However, the sealer itself gradually deteriorates and in the process becomes less effective in protecting the deck. If the second application at an age

corresponding to point A, the extension of deck life in years gained from the first application is the time from C to A. Three applications at the intervals indicated extend the deck life from E to D. Note that from B to A the deck deterioration slope is roughly parallel to that of the bare deck. This suggests that applying the sealer more frequently, before it becomes less affective, should yield greater benefit in life extension. The question becomes the optimal timing between B and A considering the application cost in comparison to the long term benefit.

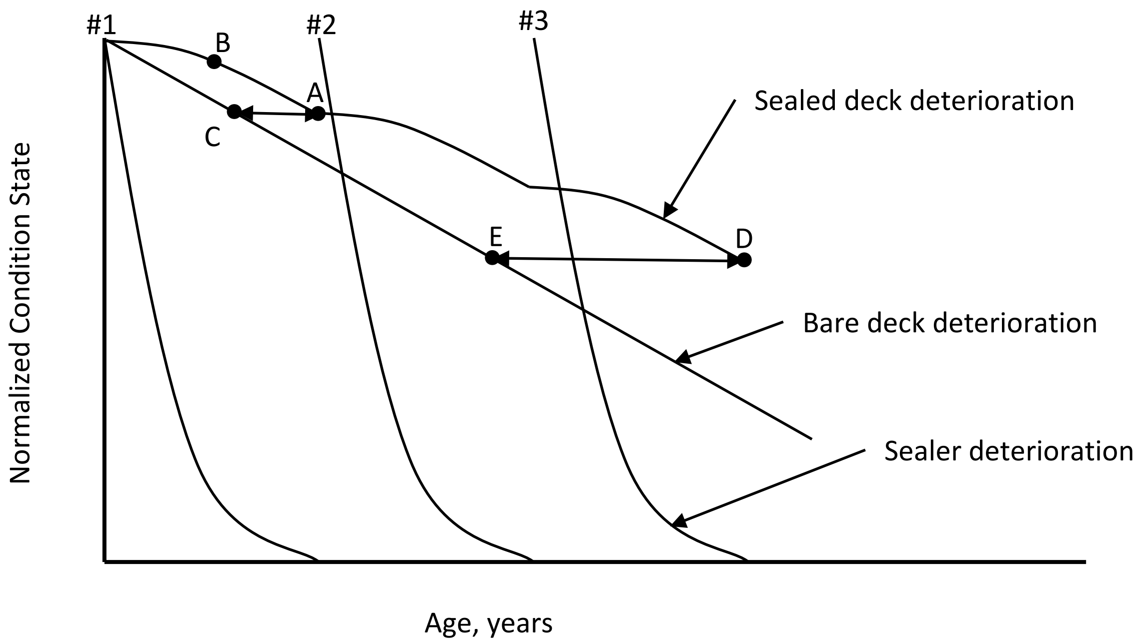

Figure 5.9 Extension of life resulting from repeated preservation actions.

Figure 5.10 shows this behaviour derived from Michigan DOT data on expected beneficial impact of sealer application on a concrete deck at 15 year intervals in comparison to a bare deck and the expected deterioration of the sealer condition with time. The similarities to the schematic idealization in Figure 5.8 can be recognized.

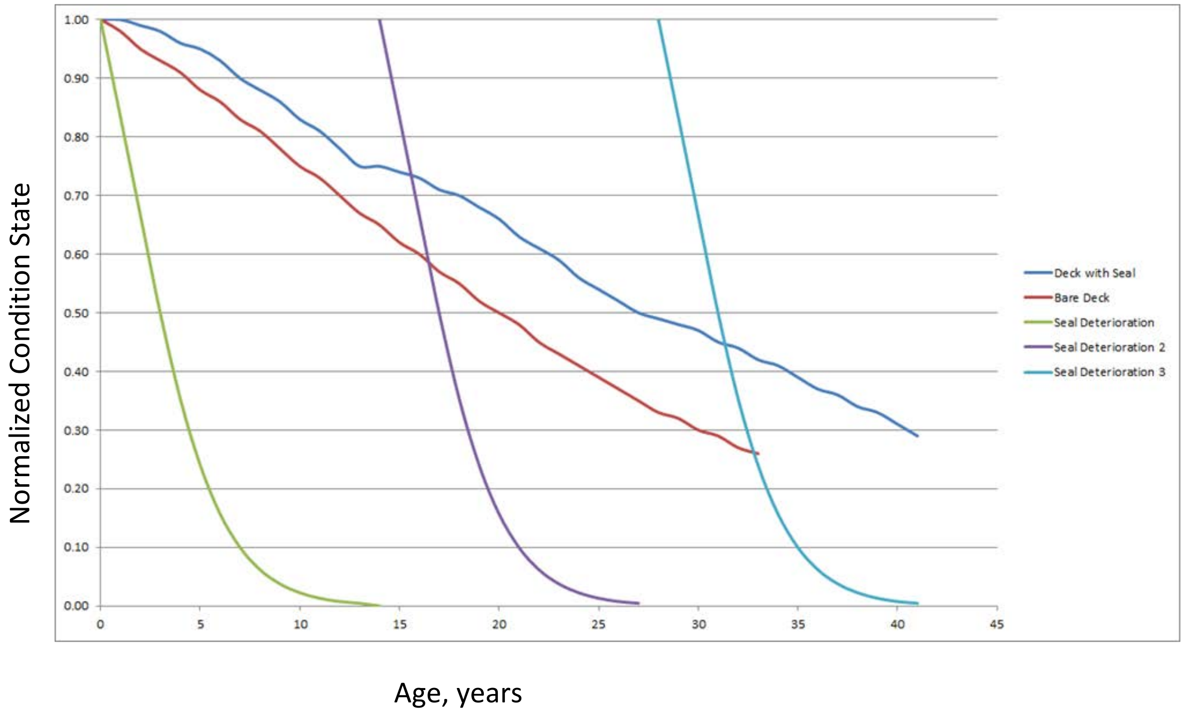

Figure 5.10 Extension of life resulting from of repeated preservation actions.

In Figure 5.11, the impacts of several alternative actions on a concrete deck are considered. The actions include:

- Do nothing to the bare deck;
- Apply a sealer in 5-year cycles up to a deck age of 50 years;
- Overlay the bare deck repeatedly when the deck has declined to 70% of its original remaining life;
- Rehabilitate the bare deck repeatedly when the deck has declined to 60% of its original remaining life;
- Replace the bare deck repeatedly when the deck has declined to 50% of its original remaining life.

The extensions of life achieved at an age of about 50 years corresponding to the lowest condition state compared to the bare deck at a similar condition is indicated by the length of the horizontal arrows.

From this figure, it becomes clear that there are many factors to consider, such as the condition state trigger for actions, the frequency of the cycle, and the cost of the actions. Selecting from among the preservation alternatives involves not just the action selection, but also the timing as a function of cost.

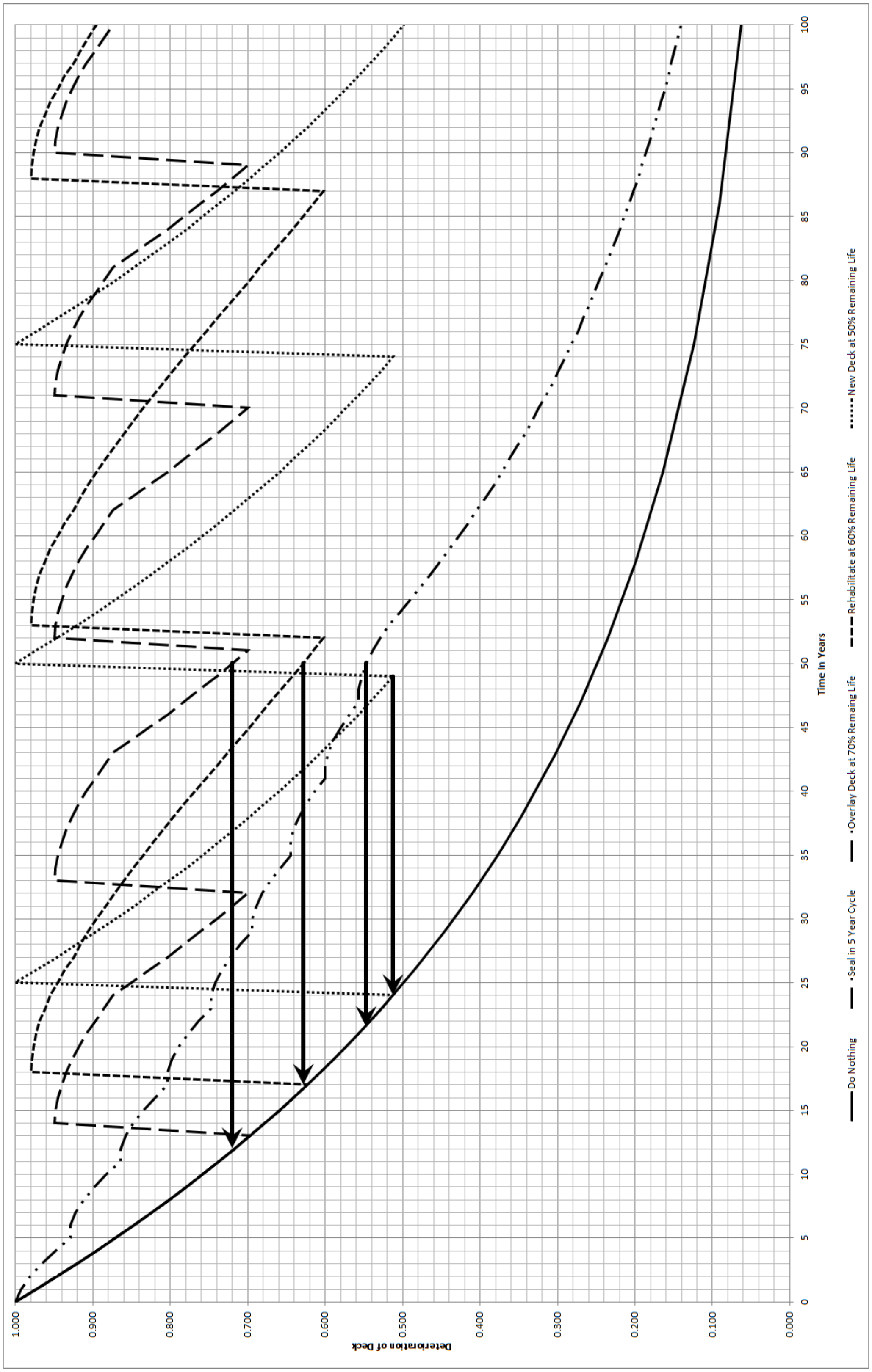

Figure 5.11 Impact of alternative actions on concrete deck condition and life.

Chapter 6 Methodology to Prioritize Element Preservation Actions

6.1 Comparison of Preservation Options

The increase in condition state of an element means the addition of some more years to its service life; the amount of added years can be determined from the deterioration rate table of that element. To translate this to dollars, the present worth of the savings from postponing the replacement or rehabilitation of the element is calculated. Figure 6.1 shows two preservation action options with different effects on the element.

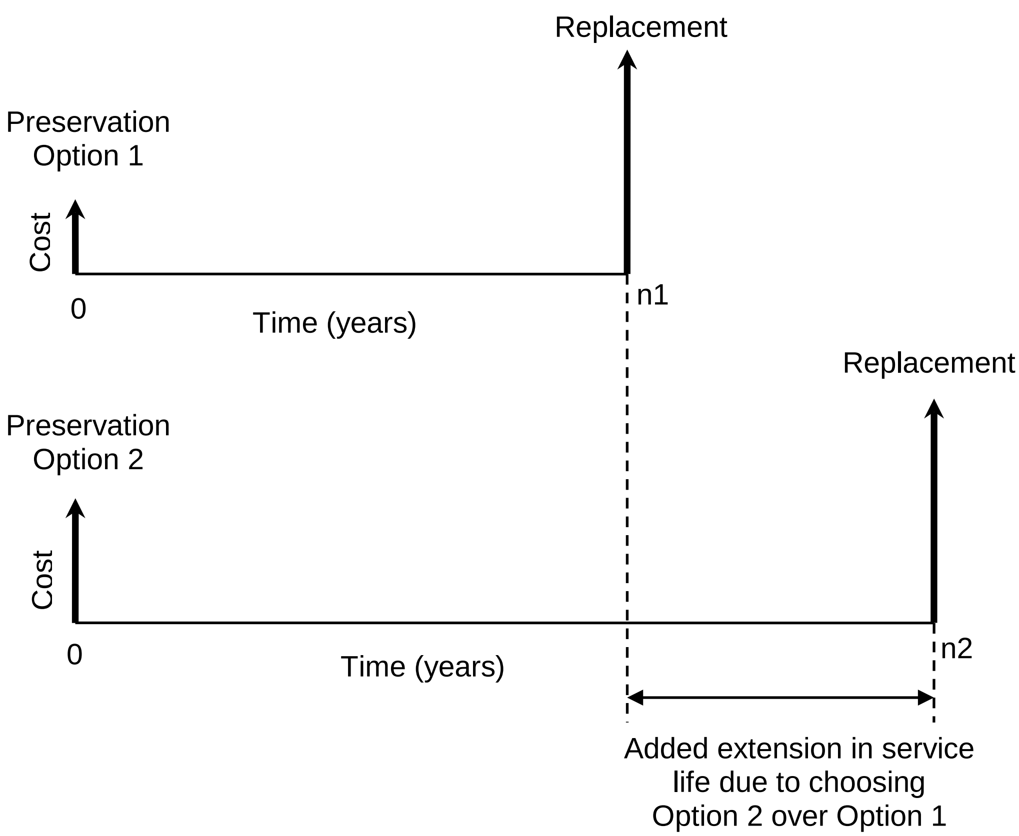

Figure 6.1 Comparison between two preservation options.

