Spring 2018

New Model for Bridge Management System (BMS): Bridge Repair Priority Ranking System (BRPRS), Case Based Reasoning for Bridge Deterioration, Cost Optimization, and Preservation Strategy

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Recommended Citation

Yari, Nasser, "New Model for Bridge Management System (BMS): Bridge Repair Priority Ranking System (BRPRS), Case Based Reasoning for Bridge Deterioration, Cost Optimization, and Preservation Strategy" (2018). *Doctoral Dissertations*. 2392.
https://scholars.unh.edu/dissertation/2392

New Model for Bridge Management System (BMS): Bridge Repair Priority Ranking System (BRPRS), Case Based Reasoning for Bridge Deterioration, Cost Optimization, and Preservation Strategy.

BY

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DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Philosophy
in
Civil Engineering

May 2018

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ABSTRACT

New Model for Bridge Management System (BMS): Bridge Repair Priority Ranking System (BRPRS), Case Based Reasoning for Bridge Deterioration, Cost Optimization, and Preservation Strategy.

Nasser Yari, P.E.

University of New Hampshire May 2018

Most public transportation agencies (Such as, state department of transportations (DOTs) and department of public works for cities and towns.) in the United States are constantly pursuing ways to improve bridge asset management to optimize their use of limited available funds for rehabilitation, replacement, and preventive maintenance. Given the realities of available funding, there is a significant difference between available funds and funds required for maintaining bridges in good condition. The proper preventative maintenance and treatments should be performed at the right time to be cost effective and extend the life of bridges. Neglecting maintenance can cause higher future costs and further deteriorate the conditions that will increase the risk of bridge closure. This would require complete or partial replacement as well as additional funds needed for detours and traffic control which interrupts services to the motorist and creates more congestion. Development and implementation of a Bridge Management System (BMS) provide states and municipalities with a tool to help identify maintenance

repair, prioritize bridge rehabilitation and replacement, develop preservation strategies, and allocate available funds accordingly.

The primary objective of this research is to develop a Bridge Management System (BMS) to manage municipal and state bridge assets. Complete, accurate data in well-designed form is vital to a Bridge Management System (BMS). This system will make available work reports, engineering drawings, photographs, and a forecasting model for management staff use. Inventory and condition data are extracted from the U.S. Federal Highway Administration (FHWA) and National Bridge Inventory System (NBIS) coding guidelines. The proposed model provides: (1) A priority ranking system for Rehabilitation and Replacement projects, which enables the decision-makers to understand and compare the overall state of all the bridges in the network. It embraces seven factors condition, criticality, risk, functionally, bridge type, age, and size. (2) A deterioration model that uses optimized case-based reasoning (CBR) method. A similarity measure of classification is developed to identify how close the characteristics of bridge components are to each other based on a scoring system. (3) A cost model that considers different repair strategies and provide bridge repair recommendations with estimated cost repairs. (4)The model feeds data to a forecasting program that prepares 120-year preservation, maintenance, repair and rehabilitation budgets and schedules to sustain a bridge network at the highest performance level under approved budgets. The forecasting option contains default management costs that are upgraded as work report data yields costs based on locality and individual bridge projects. BMS will give accessibility through linkages to all available municipal, and DOT, bridge data in the state. The data will be available through ArcGIS on tablets, laptops, and smartphones with access to cloud storage.

Acknowledgements

I would like to express my sincere appreciation and gratitude to my advisor, Dr. Charlie Goodspeed for his invaluable guidance, patience, kindness, and encouragement throughout the course of my PhD program. It has been a great honor and privilege to work with him and learn from his experience.

I would also like to acknowledge the significant input given by Dr. Ricardo Medina, Dr. Majid Ghayoomi, Dr. Eshan V. Dave and Dr. David Gress towards completing this research. I greatly appreciate their advice and support.

In addition, I would like to acknowledge and thank all the students and colleagues in the UNH Civil and Environmental Engineering Department who provided moral support.

Last but not least, I wish to express my very special gratitude to my wife and my two daughters for their continuous support, understanding, encouragement and never-ending love throughout my Ph.D. study.

Chapter 1 Introduction

1.1 General

There are approximately 607,000 public bridges in the United States with an average age of 42 years; some of these bridges have exceeded their expected lifespan of 50 years (FHWA, 2011). In total, about 11% of these bridges are rated as structurally deficient. Per Federal Highway Administration (FHWA), to eliminate the structurally deficient bridges by 2028, an investment of approximately $20.5 billion annually would be required. However, the existing annual funding is currently in the order of $12.8 billion.

Aging bridges are a major concern with a huge impact on our national economy. A significant percentage of the existing infrastructure assets are deteriorating due to age, severe environmental conditions, increasing traffic volume and insufficient capacity (Bordogna, 1995). The desired level of performance of the nation’s bridge infrastructure is vital to the social development and the economic growth of today (Abu Dabous, 2008).