By applying Option 1, the element condition state will increase to k_1 and it should be replaced (or rehabilitated) in n_1 years. If the more costly Option 2 is chosen, it will extend the service life of the element by n_2 years by increasing its condition state to k_2.

There may be secondary benefits of improving the condition of an element, which affect the other elements by preventing accelerated deterioration of these elements. For example, keeping a deck overlay in good condition will help protect the deck from deterioration. Maintaining the expansion joint seals in good condition will help protect girder ends, bent caps, and bearings. This relationship can be modelled, however, determining the magnitude of these secondary benefits requires additional research on the deterioration relation between the different bridge elements since these relations are not well defined.

Another issue to be considered is how to combine actions where the element is in multiple condition states. For example, the deck primary condition state might be 2 but a portion is at 3. Often, there would be an effort to repair and improve that portion in state 3 to state 2 and then undertake the preservation action for the entire deck. Decision rules (or trees) can be considered for these situations.

6.2 Reduced Effectiveness of Repeated Actions

As some actions are repeated, their effectiveness in prolonging element life often becomes less. As the preservation action is applied in lower states of average element condition, the service life of the action is reduced. The question becomes how to represent this behaviour in practical application. If a formula were to be used, some type of equation would be developed possibly, with a power function, to represent the reduction in added element life after the first performance of the action. Alternately, multiple deterioration formulas could be used, that is, a different one for each repetition cycle. However, past efforts by researchers, using a variety of methods, to develop deterioration relationships with good fit to user experience have proved elusive, even for basic initial deterioration. Part of the problem has been in the available data. During a transition to a new condition coding system, data problems will be even more problematic although there will be hope in the future. The disadvantages of using formulas include:

- Limited present data to develop the equations;
- Difficulty for user in understanding the relationship; and
- Difficulty in programming and updating.

Decision tables are easier to understand and update. Although data available to develop the relationships are limited, a set of values developed with subjective input could serve as a default to serve until improved values can be developed.

The effect of reduced effectiveness has been represented in the example catalog data of Appendix II where, for example, the extended service life for a concrete deck due to sealing in Condition State 3 is less than in Condition State 1.

6.3 Service Environment

The environment of a bridge element affects the rate of deterioration of the element and the rate of deterioration of any protective system for the element. Factors influencing deterioration include:

- Freeze-thaw cycles
- De-icing chemical exposure
- Wet-dry cycles
- Marine exposure
- Truck traffic loads and volume

All bridges owned by an agency are usually not in the same environment. Furthermore, all elements of a bridge are not subjected to the same environment. For example, decks are more affected by truck traffic than are superstructures and substructures. The degree to which superstructure and substructure are impacted by de-icing chemical spray from vehicles may depend on whether there is a roadway under the bridge. Thus, four Service

Environments (SE1, SE2, SE3, and SE4) have been defined. The service environments used are the same as those defined by the AASHTO Manual of Bridge Element Inspection. Although agencies may be initially coding the entire bridge in a single service environment, there are advantages to coding the deck, superstructure, and substructure environments independently. Descriptions are provided in Table 6.1.

Table 6.1 Service Environment characteristics

Environment	Description
1—Benign	Neither environmental factors nor operating practices are likely to significantly change the condition of the element over time, or their effects have been mitigated by the presence of highly effective protective systems.
2—Low	Environmental factors, operating practices, or both either do not adversely influence the condition of the element, or their effects are substantially lessened by the application of effective protective systems.
3—Moderate	Any change in the condition of the element is likely to be quite normal as measured against the environmental factors, operating practices, or both that are considered typical by the agency.
4—Severe	Environmental factors, operating practices, or both, contribute to the rapid decline in the condition of the element. Protective systems are not in place or are ineffective.

The use of Service Environments in this fashion for enhancing the preservation process implies that agencies would, when using the analysis tool, classify the elements accordingly and gradually build this inventory information as an adjunct for the system.

6.4 Element Action Triggers

The decision to undertake an action has generally involved an experienced reaction to element condition states. Some actions are proactive. For example the decision to seal a new deck or, as advocated by some agencies in severe climates, to overlay a new bridge deck. Other actions are reactive based on the degree of defect. Examples include sealing concrete deck cracks, patching deck spalls, or replacing timber deck planks.

As measured by condition state, the Average Condition State (ACS) gives some indication of the element condition. However, the portion of the element that is in condition states 3 and 4 is an indication of the need for repair or replacement. Table 6.2 shows an example of how action rule triggers could be structured. The triggers are presented in a decision table. Consider the case of reinforced concrete decks - defects and associated preservation actions are listed in rows of the table. The action rule triggers are shown in five *Severity Groups* (A through E). Depending on the severity of the element defect, the *Severity Groups* guides the user to recommended actions for consideration. An action for a *Condition Combination* can be triggered by any defect that causes any *one* of the condition measures to be exceeded. Consider the following case:

Cracking: ACS = 1.63, 3 & 4 = 10%
Efflorescence: ACS = 1.80, 3 & 4 = 15%

None of the condition measures equal or exceed the triggers listed for C, D and E. However, since Cracking 3 & 4 = 10% ≥ 5%, the possible actions listed for Group B are recommended, namely seal cracks and seal deck or possibly consider an overlay.

Table 6.2 Element action rules – decision table.

Element		Defect and Action		**Action Rule Triggers** Any of weighted average condition state **or** % in condition states 3 and 4									
				A		B		C		D		E	
				Avg	% 3+4	Avg	% 3+4	Avg	% 3+4	Avg	% 3+4	Avg	% 3+4
Deck-Concrete, reinforced	Condition Combination	Cracking		1.25	0	1.75	5	2.25	20	2.60	35	3.00	50
		Efflorescence		1.25	0	2.00	20	2.50	40	2.70	50	3.00	60
	Actions	Seal Deck		Y*		Y		N*		N		N	
		Seal Cracks		M*		Y		Y		Y		Y	
		Overlay		M		M		Y		Y		Y	
	Condition Combination	Spalling/delam	1.00	1.00	0	1.10	0	2.00	5	2.40	20	2.80	40
		Patched areas		1.25	0	1.75	5	2.25	10	2.60	30	3.00	60
	Actions	Patch		N		Y		Y		M		N	
		Overlay		M		M		Y		Y		N	
		Replace		N		N		N		M		Y	

*Y = Yes, M = Maybe, N = No

6.5 Secondary Actions Recommended in Conjunction with Primary Actions

When a preservation action is determined to be needed or desirable for a particular element, there are sometimes other actions that should occur to preserve or improve other elements. Some examples are:

- When certain work is being done on the deck to also work on the deck joints, partly due to traffic control availability;
- When working on repainting steel girder ends to also repair deck joints and thus reduce future paint deterioration; and
- When working on repair of pier caps and bearings to also repair deck joints to protect the bearings and caps.

These relations could be termed dependencies where there is a primary action driving work on the bridge to be undertaken and a secondary action (or actions) that should be done at the same time. The relationship may be due to reasons of mobilization, traffic control availability, minimizing impact on traffic, physical proximity of elements, or contribution to the service life of the primary action.

Table 6.3 provides a format for stating these relationships. In this example for concrete decks, when a primary action has been selected, recommended deck joint actions are identified. Joint actions are defined by the type of joint and joint condition states. For example, if a concrete deck with strip seal joints is to receive a polymer overlay, then the deck itself should be patched for those portions that are in condition state 3 or 4 and the joints in condition state 2 or better should be cleaned, in state 3 should be repaired and in state 4 should be replaced. Tables 2.3, 3.2 and 4.1 and the tables of the separate Appendix E incorporate this concept.

Table 6.3 Example concrete deck element actions and recommended dependent element actions with preliminary condition levels.

		Secondary Actions Recommended at Condition State Indicated																																	
	Primary Actions	**Deck, concrete Condition and Actions**							**Deck Joint Condition and Actions**																										
									Strip seal 300			Pourable seal 301			Compres-sion seal 302			Assembly w/seal 303			Open Joint 304			Assembly w/o seal 305											
		Seal deck	Seal Cracks	Patch	Patch deep				Clean	Repair	Replace	Clean	Repair	Replace	Clean	Repair	Replace	Clean	Repair	Replace	Clean	Repair	Replace	Clean	Repair	Replace									
Deck, concrete	Seal deck								2	3	4	2	3	4	2	3	4	2	3	4	2			2	3	4									
	Seal cracks								2	3	4	2	3	4	2	3	4	2	3	4	2			2	3	4									
	Patch	3	3						2	3	4	2	3	4	2	3	4	2	3	4	2			2	3	4									
	Patch deep	3	3						2	3	4	2	3	4	2	3	4	2	3	4	2			2	3	4									
	Asphalt Overlay			**3**	**4**				2	3	4	2	3	4	2	3	4	2	3	4	2			2	3	4									
	Polymer Overlay			**3**	**4**				2	3	4	2	3	4	2	3	4	2	3	4	2			2	3	4									
	Concrete Overlay			**3**	**4**				2	3	4	2	3	4	2	3	4	2	3	4	2			2	3	4									
	Replace										1			1			1			1			1			1									

6.6 Analysis Process Overview at Bridge Level

An overview of the analysis process at the individual bridge level is presented in Figure 6.2. A number of tasks are indicated as being possible for the general tool in the task list. At the bridge level, these could involve modifying the default values provided, loading bridge inventory/inspection data for a single bridge or multiple bridges, selecting a bridge for analysis, summarizing results for the actions elected.

The process is then started by selecting a bridge and then selecting the first element to be considered. Some elements will have only one obvious action, either a single preservation action or a do-nothing action. In other cases, there may need to be a comparison among multiple possible actions (including a do-nothing action) to determine which action results in the lowest life cycle cost. The selection will often result in a set of expected actions on the element during the life of the bridge. For the first element, the costs occurring in particular years for the near term horizon are tabulated along with the impacts. The next element is then selected and the process repeats until element needs and impacts for the bridge have been tabulated. The next bridge is then selected and the process repeats until needs and impacts for each bridge in the group are understood and tabulated by bridge.

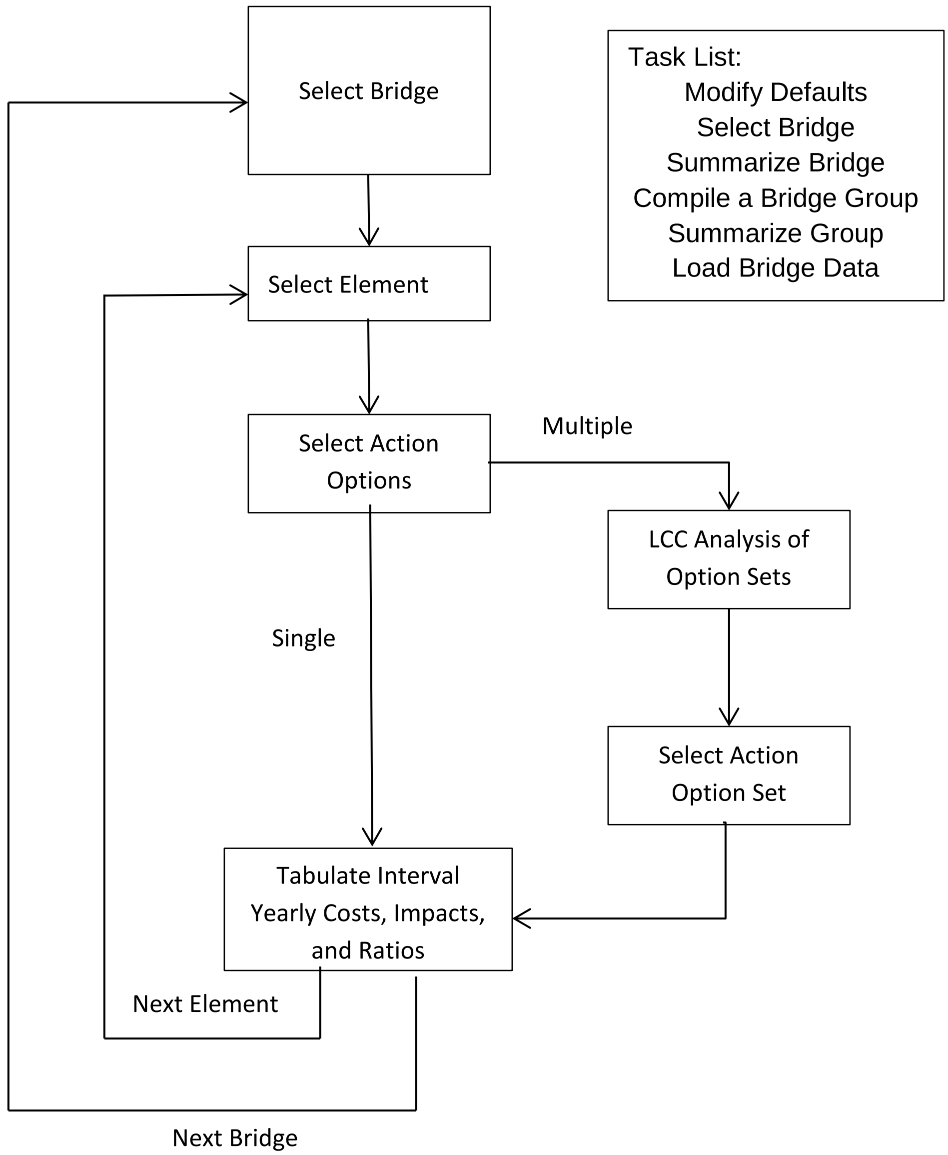

Figure 6.2 Bridge analysis methodology flow chart.

6.7 Refining Action Costs by Element Defect Density

Action costs are dependent not solely on the condition state distribution, but the distribution of a defect within the quantity by state, or the 'intensity' of the distress as illustrated in Fig. 6.3. Otherwise, some degree of over counting will result. Thus a deck with defects in states 2-4 that is to be cleaned and patched must recognize how intense or localized the defect is in each state. For state 2, if the spalls are spread over 10% of the affected area, the cost would be the amount in the state multiplied by the intensity (in this case, 30 sq. ft. *0.1 or 3 sq. ft. of area to patch) multiplied by the unit cost of patching ($100) which results in a cost of $300 for state 2. By contrast, for an action that affects an entire element, such as sealing, the intensity factor is 100%. Using the condition

distribution in the earlier example, the 30 sq. ft. in state 2 would be sealed at $2 per sq. ft., or $60.

Service environment may have additional effects on the action costs, particularly if more aggressive actions or more intensive alternatives for an action type are necessitated. What might suffice as ‘Clean and Patch’ work for a deck in a benign SE may need to be more thorough or may just be more costly due to external factors such as requiring night work to minimize traffic congestion, if the work is occurring to a deck in a severe SE.

Condition Distribution	**Corrosion**							
	Quantity	1	2	3	4			
	1,000.00	90%	3%	4%	3%		Observed Condition (%)	
		900.00	30.00	40.00	25.00		Derived Quantity (SF)	
Whole Element Action	"Seal Deck"							
Unit Cost								
$ 2.00	Extent	100%	100%	100%	100%		<< by Service Condition	
	Area	1,800.00	60.00	80.00	50.00			
Area Action	"Clean and Patch"							
Unit Cost								
$ 100.00								
	Extent	0%	10%	40%	50%		<< by Service Condition	
	Area	-	3.00	16.00	12.50			
			$ 300.00	$ 1,600.00	$1,250.00			

Figure 6.3 Action costs by element defect density.

6.8 Approaches for Selecting Element Actions

A simplifying alternate to benefit-cost ratios and incremental benefit-cost analysis would be a comparison based on Life-Cycle Costs (LCC) or on Equivalent Uniform Annual Costs (EUAC) considering potential feasible profiles of actions. The preferred method for selecting element actions among the alternatives is through consideration of life-cycle costs. However, it must be recognized that these methods are not perfect because:

- Predicting the timing and cost of future actions is at best approximate.
- Knowledge of deterioration is only approximate since construction materials and constructed quality can vary, environmental history varies, and knowledge of past maintenance may be limited.
- Procedures for inspection rating of element condition states are in a process of change and deterioration and other factor data on this basis is not available at present.
- Knowledge of costs is often approximate.

Hopefully, ability to better quantify future actions will improve. For now, life-cycle cost methods can still be applied but practical implementation is needed and engineering judgment and input is required.

Knowledge of the element condition beyond the simple condition state rating is required to make good decisions. Goals of the action prioritization portion of this study are to provide a catalog of possible actions with performance parameters as may be available or approximated and a practical method for selecting the most cost effective actions in particular situations. Implementation of the new AASHTO Manual for Bridge Element Inspection will provide detailed defect assessments which should make selecting an action more precise.

6.9 Selection of Element Preservation Actions

Based upon the bridge element, element type and material, and condition states, possible preservation actions can be identified from the catalog of actions. Appropriate action profiles are assembled and time to first action estimated. It is planned that decision trees defining triggers for action based on element condition state distribution will facilitate developing initial actions.

All actions on all bridges cannot occur in the same year. For each action considered, the urgency must be estimated considering potential near term impacts of delay. After comparing the life-cycle costs of feasible actions, element action packages can be assembled. This is necessary since some element actions would normally be considered to occur in concert with others depending on condition states. For example, if a deck overlay is planned, work on joints would likely be programmed to occur at the same time, either in consideration of traffic control or for technical reasons.

Figure 6.4 illustrates cost profiles of various element action scenarios including minor preservation (e.g. washing decks, sealing decks, spot painting steel), major preservation (e.g. deck overlay, zone painting steel) and element replacement (e.g. deck replacement, joint replacement). Terminology varies and there is no strict hierarchy of terms. Reference is often made to do-nothing, protect, preserve, maintain, rehabilitate, replace, etc.

Prediction of a long term action profile is difficult and in fact is likely to change with time. However, even when an approximation of the future, it provides a basis for economic comparison today and the hope of best using limited funds. The profiles listed include provision for actions to be done as necessary to obtain a bridge service life of 100 years since the objective of preservation is long term use of the bridge as an asset. The examples include repetition of single actions such as (Figure 6.4a) for periodic replacement of an element under a do-nothing approach, (Figure 6.4b) for periodic major preservation with no minor preservation actions between, (Figure 6.4h) for minor cyclic preservation actions only, and (Figure 6.4c, d, e) for combinations of replacement, major and minor preservation. Single actions Figure 6.4 (f, g) may also be required at the beginning of a preservation profile to correct low condition states in limited areas of an element.

It will be assumed that the element may have portions that are in different condition states due to varied deterioration. However, for simplicity of a practical approach, future deterioration after initial preservation action will be assumed to be deterministic starting with an average condition state for the element.

Typically, a bridge has been in service for some time and its elements are in some state of deterioration. Thus, it is necessary to estimate the time to first application of a minor or major preservation action or replacement action at less than the normal action service life.

For many elements, the possible actions will be limited and the selection and programming fairly obvious. However, some elements may have many possible action strategies so that it is not obvious which strategy to pursue. In those cases, the strategy having the least cost over the life of the bridge should be selected.

6.10 Real Required Rate of Return and Rate of Inflation

The Nominal Rate of Return (*NRR*) is composed of two components, the Real Rate of Return (*RRR*) and a component which is larger than the perceived rate of inflation (f).

$$NRR = RRR + \left(1 + RRR\right) f \tag{6.1}$$

For example, if the desired *RRR* = 4.5% and f = 3%, the investor would be seeking a nominal return as follows:

NRR = 0.045 + (1 + 0.045)(0.03) = 0.0763 or 7.63%

It is assumed that the cost data will be in today's dollars corresponding to the time of the analysis. This means that the tables of cost data will need to be updated periodically by the user to reflect effects of inflation and other factors that impact changes in unit costs of doing the preservation and other bridge work activities.

Cost of future actions and budgets in future years can initially be expressed in terms of today's dollars corresponding to the year of analysis and then converted to future, then current, dollars. With this approach the rate of inflation is set to zero, $f = 0$, and the *NRR* = *RRR* for this special case. After calculation of costs and budgets in today's dollars occurring in future years, they can be converted to future dollars by multiplying by the factor $(1 + f)^{t-t_a}$ where t_a is the year of analysis and t is the future year so that $t-t_a$ is the time difference in years between the year of analysis and the future year.

6.11 Element Preservation Life-Cycle Cost Alternatives

Element Preservation Timing

Although we may be in a current year, t0, planning actions for element preservation, those actions are often not initiated in the current year. Rather, the action is likely to be programmed for some future year, such as t1. That action could be any of the following:

- A single action that is not repeated, e.g. rehabilitation of a small portion of a deck in poor condition before applying an overlay to the entire deck;
- The first of a series of actions repeated at a cycle equal to the service life, SL, of the preservation action, e.g. application of deck sealer;
- A combination of multiple actions, each having a different service life, e.g. cyclic spot painting of steel girders at a short service life for each cycle between actions to remove paint and repaint at a long service life all girders entirely.

Examples of single, and cyclic actions, and combinations of actions are illustrated in Figure 6.4a-g.

Single Action of Element Preservation

Sometimes as shown in Figure 6.4f a single action of major preservation may be required on a portion of an element to bring its condition in line with other portions of the element before applying other major or minor preservation actions. An example might be major element preservation repair, *EP*1, of some deck areas before applying a sealer to the entire deck. The initial cost of the EP1 action on element e in year t2 is expected to be $IC(e,EP1,t2)$. The life cycle cost of this single action relative to $t0$, $LCC(e,EP1,t0)$, is:

$$LCC\left(e,EP1,t0\right)=IC\left(e,EP1,t2\right)\left(P/F,RRR,t2-t0\right) \tag{6.2}$$

where

$$\left(P/F,RRR,n\right)=\frac{1}{\left(1+RRR\right)^{n}} \tag{6.3}$$

and in this case $n = t2 - t0$

Single Action of Element Replacement

Sometimes as shown in Figure 6.4g a single action of replacement may be required on a portion of an element to bring its condition in line with other portions of the element before applying other major or minor preservation actions. An example might be element replacement, *ER*1, of some deck joints before, or coincident with, cleaning other joints. The life cycle cost of this single replacement action occurring at $t3$ relative to $t0$, $LCC(e,ER1,t0)$, is:

$$LCC\left(e,ER1,t0\right)=IC\left(e,ER1,t3\right)\left(P/F,RRR,t3-t0\right) \tag{6.4}$$

The single action could also be for complete replacement of the element and could occur multiple times in the life of a bridge. This could also represent a do-nothing alternative.

Element Cyclic Preservation Alternative for Limited Number of Cycles

The initial cost of a cyclic preservation action for element *e* in year $t2$ can be stated as $IC(e,CP,t2)$. When a cyclic action is planned for a limited number of cycles, *nc*, and each action has a service life, *SL*, the effective *RRR* over each service life is:

$$RRR_{SL}=\left(1+RRR\right)^{SL}-1 \tag{6.5}$$

For bridge element preservation actions, the cost is incurred at the beginning of the cycle and the action is not repeated at the end of the last cycle. If a cycle is initiated in year t2, then the life cycle cost relative to $t1 = t2-SL$ is

$$LCC\left(e,CP,t1\right)=IC\left(e,CP,t2\right)\frac{\left(1+RRR_{SL}\right)^{nc}-1}{RRR_{SL}\left(1+RRR_{SL}\right)^{nc}} \tag{6.6}$$

Relative to the current year t0, the life cycle cost of the cyclic action is

$$LCC\left(e,CP,t0\right)=IC\left(e,CP,t1\right)\left(P/F,RRR,t1-t0\right) \tag{6.7}$$

Element Major Preservation Alternative (with minor cyclic preservation)

When multiple types of actions are included in the action profile for a major preservation option, the *LCC* is a combination of the costs associated with each. However, the service life of the major preservation action is extended to SL+SLX and must be accounted for in the calculation of *LCC* for the Major Preservation option.

Element Replacement Alternative (with minor cyclic preservation)

When multiple types of actions are included in the action profile with the element replacement option, the *LCC* is a combination of the costs associated with each. However, the service life of the replacement option is extended to SL+SLX and must be accounted for in the calculation of *LCC* for the Element Replacement option.

Comparison of Alternatives with Different Resulting Bridge Life

If it becomes necessary to compare situations where the alternatives considered would not result in the same long term bridge life, the comparison cannot be based on present value of life cycle costs. In those cases, the equivalent uniform annual cost, EUAC, of each bridge preservation alternative can be calculated from the present values as a basis of comparison.

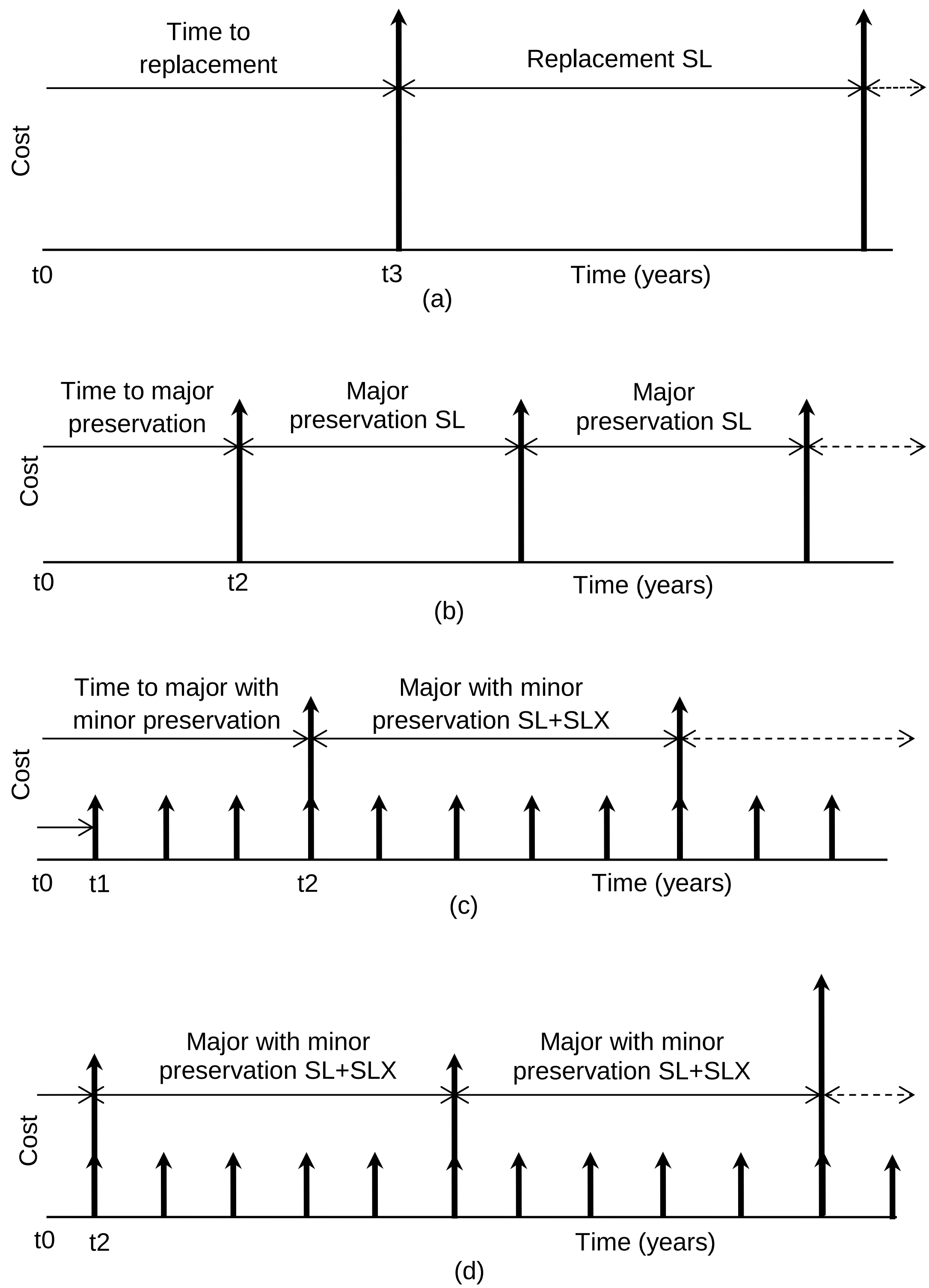

Figure 6.4 Cost profiles for element action options.