The success and advancement of our society is influenced by the transportation infrastructure as it provides vital transportation services to the public to sustain the nation’s standard of living. The wellbeing of this infrastructure has direct effects on the nation’s economy, social system and quality of life. Aging transportation infrastructures are deteriorating due to overuse, lack of maintenance, misuse, and mismanagement which has made it more vulnerable to natural disasters (Uddin, et al., 2013)

Significant portions of the $1.75 trillion transportation infrastructure budget are deteriorating due to increased traffic volume, environmental impacts, and aging. The costs of Maintenance, Rehabilitation, and Replacement (MR&R) have increased dramatically in recent years. At this rate State DOTs and municipalities are faced with increased budget needs. Many states and municipalities are partnering with private industries to further the knowledge and practice of asset management (FHWA, 2007).

The bridge is defined according to The National Bridge Inspection Standards published in the Code of Federal Regulations (23 CFR 650.3) as:

> *Bridge: structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening(FHWA. 1995. Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges).*

Figure 1.2 illustrates the age distribution of NHDOT bridges. About 95% of NHDOT bridges in New Hampshire require some type of maintenance or rehabilitation. New bridges could use some type of proper preventive maintenance to extend their service life. Figure 1.3 illustrates the nation's bridge age distribution and the number of bridges that are either structurally deficient or functionally obsolete which increases in correlation with their age, and thus the maintenance and rehabilitation needs increase as well (Johnson, 2012).