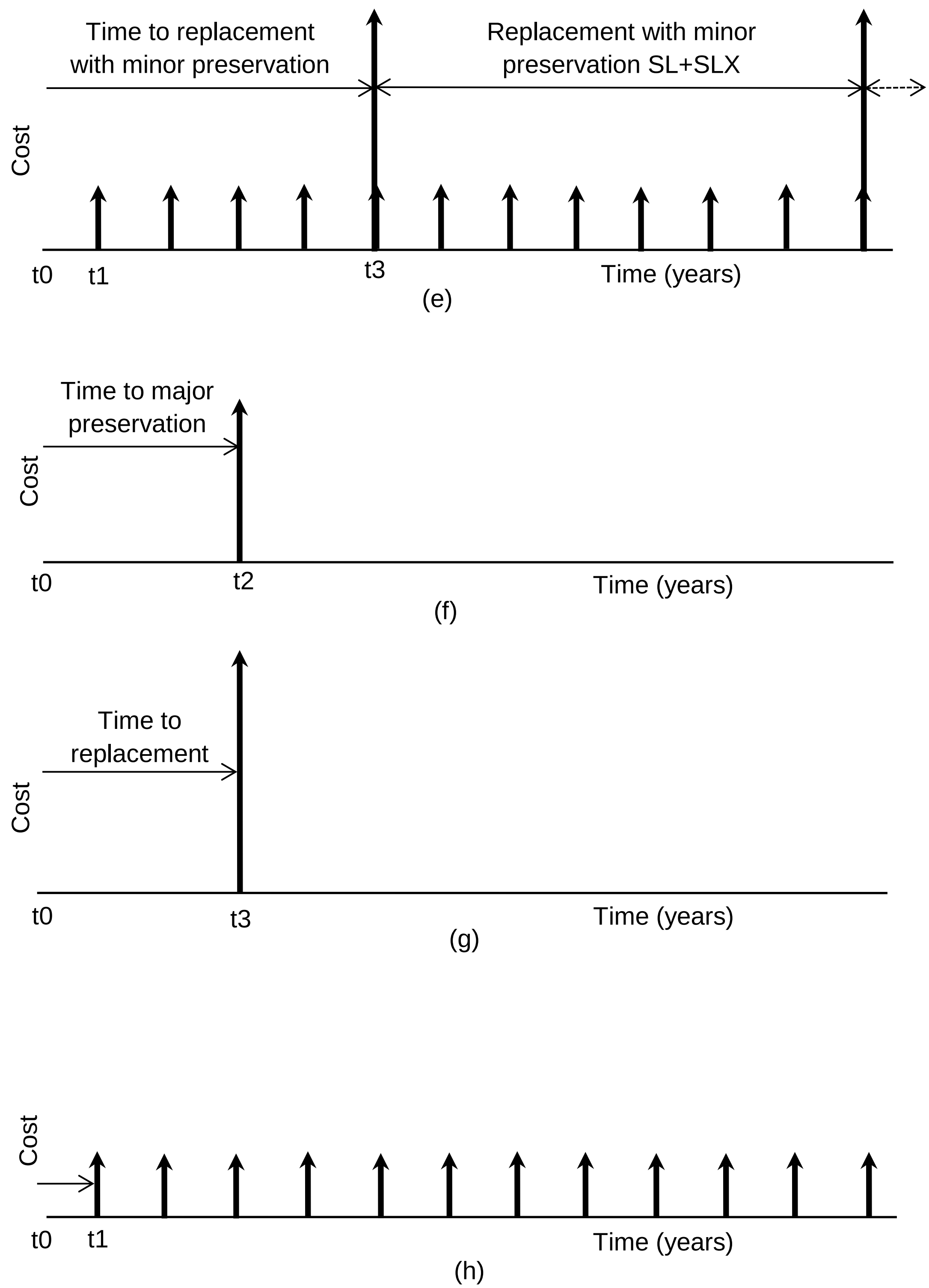

Figure 6.4 (cont'd) Cost profiles for element action options.

6.12 Impact on Element Condition

Some preservation actions improve condition state; others extend service life of the element in the current state. Both extend service life of the element. Once the actions are selected based on *LCC* and logical action packages resulting in action profiles, the predicted condition state profiles can be estimated over a reasonable horizon. An horizon of about five to ten years would be a practical duration, long enough to see the impact of the preservation strategy, but not so long as to be greatly impacted by limited ability to predict deterioration. The tracking of each element's actual average condition state with time can be compared to that predicted originally and adjustments can be made to the basic analysis data to improved predictions in the future if average condition states are over or under predicted.

6.13 Example Bridge Element Decision Analysis Situations

In order to clarify the life cycle analysis for an individual element, examples are provided for bridge decks examining several alternate cases that might be considered by an agency. The example values are preliminary. Additional cases analyzing other strategies could also be considered.

6.13.1 New Bridge Deck Example

A bridge deck has the following parameters and conditions.

Element: 012 Reinforced concrete deck/slab

Service Environment: SE2 (see Table 6.1)

Quantity: 8603 SF all in weighted Average Condition State ACS = 1.0

Bridge age: 0 years

Desired life: 100 years

RRR = 0.04 (4%)

The handbook catalog lists several possible actions. A comparison is to be made between the following cases:

1. Doing nothing until an average condition state of 3.3 is reached followed by deck replacement

2. Patching and an overlay when the average condition state of 2.4 is reached.

3. Sealing at a 6 year cycle followed by patching and an overlay when the average condition state of 2.4 is reached.

Service life information extracted from the catalog for the bridge deck environment is tabulated as shown in Table 6.4.

Table 6.4 Example bridge data for new deck.

	Cost ($/SF)	Life extension (Years)	Average time in condition state range (Years)			
Average Condition State			1 – 1.6	1.6 – 2. 4	2.4 – 3.3	3.3 - 4
Bare concrete deck	65.00		12	15	10	4
Clean and wash deck every 2 years	1.50	0.5				
Seal at 6 year intervals	2.00	2.0				
Patch and overlay	20.00	15				

Case 1: Replace deck at 37 years and 74 years at cost of 8603 SF x $65/SF = $559,000 each time.

Substituting in Eq. (6.3) for n = 37 years and n = 74 years

$$(P/F, RRR, 37) = \frac{1}{(1+0.04)^{37}} = 0.234$$

$$(P/F, RRR, 74) = \frac{1}{(1+0.04)^{74}} = 0.0549$$

From Eq. (6.4)

$$LCC(e, ER1, t0) = IC(e, ER1, t3)(P/F, RRR, t3 - t0)$$

$$LCC(e, ER1, 0) = LCC(e, ER1, 37)(0.234) = \$559,000(0.234) = \$131,000$$

$$LCC(e, ER1, 0) = LCC(e, ER1, 74)(0.0549) = \$559,000(0.0549) = \$31,000$$

Total LCC for the two deck replacements = $131,000 + $31,000 = $162,000

Case 2: Patch and Overlay at 27 years and repeat at 15 year intervals at cost of 8603 SF x $20/SF = $172,000.

On this basis, actions would be needed in year 27, 42, 57, 72, and 87. From Eq. (6.5) with SL = 15 years

$$RRR_{15} = (1+0.04)^{15} - 1 = 1.801 - 1 = 0.801$$

Applying Eq. (6.6) with t2 = 27, SL = 15, and t1 = 27 – 15 = 12 years

$$LCC(e,CP,t1) = IC(e,CP,t2)\frac{(1+RRR_{SL})^{nc}-1}{RRR_{SL}(1+RRR_{SL})^{nc}}$$

$$LCC(e,CP,12) = IC(e,CP,27)\frac{(1+RRR_{15})^{5}-1}{RRR_{15}(1+RRR_{15})^{5}}$$

$$LCC(e,CP,12) = \$172,000\frac{(1.801)^{5}-1}{0.801(1.801)^{5}} = \$172,000\left(\frac{17.95}{15.18}\right) = \$203,000$$

Transferring the LCC of year 12 to year 0 using Eq. (6.3)

$$(P/F, RRR, 12) = \frac{1}{(1+0.04)^{12}} = 0.624$$

Relative to the current year t0, the life cycle cost of the cyclic action from Eq. (6.7) is

$$LCC(e,CP,t0) = IC(e,CP,t1)(P/F, RRR, t1-t0)$$

$$LCC(e,CP,t0) = \$203.000(0.624) = \$127,000$$

Case 3: Initially seal at 6 year intervals extending deck life 2 years with each application, followed by patch and overlay at 15 year intervals. Estimate number of sealer applications @ 6 x 6 = 36 years compared to duration to average condition state 2.4 of 27 + (6 x2) = 39 years.

a) Sealer cycles at 8603 SF x \$2/SF = \$17,200. . From Eq. (6.3) with SL = 6 years

$$RRR_{6} = (1+0.04)^{6}-1 = 0.265$$

Applying Eq. (6.6) with t2 = 0, SL = 6, and t1 = 0 – 6 = - 6 years

$$LCC(e,CP,t1) = IC(e,CP,t2)\frac{(1+RRR_{SL})^{nc}-1}{RRR_{SL}(1+RRR_{SL})^{nc}}$$

$$LCC(e,CP,-6) = IC(e,CP,6)\frac{(1+RRR6)^{6}-1}{RRR_{6}(1+RRR_{6})^{6}}$$

$$LCC(e,CP,-6) = \$17,200\frac{(1.265)^{6}-1}{0.265(1.265)^{6}} = \$17,200\left(\frac{3.10}{1.086}\right) = \$49,100$$

Transferring the LCC of year -6 to year 0 using Eq. (6.3)

$$\left(P/F, RRR, -6\right) = \frac{1}{\left(1+0.04\right)^{-6}} = 1.265$$

Relative to the current year t0, the life cycle cost of the cyclic action from Eq. (6.7) is

$$LCC\left(e, CP, t0\right) = IC\left(e, CP, t1\right)\left(P/F, RRR, t1-t0\right)$$

$$LCC\left(e, CP, t0\right) = \$49{,}100\left(1.265\right) = \$62{,}000$$

b) Patch and overlay at 39 years and repeat at 15 year intervals in years 54, 69, 84

The solution can be obtained either using the approach of Case 2 with 4 instead of 5 cycles in the appropriate years or by applying the approach of Case 1 by calculating four separate present values of the future costs. Using the later approach,

Substituting in Eq. (6.3) for n = 39, 54, 69, and 84 years

$$\left(P/F, RRR, 39\right) = \frac{1}{\left(1+0.04\right)^{39}} = 0.217$$

$$\left(P/F, RRR, 54\right) = \frac{1}{\left(1+0.04\right)^{54}} = 0.120$$

$$\left(P/F, RRR, 69\right) = \frac{1}{\left(1+0.04\right)^{69}} = 0.0668$$

$$\left(P/F, RRR, 84\right) = \frac{1}{\left(1+0.04\right)^{84}} = 0.0371$$

From Eq. (6.2)

$$LCC\left(e, EP1, t0\right) = IC\left(e, EP1, t2\right)\left(P/F, RRR, t2-t0\right)$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 39\right)\left(0.217\right) = \$172{,}000\left(0.217\right) = \$37{,}300$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 54\right)\left(0.120\right) = \$172{,}000\left(0.120\right) = \$20{,}600$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 69\right)\left(0.0668\right) = \$172{,}000\left(0.0668\right) = \$11{,}500$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 84\right)\left(0.0371\right) = \$172{,}000\left(0.0371\right) = \$6{,}400$$

Total LCC for the Case 3 actions = \$62,000 + 37,300 + 20,600 + 11,500 + 6,400 = \$137,800

Summarizing:

Case 1 = $162,000

Case 2 = $127,000

Case 3 = $137,800

Thus, based on the parameters of the example, the Case 2 strategy for the deck considered alone would provide the lowest long term cost to extend bridge life to approximately 100 years.

6.13.2 Deteriorated Bridge Deck Example

In this second example, assume the same basic parameters for the bridge deck regarding deck material, deck area, service environment and desired life. However, assume it is a bridge at an age of 25 years with several condition defects.

The bridge deck has the following parameters and conditions.

Element: 012 Reinforced concrete deck/slab

Service Environment: SE2 (see Table 6.1)

Quantity: 8603 SF all in weighted Average Condition State ACS = 2.3

Bridge age: 25 years

Desired life: 100 years (75 additional years)

RRR = 0.04 (4%)

The handbook catalog lists several possible actions. A comparison is to be made between the following cases:

1. Doing nothing until an average condition state of 3.3 is reached followed by deck replacement
2. Patching and an overlay when the average condition state of 2.4 is reached.
3. Do nothing until an average condition state of 3.3 is reached followed by deck replacement, sealing at a 6 year cycle followed by patching and an overlay when the average condition state of 2.4 is reached.

Service life information extracted from the catalog for the bridge deck environment is tabulated as shown in Table 6.5.

Table 6.5 Example bridge data for deteriorated deck.

	Cost ($/SF)	Life extension (Years)	Average time in condition state range (Years)			
Average Condition State			1 – 1.6	1.6 – 2. 4	2.4 – 3.3	3.3 - 4
Bare concrete deck	65.00		12	15	10	4
Clean and wash deck every 2 years	1.50	0.5				
Seal at 6 year intervals	2.00	2.0				
Patch and overlay	20.00	15				

Case 1: Replace deck at bridge age 37 years and 74 years (12 and 49 years from present) at cost of 8603 SF x $65/SF = $559,000 each time.

Substituting in Eq. (6.3) for n = 12 years and n = 49 years

$$\left(P/F, RRR, 12\right) = \frac{1}{\left(1+0.04\right)^{12}} = 0.625$$

$$\left(P/F, RRR, 49\right) = \frac{1}{\left(1+0.04\right)^{49}} = 0.146$$

From Eq. (6.4)

$$LCC\left(e, ER1, t0\right) = IC\left(e, ER1, t3\right)\left(P/F, RRR, t3-t0\right)$$

$$LCC\left(e, ER1, 0\right) = LCC\left(e, ER1, 12\right)\left(1.60\right) = \$559,000\left(0.625\right) = \$349,000$$

$$LCC\left(e, ER1, 0\right) = LCC\left(e, ER1, 49\right)\left(0.146\right) = \$559,000\left(0.146\right) = \$81,600$$

Total LCC for the two deck replacements = $349,000 + $81,600 = $431,000

Case 2: Patch and Overlay at 27 years age (in two years when ACS reaches 2.4) and repeat at 15 year intervals at cost of 8603 SF x $20/SF = $172,000.

On this basis, actions would be needed in bridge age years 27, 42, 57, 72, and 87 (2, 17, 32, 47, and 62 years from the present). From Eq. (6.5) with SL = 15 years

The solution can be obtained either using the approach of Example 1, Case 2 from Eq. (6.5) with adjusted timing or by applying the approach of Case 1 by calculating five separate present values of the future costs. Using the later approach,

Substituting in Eq. (6.3) for n = 2, 17, 32, 47 and 62 years

$$\left(P/F, RRR, 2\right) = \frac{1}{\left(1+0.04\right)^{2}} = 0.924$$

$$\left(P/F, RRR, 17\right) = \frac{1}{\left(1+0.04\right)^{17}} = 0.513$$

$$\left(P/F, RRR, 32\right) = \frac{1}{\left(1+0.04\right)^{32}} = 0.285$$

$$\left(P/F, RRR, 47\right) = \frac{1}{\left(1+0.04\right)^{47}} = 0.158$$

$$\left(P/F, RRR, 62\right) = \frac{1}{\left(1+0.04\right)^{62}} = 0.0879$$

From Eq. (6.2)

$$LCC\left(e, EP1, t0\right) = IC\left(e, EP1, t2\right)\left(P/F, RRR, t2-t0\right)$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 2\right)\left(0.924\right) = \$172,000\left(0.924\right) = \$158,900$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 17\right)\left(0.513\right) = \$172,000\left(0.513\right) = \$88,200$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 32\right)\left(0.285\right) = \$172,000\left(0.285\right) = \$49,000$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 47\right)\left(0.158\right) = \$172,000\left(0.158\right) = \$27,200$$

$$LCC\left(e, EP1, 0\right) = LCC\left(e, EP1, 62\right)\left(0.0879\right) = \$172,000\left(0.0879\right) = \$15,100$$

Total LCC for the Case 2 actions = $158,900 + 88,200 + 49,000 + 27,200 + 15,100 = $338,400

Case 3: Due to current condition, sealing is not a beneficial action. Replace the deck when the average condition declines to 3.3 at age 37 years in 2025 followed by sealing at 6 year intervals extending deck life 2 years with each application, followed by patch and overlay at 15 year intervals beginning in 2064. Estimate number of sealer applications @ 6 x 6 = 36 years compared to duration to average condition state 2.4 of 27 + (6 x2) = 39 years.

a) Replace deck at bridge age 37 years in 2025 (12 years from present year).

Substituting in Eq. (6.3) for n = 12 years

$$\left(P/F,RRR,12\right)=\frac{1}{\left(1+0.04\right)^{12}}=0.625$$

From Eq. (6.4)

$$LCC\left(e,ER1,t0\right)=IC\left(e,ER1,t3\right)\left(P/F,RRR,t3-t0\right)$$

$$LCC\left(e,ER1,0\right)=LCC\left(e,ER1,12\right)\left(1.60\right)=\$559,000\left(0.625\right)=\$349,000$$

b) Seal 8603 SF of deck at 6-year intervals beginning in 2025. Since deck condition will decline, even with sealing, assume that the cost of sealing cracks and the deck will gradually increase from $2.00/SF for first two applications, $2.25 for applications 3 and 4 and $2.50 for applications 5 and 6. On this basis, the application costs would be $17,200, $19,400 and $21,500 respectively.

Calculate six separate present values of the future costs. Substituting in Eq. (6.3) for n = 12, 18, 24, 30, 36 and 42 years

$$\left(P/F,RRR,12\right)=\frac{1}{\left(1+0.04\right)^{12}}=0.625$$

$$\left(P/F,RRR,18\right)=\frac{1}{\left(1+0.04\right)^{18}}=0.494$$

$$\left(P/F,RRR,24\right)=\frac{1}{\left(1+0.04\right)^{24}}=0.390$$

$$\left(P/F,RRR,30\right)=\frac{1}{\left(1+0.04\right)^{30}}=0.308$$

$$\left(P/F,RRR,36\right)=\frac{1}{\left(1+0.04\right)^{36}}=0.244$$

$$\left(P/F,RRR,42\right)=\frac{1}{\left(1+0.04\right)^{42}}=0.193$$

From Eq. (6.2)

$$LCC\left(e,EP1,t0\right)=IC\left(e,EP1,t2\right)\left(P/F,RRR,t2-t0\right)$$

$$LCC\left(e,EP1,0\right)=LCC\left(e,EP1,12\right)\left(0.625\right)=\$17,200\left(0.625\right)=\$10,800$$

$$LCC\left(e,EP1,0\right)=LCC\left(e,EP1,18\right)\left(0.494\right)=\$17,200\left(0.494\right)=\$8,500$$

$$LCC(e,EP1,0)=LCC(e,EP1,24)(0.390)=\$19,400(0.390)=\$7,600$$

$$LCC(e,EP1,0)=LCC(e,EP1,30)(0.308)=\$19,400(0.308)=\$6,000$$

$$LCC(e,EP1,0)=LCC(e,EP1,36)(0.244)=\$21,500(0.244)=\$5,200$$

$$LCC(e,EP1,0)=LCC(e,EP1,42)(0.193)=\$21,500(0.193)=\$4,100$$

Thus, total sealing *LCC*(*e*, *EP*1, 0) = $42,200.

c) Patch and overlay at deck age of 39 years (51 years from current year) and repeat at 15 year intervals in years 66, 81.

The solution can be obtained applying the approach of Case 1 by calculating three separate present values of the future costs. Using the later approach,

Substituting in Eq. (6.3) for n = 51, 66, and 81 years

$$(P/F,RRR,51)=\frac{1}{(1+0.04)^{51}}=0.135$$

$$(P/F,RRR,66)=\frac{1}{(1+0.04)^{66}}=0.0751$$

$$(P/F,RRR,81)=\frac{1}{(1+0.04)^{81}}=0.0417$$

From Eq. (6.2)

$$LCC(e,MP1,t0)=IC(e,MP1,t2)(P/F,RRR,t2-t0)$$

$$LCC(e,MP1,0)=LCC(e,MP1,51)(0.135)=\$172,000(0.135)=\$23,200$$

$$LCC(e,MP1,0)=LCC(e,MP1,66)(0.0751)=\$172,000(0.0751)=\$12,900$$

$$LCC(e,MP1,0)=LCC(e,MP1,81)(0.0417)=\$172,000(0.0417)=\$7,200$$

Total LCC for the Case 3 actions = $349,000 + 42,200 + 23,200 + 12,900 + 7,200 = $434,500

Summarizing:

Case 1 = $431,000

Case 2 = $338,400

Case 3 = $434,500

Thus, based on the parameters of the example, the Case 2 strategy for the deck considered alone would provide the lowest long term cost to extend bridge life to approximately 100 years.

This second example is alternately shown in spreadsheet format in Figure 6.5 with the three cases listed in column 1 and each row representing an action in a designated year. The calculated values vary from the presented example only due to rounding of values in the long-hand presentation. Calculated LCC values for each case are shown in three columns. By designating the selected option LCC2 with a "1" and deselecting the other options LCC1 and LCC3 with a "0", the expected cost of $172,060 over the 10-year programming cycle for this element is tabulated in 2015.

Bridge Number	123456
Bridge Age (yrs)	25
Current Year, t0	2013
Required Rate of Return (%)	4.0
Total Required Life (yrs)	100
End Year	2088

Case	Element	AvgCond Trigger	Quantity	Action Code	Action Year, t1	Unit Cost	TotCost ($)	(P/F,RRR,t1-t0)	LCC1 ($)	LCC2 ($)	LCC3 ($)
1	12	3.3	8603	Replace	2025	65.00	559195	0.6246	349272	0	0
1	12	3.3	8603	Replace	2062	65.00	559195	0.1463	81833	0	0
2	12	2.4	8603	Patch/Overlay	2015	20.00	172060	0.9246	0	159079	0
2	12	2.4	8603	Patch/Overlay	2030	20.00	172060	0.5134	0	88331	0
2	12	2.4	8603	Patch/Overlay	2045	20.00	172060	0.2851	0	49047	0
2	12	2.4	8603	Patch/Overlay	2060	20.00	172060	0.1583	0	27234	0
2	12	2.4	8603	Patch/Overlay	2075	20.00	172060	0.0879	0	15122	0
3	12	3.3	8603	Replace	2025	65.00	559195	0.6246	0	0	349272
3	12	1.0	8603	Seal	2025	2.00	17206	0.6246	0	0	10747
3	12	1.2	8603	Seal	2031	2.00	17206	0.4936	0	0	8493
3	12	1.5	8603	Seal	2037	2.25	19357	0.3901	0	0	7551
3	12	1.7	8603	Seal	2043	2.25	19357	0.3083	0	0	5968
3	12	2.0	8603	Seal	2049	2.50	21508	0.2437	0	0	5241
3	12	2.2	8603	Seal	2055	2.50	21508	0.1926	0	0	4142
3	12	2.4	8603	Patch/Overlay	2064	20.00	172060	0.1353	0	0	23280
3	12	2.4	8603	Patch/Overlay	2079	20.00	172060	0.0751	0	0	12926
3	12	2.4	8603	Patch/Overlay	2094	20.00	172060	0.0417	0	0	7178

	LCC1 ($)	LCC2 ($)	LCC3 ($)
Total LCC	$ 431,105	$ 338,813	$ 434,798
Selected Option	0	1	0
Expenditures by Year			
2014	0	0	0
2015	0	172060	0
2016	0	0	0
2017	0	0	0
2018	0	0	0
2019	0	0	0
2020	0	0	0
2021	0	0	0
2022	0	0	0
2023	0	0	0

Figure 6.5 Spreadsheet solution format for second example.

CHAPTER 7 Methodology to Determine Appropriate Levels of Funding

7.1 Consideration of Analysis Processes

Once the agency has selected a group of bridges desired for preservation, by use of a BMS or another process, there is a need to determine the appropriate levels of funding or to determine which of those bridges can be accommodated within the budget available. It is the initial costs of the actions in a given year that must be accommodated. However, selection should be based on comparison of life cycle costs, perhaps converted to equivalent uniform annual costs for the predicted life of the bridge under the action alternatives. Steps in the process include:

- Tabulating individual bridge costs by year for a planning horizon of perhaps 5 to 10 years;
- Tracking the element conditions (individually, by component, or as a weighted condition state) over the horizon;
- Selecting a group of bridges for consideration;
- Tracking average condition for the group on bridges;
- Comparing costs for the group selected to budget constraints, if any;
- Selecting the group for action; comparison of the life-cycle cost of preserved bridges to the life-cycle costs of the do-nothing and replace option.

An overview flow chart for the process is illustrated in Figure 7.1.

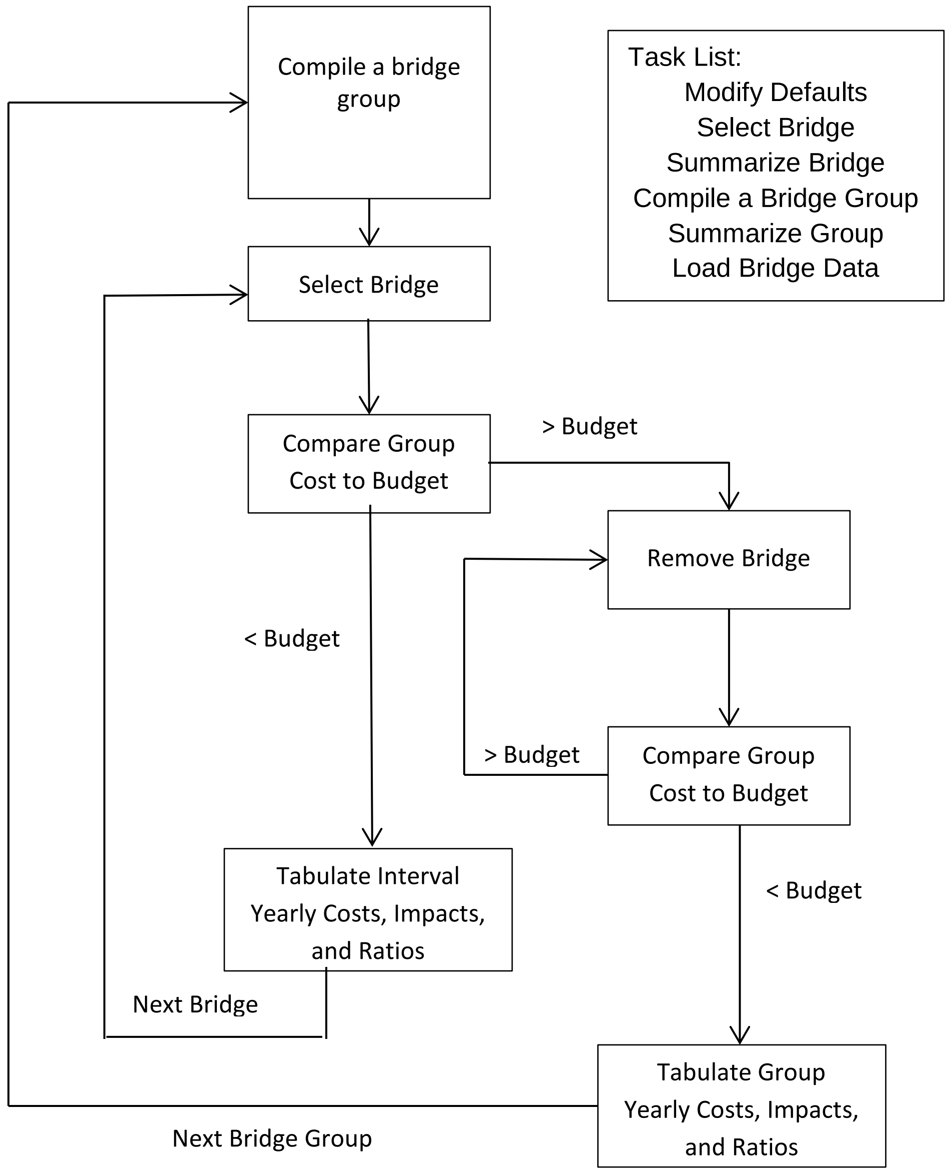

Figure 7.1 Bridge group analysis methodology flow chart.

7.2 Budget Demand for an Individual Bridge

After selection of element preservation actions for a single bridge based on comparison of life-cycle costs, the expected yearly expenditures over a reasonable horizon, perhaps 10 years, can be tabulated. Table 7.1 provides example tabulations for a limited number of elements (A, B and C) of a single bridge. The year of analysis is indicated as t0 = 2015. Element A has planned major preservation (MP) actions in 2017 (t2) and 2023 and cyclic preservation (CP) at 2-year intervals (examples might be deck joint repair and deck joint cleaning). Element B has planned a major preservation action in 2017 and two cyclic preservation actions, CP1 at 5 year intervals and CP2 annually (examples might be deck patching in 2017, sealing every 5 years and washing annually). Element C has cyclic

preservation initiated in 2015 at 4-year intervals and major preservation in 2023 (examples might be cyclic spot cleaning and painting of steel every 4 years and general repainting in 2023).

Cost predictions will be in today's dollars (year of analysis) without effects of inflation included. If predictions in future dollars are desired, the totals can be adjusted by applying a compounded inflation adjustment.

Table 7.1 Example tabulation of expected costs for bridge No. 352466 ($-thousands).

Element and Action	Analysis Year	Future Years								
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
A-MP	0	0	5	0	0	0	0	0	5	0
A-CP	0	0	2	0	2	0	2	0	2	0
B-MP	0	0	30	0	0	0	0	0	0	0
B-CP1	0	0	12	0	0	0	0	12	0	0
B-CP2	0	0	1	1	1	1	1	1	1	1
C-CP	8	0	0	0	8	0	0	0	8	0
C-MP	0	0	0	0	0	0	0	0	40	0
Total Cost	8	0	50	1	11	1	3	13	56	1

The number of elements included is only limited by practicality. Following the general principle of the 80-20 rule-of-thumb, 80% of the work is in 20% of the elements. It may not be realistic to include the 80% of elements where work is rare and unpredictable. Rather, a general allowance is more practical to budget for that 20% of costs.

The analysis year advances each year. At the beginning of each new analysis year, review will be needed to determine if planned actions were done or if actions were delayed and need to be re-programmed, perhaps by resetting the entire planned action profile.

7.3 Budget Demand for a Designated Group of Bridges

Network level analysis of budget demand involves a tabulation of the expected annual cost of work on bridges included in selected network subgroup, a portion of the inventory. The network subgroup might be designated by the agency on any basis such as:

- Bridges clustered on a single route selected to coordinate traffic control;
- Bridges of a similar design selected to be included in a single contract;
- Bridges in a region (e.g. county) selected as the responsibility of an agency maintenance subgroup.

Example tabulations for a group of bridges are shown in Table 7.2 for each year over a 10-year horizon. Predictions are in today's dollars and would need would need adjustment for expected inflation if future dollar amounts are desired.

Table 7.2 Example tabulation of expected costs for a designated group of bridges.

Bridge No.	Current Year	Future Years								
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
352466	8	0	50	1	11	1	3	13	56	1
352523	80	0	2	0	2	0	2	0	2	0
352556	0	40	1	1	1	1	3	1	1	1
352602	0	5	0	0	0	30	0	0	0	10
352627	1	1	1	36	1	1	1	1	1	1
352640	4	0	0	0	8	0	0	0	8	0
352708	0	0	0	0	5	0	0	0	0	14
Total Cost	93	46	54	38	28	33	9	15	68	27

7.4 Tracking Impacts of Preservation Actions

For the individual element, some preservation actions are triggered by low condition state and the resulting condition state improvement. Others are selected among preservation options that extend the life of the element. All options impact the average condition state over the life of the bridge and the resulting average condition state can be forecasted over the analysis horizon. With time, the impact of past actions can also be tracked from analysis of inspection data.

Due to limited funding, agencies are likely to prefer action plans the result in lowest life-cycle costs. This does not imply low condition states generally, but it may involve some low condition states before major actions or element replacement when that solution produces the lowest life cycle costs. However, if the priority is to seek even higher levels of condition regardless of cost, more aggressive and costly preservation actions and profiles can be programed. This can be accepted by the system by:

- Increasing the condition state levels that trigger required action;
- Shifting the trigger closer to the beginning of service in a state (e.g. soon after reaching a 3 rather than near the time it would drop to a 4); or
- Revising the decision trees so that the trigger is reached when less percentage quantity of the element is in the lowest acceptable condition state than might be indicated in the catalog.

At the individual bridge level, forecasting condition can be done based on:

- Average condition state (ACS) of the individual element;
- Weighted average condition state of a designated group of elements;
- A default health or tracking index.

At the network level, forecasting condition can be done based on:

- Average condition state (ACS) of the individual element for designated bridges;
- Weighted average condition state of a designated group of elements for designated bridges;
- A default health or tracking index for the designated group of bridges.

CHAPTER 8 Decision and Analysis Support Tool

8.1 Tool Description

Development has been initiated on an analysis tool integrating the methodology determined to prioritize bridge preservation actions to facilitate use of the method by agencies. The tool is one that can be easily used on readily available Windows PC platforms and based in normally available software such as Microsoft Excel. The exact nature of the software tool cannot be predicted until the metrics and prioritization method are known. However, the researchers and developers anticipate that it might have parallels to the Excel OPTime software developed in NCHRP Project 14-14 and documented in NCHRP Report 523. The goal is to make an easy to use, but powerful software tool, that users can quickly enter in basic information and needs and be presented with recommended options. The various preservation actions and their benefits would be directly integrated in as part of the tool.

The software tool envisioned would allow inputs of condition information on both new element level data and NBI data to assist in meeting the desired performance measures and levels of funding needed. The is intended to be implemented within an Excel-like interface and be part of the same tool described in section 2.1. This tool could even be made to directly import/interface with AASHTOWare Bridge Management element data via the PDI/XML format or NBI text information to allow information to be easily pulled in.

The software tool would contain a basic interface to allow for the bridge inventory and condition data to be input. This would allow agencies to specify the specific bridge or bridges that are to be considered. Once the information is entered the software would run through its analytical logic and present the calculated results in text and graphical form to the user. The goal would be to present the results and various options in an easy to understand manner. Users would have the ability to change bridge data and possible weightings and priorities to allow for calculations to be rerun and results compared.

8.2 Data Requirements

The decision support tool has minimal bridge and inspection data requirements. Standard NBI information is used for bridge selection lists and other windows, along with standard AASHTO element inspection data that conforms to the AASHTO Manual for Bridge Element Inspection, First Edition (AASHTO, 2013). These data can be downloaded from an AASHTO BrM 5.1.3 database (or later versions), may be entered into the supporting database tables by an external process, or entered directly.

All typical preservation action and cost data used by the tool are assumed to conform to the specifications of the NCHRP/AASHTO Bridge Preservation Handbook . Examples of these data for standard bridge elements may be found in that document.

8.3 Example Analysis Support Tool Screen Layouts

A preliminary screen mock-up for the analysis tool is shown in Figure 8.1. The example shows a wireframe the first of 4 planned tabs as indicated by callout (A). This screen is intended to show the current state of each bridge in the picklist (B) by presenting all the

NBI and element inspection data in (C) and (D). For each element, the effect of any preservation work on future Average Condition State (ACS) is shown in panel (E).

Panel (F) presents the planned work for the selected bridge in the picklist (B). Panel (G) presents the deterioration profile for the element, and will show the do-nothing profile along with the deterioration forecast showing preservation work effects.

A standard set of action buttons will appear at the bottom of each page (H). The Plan button will reveal an interactive form for assigning preservation work to the bridge based on the handbook methodology. The Reports button will present a list of built-in reports for the application. View Handbook will bring up the actual handbook in HTML format for review and reference at any time. Refresh will reload any data that is downloaded from external sources (such as bridges and inspection information), and wherever a help question mark appears user guidance will be provided.

Figure 8.2 presents an interface to the catalog entries. As shown in earlier sections of this report, each element and defect has a roster of possible preservation actions depending on the level of distress. The values for elements and defects are preloaded, along with default values for each state and action option in the preservation action decision matrix (C) and the cost/effectiveness dimensions for each service environment (D). Section (E) is a key to the possible icons. Some rows (particularly Do-Nothing) may not permit editing, removal or disabling, or may be set to be ignored by the application (unused actions). Others may be locked, so the values are preserved against ad hoc changes. Finally, new catalog entries can be added at any time in place of or to extend the built in alternatives, and those rows are indicated with a .

Figure 8.3 shows a sketch of a raw data review and management panel. The exact number of tables and content is still in development. The purpose of this tab is to permit direct access to the raw data for review and quick data entry. While this is not an optimal data management strategy from a security or multi-user perspective, the twin advantages of simplicity and expeditious development make offering this capability very effective.

Figure 8.4 is a sketch level exhibit. There will be a number of planning parameters, configuration values, and other operating settings that the system will require. These will be located on this tab organized by topical area, as suggested in the example.

These high-level wireframes are preliminary and dependent on the final Handbook methodology and data requirements. As the Handbook is finalized and the software design evolves, new versions will be published to an Internet location for team and panel review. The current prototype is available online at http://share.axure.com/QD6AM3.

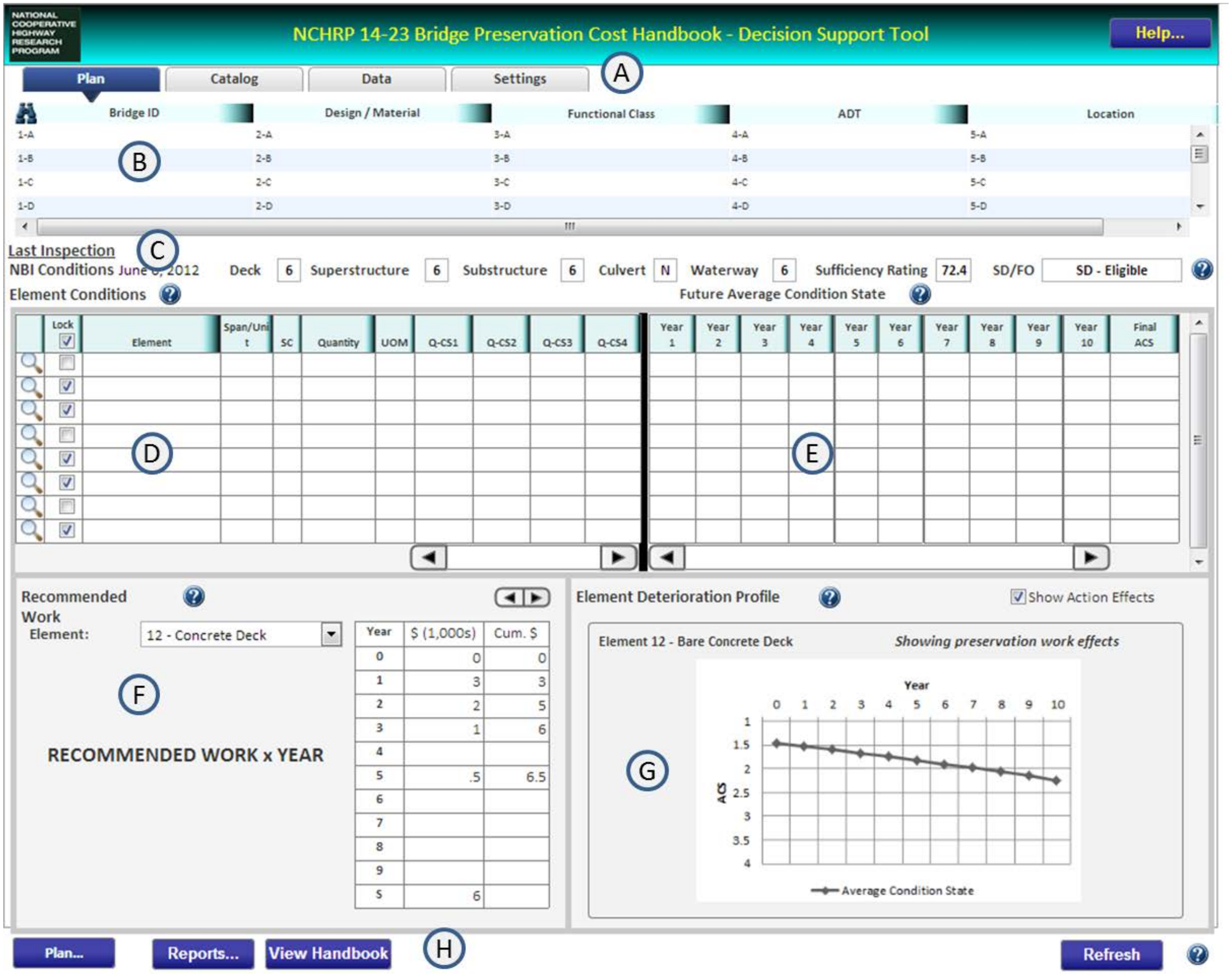

Figure 8.1 Example analysis tool screen layout – Planning screen.

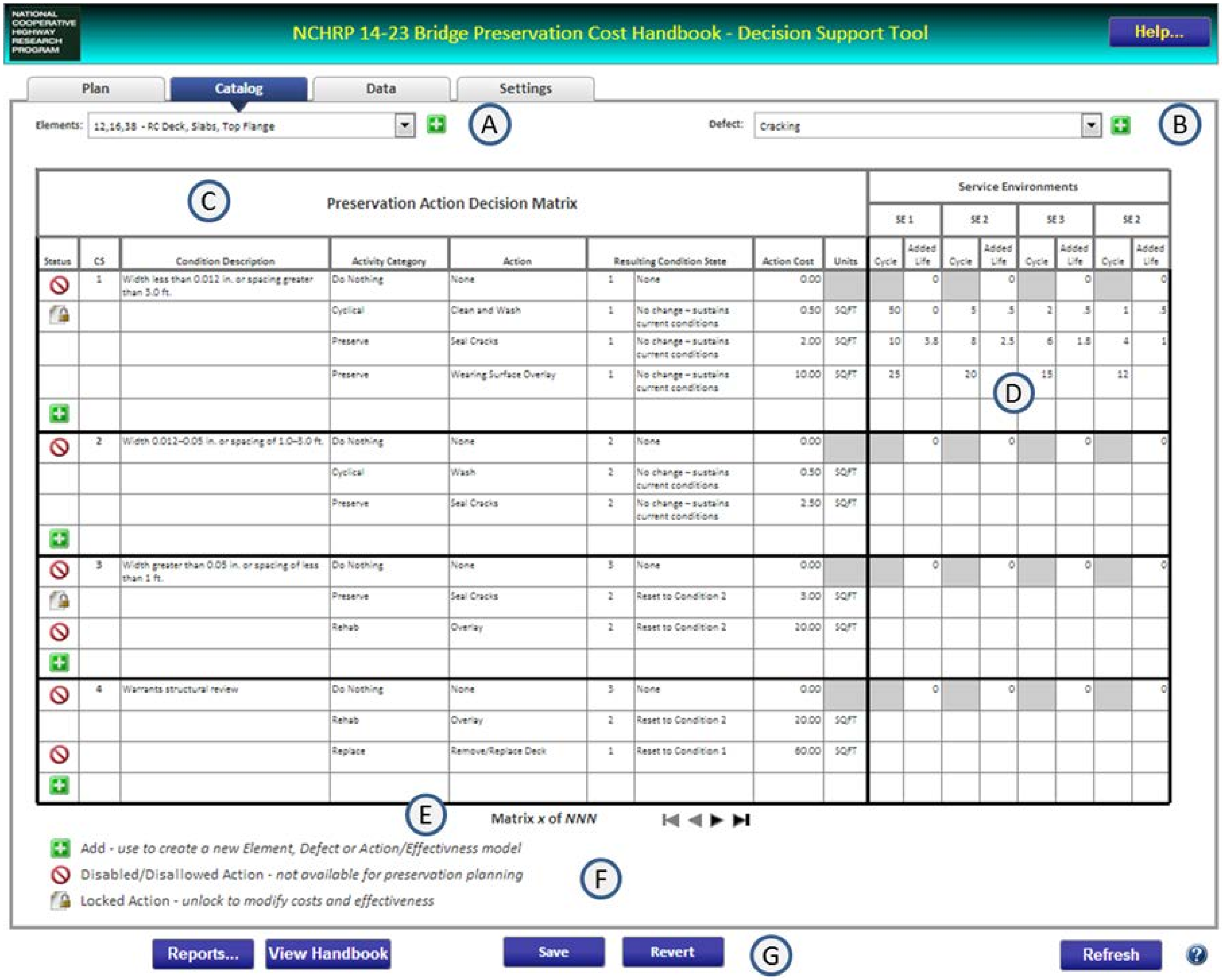

Figure 8.2 Example analysis tool screen layout – Catalog screen.

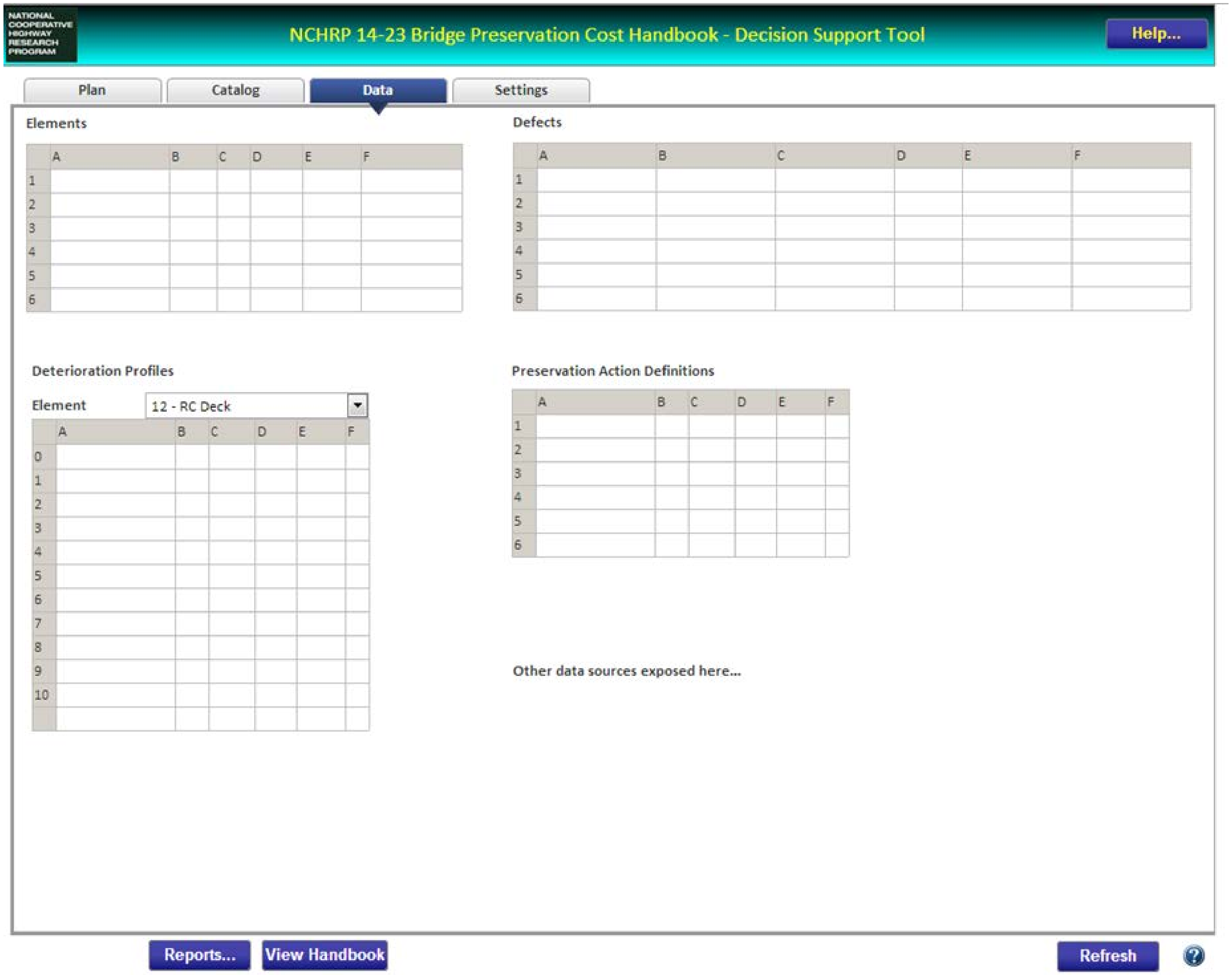

Figure 8.3 Example analysis tool screen layout - Data screen.

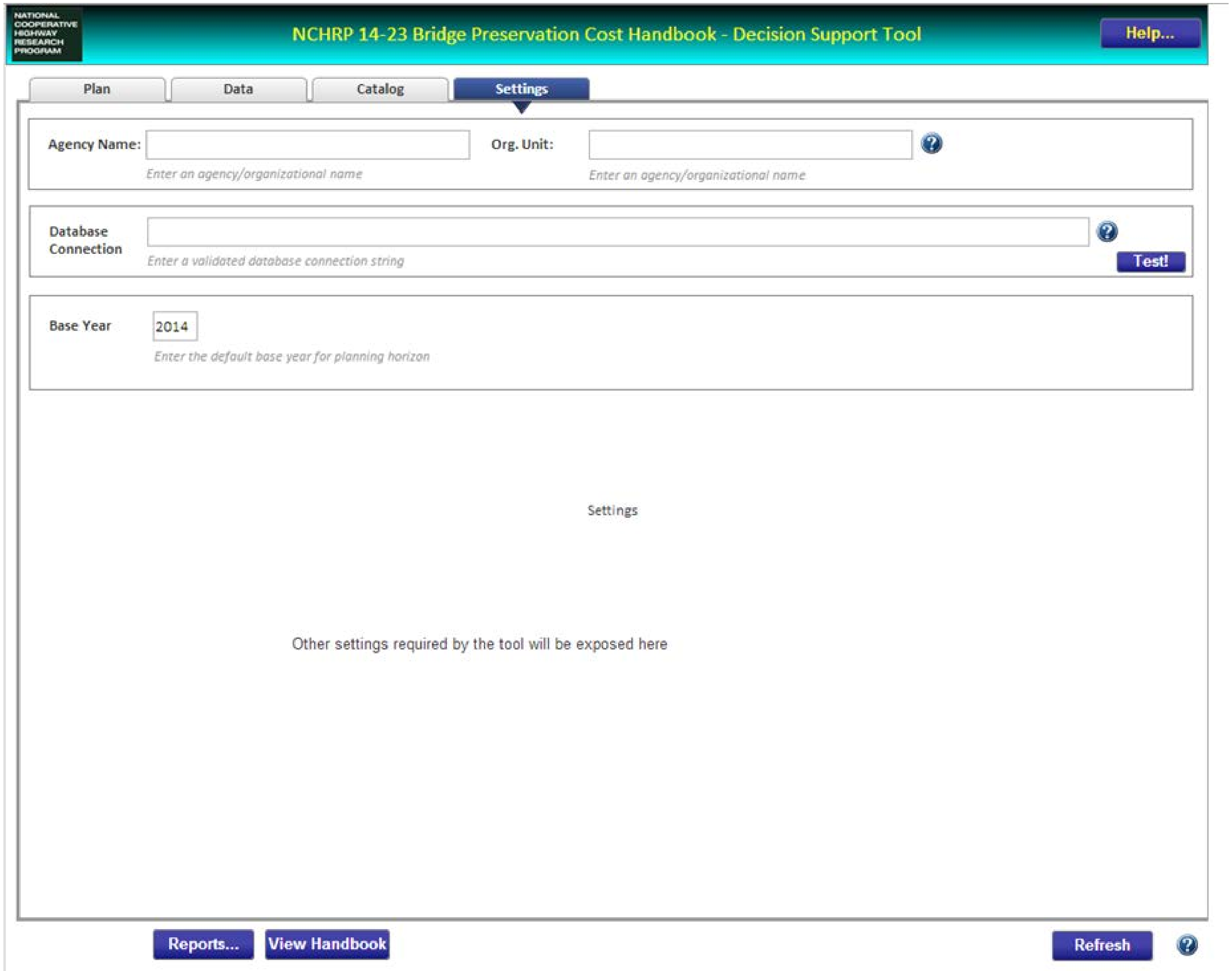

Figure 8.4 Example analysis tool screen layout – Settings screen.

CHAPTER 9 Conclusions and Recommendations

9.1 Conclusions

Progress was made toward development of a system for assessing practical bridge preservation actions and investment strategies. The various additional tasks need improved definition for successful completion of the system originally envisioned by the project objectives. The following conclusions are offered:

1. The service environment of the bridge element will impact its rate of deterioration and the selection of the best option for preservation. Use of the service environments defined by the AASHTO Manual for Bridge Element Inspection (MBEI) at the level of the deck, superstructure and substructure is recommended.
2. The condition states of the element as defined by the MBEI are proposed as the initial trigger for decision making for development of the preservation actions, impacts and metrics.
3. Impacts on preservation of secondary elements should be considered and modeled by the decision making system and data base.
4. In order to defend preservation actions as optimal, the evaluation of preservation action options should be based on life-cycle costs.
5. A starting catalog of bridge preservations actions was developed. Agencies can add to or revise the catalog action information so that it is more reflective of their own experiences.
6. A starting database of impacts of the actions has been developed. Agencies can add to or revise the impact data so that is more reflective of their own experiences.
7. A starting database of metrics for the actions has been developed. Agencies can add to or revise the metric cost, and duration data so that is more reflective of their own experiences and the effects of inflation at that time.
8. An *optimal* solution to a complex problem requires suitable data to allow decisions among alternatives to be accurately quantified.
9. Most agencies have difficulty defining reliable cost information for bridge preservation, maintenance, rehabilitation, and replacement. The unit measures for costs have also varied.
10. Prediction of deterioration continues to be problematic due to varying environments, varying construction materials and practices, and limited record of historical maintenance intervention.
11. Although agencies have collected bridge condition data under several different systems for years, data collection at the element level varies and is in the process of conversion to a new system based on the 2013 AASHTO Manual for Bridge Element Inspection. This conversion has caused some elements, element defects, and condition descriptions to be a moving target with data for a complete cycle not yet available and certainly historical data not yet accumulated.
12. Quantifying the benefits of bridge preservation actions is problematic without reliable data.

13. It is clear that some agencies desire a system that will produce optimum recommendations for decision support and accept that life cycle economic analysis is an important tool for decision making.
14. However, during this period of transition, other agencies desire approximate solutions for management until more reliable data is available to justify approaches that might be more optimal.

9.2 Recommendations

The project research team offers the following recommendations:

1. The project objectives should be clarified as to the expectation of an optimal solution and its basis.
2. Early clarification of the nature and content of the envisioned catalog of actions is needed.
3. The project timing should consider the impact of the timing of data being available under the new AASHTO Manual for Bridge Element Inspection.
4. If a particular approach is envisioned, that approach should be defined in the project objectives and given structure in the task definitions.

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ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
BPP	Bridge Preservation Partnership
DOT	Department of Transportation
FHWA	Federal Highway Administration
MAP-21	Moving Ahead for Progress in the 21st Century Act
MBEI	Manual for Bridge Element Inspection
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
NCPP	National Center for Pavement Preservation
NHS	National Highway System
SCOBS	AASHTO Subcommittee on Bridges
SCOMS	AASHTO Subcommittee on Maintenance
TSP-2	AASHTO Transportation System Preservation Technical Services Program
USDOT	United States Department of Transportation

APPENDIX I Annotated Handbook Outline

The proposed content of the Handbook is shown on the following pages. Each section and subsection of Sections 4 through 6 is annotated in italics with a description of the expected coverage. Sections 1, 2, and 3 are not annotated since their fully developed and formatted content is provided in Appendix II to this Progress Report.

The Catalog of Actions in Handbook Appendix A is planned to have tables similar to the examples provided the developed Handbook Section 3 (see Appendix II of this Progress Report) and Handbook Appendix B (annotated in this Appendix I) is planned to contain worked examples of bridge level and network level analysis.

This Handbook follows the element and defect naming and numbering terminology of the AASHTO Manual for Bridge Element Inspection (AASHTO 2013).

Handbook Contents

1. Introduction
    1.1. Background, Objectives and Development Process
    1.2. How to Use the Handbook
2. Definitions and Descriptions
    2.1. Bridge Condition Assessment
        2.1.1. Bridge Components and Elements
        2.1.2. Condition State Systems
        2.1.3. Service Environment Definitions
    2.2. Preservation Action Descriptions
        2.2.1. General Categories
        2.2.2. Action Lists
    2.3. Preservation Decision Metrics
3. Orientation to the Catalog of Preservation Actions
4. Analytical Method for Prioritization of Actions

    This section presents the methodology for decision support among alternate preservation actions for elements, determining the impact on the element, determining costs, and compiling those actions for an individual bridge strategy.

    4.1. Methodology Background
    Sub-section includes a discussion of the need to target expenditures in a way that extends bridge life to a desired length of service at the lowest cost possible. The principles of life cycle costs are introduced. The public decision of making investments in bridges as essential infrastructure is considered. The roles of the real required rate of return and inflation are discussed. The need to project future element condition without preservation and compare to the condition impact of a preservation strategy is discussed in relation to MAP-21 expectations.

    4.2. Element Service Life
    Sub-section includes a discussion of factors influencing element condition deterioration. How preservation and maintenance actions extend service life in each condition state or may improve the condition state, either extending the service life of the element. The average condition state of an element is defined as one method of assessing overall element condition. Methods for assessing deterioration relationships are provided. Estimating element service life and projecting future condition from the current average condition state is explained. Examples related to service life and condition state projection are provided.

    4.3. Identifying and Selecting Preservation Actions
    Condition state triggers for preservation action are introduced. Triggers are based on a combination of the average condition state of the element and the percentage of the element in condition states 3 and 4. Possible actions are identified from the Catalog of actions along with the associated condition, extension of element life, and cost impacts for the service environment of the element. Action timing scenarios are entered into the analysis tool for determination of life-cycle costs.

    4.4. Calculation of Element Action Life-Cycle Costs
    This sub-section illustrates step-by-step procedures for calculating life-cycle costs of element actions for comparison. Expected impact on element condition is tracked. Simple examples are formulated and reference is made to more comprehensive examples located in Appendix B.

    4.5. Formulating the Bridge Strategy
    The strategy for an individual bridge is composed of the set of actions selected for its elements over the proposed 10-year planning horizon. Actions selected based on lowest life-cycle costs are normally the actions selected. However, provision is made for alternate selections where other

factors are significant in the choice or where information to evaluate life-cycle costs is judged inadequate. The costs for all elements considered are tabulated by year for the bridge and conditions are tracked without action and with action. The need to make allowance for non-covered elements and unexpected events is discussed. A step-by-step process is defined.

5. Analytical Method to Determine Appropriate Levels of Funding

   This section presents the methodology for determining the appropriate level of funding over the planning horizon for a group of bridges and assessing the impact of the actions on the group of bridges.

   5.1. Identifying Bridge Groups for Analysis
   Bridge groups representing a logical network are compiled. The network may be selected based on similar bridge element and design characteristics, condition state, geographic location or route carried, as examples.

   5.2. Tabulating Preservation Costs and Condition State Impact
   To determine the network group preservation costs for the long term least cost solution, the element action costs are tabulated for each year in the planning horizon. For each element, average condition states can be determined and tracked for the network group on the basis of without action and with action and compared. Agencies desiring to apply and track a health index can also input the element values to arrive at the index for either the individual bridges or the group of bridges.

   5.3. Fitting the Budget
   Budgets may or not be a constraint. When determination of the appropriate level of funding for network preservation is the objective, annual costs for preservation actions can simply be tabulated in each year of the planning horizon. When budgets are a constraint, the options are budget leveling if spikes are the issue, or eliminating some bridge or element actions which would be non-optimal but sometimes necessary.

   5.4. Impact of Budget Constraint on Condition
   When preservation budgets are a constraint, the conditions resulting from constrained preservation budgets can be compared to conditions resulting from unconstrained budgets.

6. Decision Support Tool Overview

   This section of the handbook will provide a brief introduction to the capabilities and use of the paired decision support tool. A full User's Guide will be provided as an appendix to the handbook, and may also be published separately as determined by project requirements.

   6.1. Integration with Handbook
   This section will discuss the integration and interdependencies between the published handbook and the decision support tool. In particular it will highlight fixed and user-customizable data elements in the Handbook that are used by the decision support tool.

   6.2. Data Requirements
   This section will touch on the data requirements for the decision support tool. The tool is expected to have modest bridge data requirements that can be fulfilled from widely available sources. Standard NBI information will be used for all bridge selection lists and other windows, along with standard AASHTO element inspection data that conforms to the AASHTO Manual for Bridge Element Inspection (AASHTO, 2013). These data can be downloaded from an AASHTO BrM 5.1.3 database (or later versions), or may be entered into the supporting database tables by an external process or direct entry.
   All typical preservation action and cost data used by the tool are assumed to conform to the specifications of this NCHRP/AASHTO Bridge Preservation Handbook.

   6.3. Loading Bridge Data
   This section will discuss the process of quantifying the decision support tool, including mechanisms/processes for downloading bridge and element inspection data, as well as importing actions and costs from the Handbook or other sources.

6.4. Modifying and Updating Data

This section will describe the basic data management capabilities of the decision support tool by providing examples of bridge and element data input and reporting screens.

6.5. Modifying Parameters

This section will describe the configuration of the decision support tool by providing examples of parameter input and reporting screens for the several planning and analysis functions.

6.6. Element-level Analysis

This section will present an overview of the element level analysis. While detailed element analysis examples will be included in the User's Guide, this section will introduce the analysis capabilities and provide examples of using the element level work planning and analysis functions

6.7. Bridge-level Analysis

Building on the previous element level analysis section, this section will present an overview of individual bridge level analysis. While full bridge level analysis examples including g development of preservation work plan alternatives will be included in the User's Guide, this section will introduce these analysis capabilities with example screens and reports demonstrating the bridge level work planning and analysis functions

6.8. Network-level Analysis

The introduction to the decision support tool will culminate in a brief example of development of a plan for a set of bridges or 'network' with example screens and reports.

6.9. Availability and distribution information

This section will provide the information on the software versioning, release dates, and download location or installation instructions. It should be noted that this information will only be correct as of the Handbook's publication date and may change over time. Consequently, a reference location (download site) for the latest version of the tool must be identified and included in this section.

Handbook Appendix A - Catalog of Actions

Appendix A is planned to be the entire Catalog of Actions for bridge preservation, organized by element types and number, then by defects, based on the agreed element numbering and defect types in the AASHTO Manual for Bridge Element Inspection.

1. Reinforced Concrete Decks, Slabs and Top Flanges [#12, 16, 38]
    - 1.1. Cracking
    - 1.2. Delamination/Spall/Patched Area
    - 1.3. Exposed Rebar
    - 1.4. Efflorescence/Rust Staining
2. Prestressed Concrete Decks and Top Flanges [#13, 15]
    - 2.1. Cracking
    - 2.2. Delamination/Spall/Patched Area
    - 2.3. Exposed Rebar
    - 2.4. Efflorescence/Rust Staining
3. Timber Deck and Slab [#31, 54]
    - 3.1. Cracking
    - 3.2. Shakes / Checks
    - 3.3. Splits/Delamination (Timber)
    - 3.4. Decay / Section Loss
4. Sealed Joints [#300, 301, 302, 303]
    - 4.1. Leakage
    - 4.2. Seal Adhesion
    - 4.3. Seal Damage & Seal Cracking
    - 4.4. Debris Impaction
    - 4.5. Adjacent Deck or Header
    - 4.6. Metal Deterioration or Damage
5. Open Joints [#304, 305]
    - 5.1. Debris Impaction
    - 5.2. Adjacent Deck or Header
6. Elastomeric Bearings [#310]
    - 6.1. Corrosion
    - 6.2. Connection
    - 6.3. Movement
    - 6.4. Alignment
    - 6.5. Bulging, Splitting or Tearing
7. Moveable and Fixed Bearings [#311, 313]
    - 7.1. Corrosion
    - 7.2. Connection
    - 7.3. Movement
    - 7.4. Alignment
8. Timber Superstructure [#111, 117, 146]

8.1. Connection
8.2. Decay / Section Loss
8.3. Shakes / Checks
8.4. Cracking
8.5. Splits/Delamination (Timber)

9. Reinforced Concrete Superstructure [#110, 116, 155]
   9.1. Delaminations / Spalls / Patched Areas
   9.2. Exposed Rebars
   9.3. Efflorescence / Rust Staining
   9.4. Cracking
10. Prestressed Concrete Superstructure [#109, 115, 154]
   10.1. Delaminations / Spalls / Patched Areas
   10.2. Exposed Rebars
   10.3. Exposed Prestressing
   10.4. Cracking
   10.5. Efflorescence / Rust Staining
11. Steel Superstructure [# 107, 113, 120, 152]
   11.1. Corrosion
   11.2. Cracking
   11.3. Connection
12. Timber Substructures [# 206, 216, 235]
   12.1. Connection
   12.2. Decay / Section Loss
   12.3. Shakes / Checks
   12.4. Cracking
   12.5. Splits/Delamination (Timber)
13. Reinforced Concrete Substructures [# 205, 234]
   13.1. Delaminations / Spalls / Patched Areas
   13.2. Exposed Rebars
   13.3. Efflorescence / Rust Staining
   13.4. Cracking
14. Prestressed Concrete Substructures [# 204, 233]
   14.1. Delaminations / Spalls / Patched Areas
   14.2. Exposed Rebars
   14.3. Exposed Prestressing
   14.4. Cracking
   14.5. Efflorescence / Rust Staining
15. Masonry Substructures [#217]
   15.1. Mortar Breakdown
   15.2. Split/Spall
   15.3. Patched Area

16. Steel Protective Coatings [# 515]
    16.1. Chalking
    16.2. Peeling / Bubbling / Cracking
    16.3. Oxide Film Degradation: Color / Texture Adherence
    16.4. Effectiveness
17. Wearing Surfaces [# 510]
    17.1. Delamination/Spall/Patched Area/Pothole
    17.2. Cracking
    17.3. Effectiveness

Handbook Appendix B – Worked Examples

Examples of a bridge level and network level analysis should be provided here as Handbook Appendix B for reference and to document the use of the handbook and behavior of the decision support tool.

1. Bridge Level

    Examples will include one new bridge and one bridge perhaps 25 years into its life with condition problems due to limited past preservation. The bridges would probably be bridges with painted steel girders and concrete decks. Since the new bridge would hopefully not see much deterioration within a 10-year planning horizon, the comparison between active preservation and a do-nothing approach would consider the role of bridge washing, use of deck sealers, and early or new bridge overlays for the service environment of the bridge. the impacts would be derived from extension of life in condition state. The aged bridge possible actions would consider the needs of more elements, perhaps adding in joints and bearings for example, and in some cases improvement in condition state within the planning horizon would occur as well extension in condition state.

2. Network Level

    Actions for a group of selected bridges are tabulated over the planning horizon. The annual costs and impacts on element condition state are tracked. Condition comparisons can be made to the do-nothing alternative for the group of bridges. Discussion is provided of the possible need to adjust the plan by eliminating bridges from the group due to budget constraint and adjusting year of action for common contract letting of certain actions.

Handbook Appendix C – Decision Support tool Users Guide

The entire user's guide for the decision support tool is planned to be provided in Handbook Appendix C. This section may be integral or published separately as appropriate.

APPENDIX II Handbook Sections 1, 2 and 3

The proposed example content of the Handbook Sections 1, 2, and 3 is shown as a separate attachment formatted in the AASHTO style. Example title pages and table of contents are not provided at this time.

APPENDIX III: Sample Catalog of Bridge Preservation Actions, Impacts, and Metrics

This appendix contains tables displaying the catalog of actions, their resulting impacts and metrics that measure those impacts. The tables are organized for inclusion in Appendix E of the Handbook formatted in groups of three, for example, Tables E-1.1a, E-1.1b, and E-1.1c for the catalog of actions, impacts, and metrics respectively. The line numbers in the tables match in each set of three tables and each line number correspond to a single preservation action.