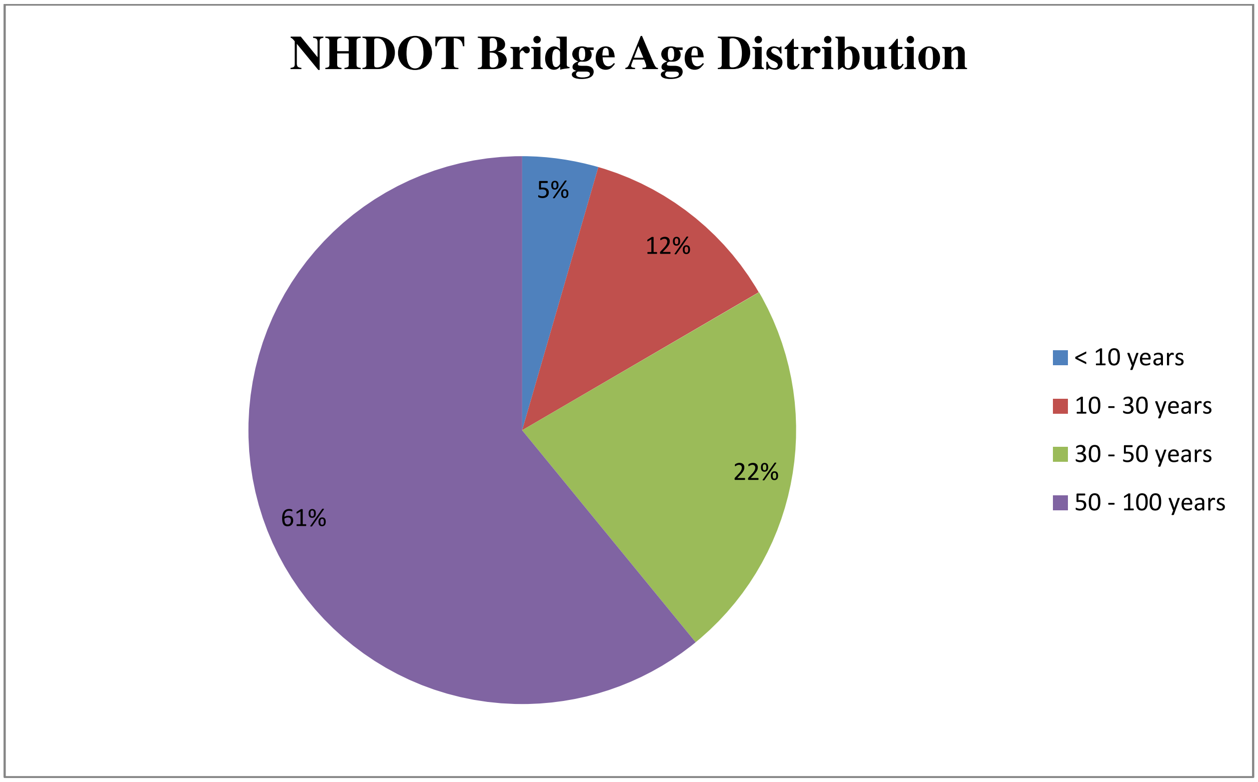


Figure 1.2: NHDOT Bridge Age Distribution

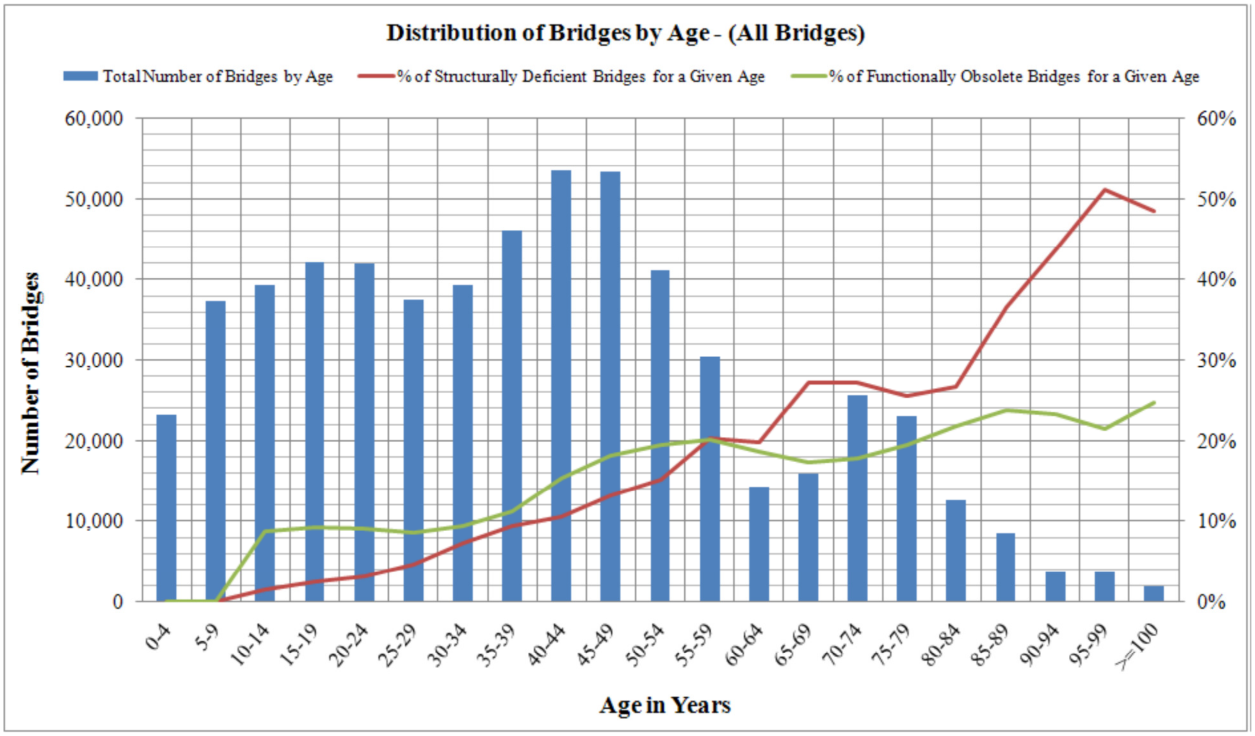


Figure 1.3: US Bridge Age Distribution (FHWA, 2010)

1.2 Problem Statement

More than 70% of in-service United States bridges were built before 1935. These bridges are deteriorating and are in need of MR&R which is being restricted by limited funding (Abudayyeh et al., 2004). There is a significant difference between funds needed and funds available to maintain the nation's bridges in good condition. The lack of adequate funds to maintain aging bridges in good conditions has prompted bridge owners to continually pursue ways and procedures to maintain theses bridge in good condition and determine which bridges to fix first, when to fix them and what type of treatment is more cost effective. A Bridge

Management System (BMS) can effectively extend the useful life of bridges and will help transportation agencies develop financial plans to identify how much funding they require to sustain their desired level of service. BMS can justify funding for bridge preventive maintenance, rehabilitation and replacement programs, and can help the public and politicians understand where their tax dollars are being spent.

There is a significant demand for more effective Bridge Management Systems (BMS) that can provide efficient and effective maintenance and preservation strategies. A Web-GIS BMS that can link data collection to decision making and can provide on-line information using a laptop, IPad or smartphone. The majority of State DOTs use BrM (Pontis) software for BMS. This software is primarily used for bridge inspection, providing an inspection form and storing the coding guide items. Most states DOT agencies have implemented a Bridge Management System (BMS), the level of implementation is varied among each state, however, the overall input from BMSs to network-level decisions making remains minimal (Basak, 2011). About 80% of the structurally deficient bridges are in rural areas and most are small with low traffic (Kirk, 2016). The majority of local transportation agencies have insufficient specialized technical bridge expertise with no BMS program in place. They are facing the need for increased Maintenance, Rehabilitation, and Replacement (MR&R) with very limited funding.

A BMS that meets managers and decision maker's requirements provides real time information and bridge expertise is a significant tool that should improve this practice.

1.3 Research Methodology

The goal of this research is to develop comprehensive BMS components that are capable of linking data collection to decision making by providing a tool for the decision maker to manage municipal and state bridges. This will provide them with information and data analysis capabilities for maintenance management and budget planning.

The main objectives of this research project are:

1. Conduct a literature review on existing BMS models. Review available deterioration models, priority ranking systems and cost models.

2. Develop a forecasting model including deterioration and cost models to provide improvement strategies to manage bridge sustainability and prepare maintenance budgets.
3. Develop an algorithm to determine a Bridge Repair Priority Ranking System (BRPRS). This is to rank bridges for MR&R and preservation.

4. Develop framework to provide a 120-year Bridge Preservation Strategy for each bridge in the network. This can extend the service life of all bridges, independent of current condition.

1.4 Thesis Outline

Chapter 2 literature review

This chapter presents a comprehensive review of current and most recently adopted methods in managing bridges in developing countries. The major components of any bridge management system (BMS) include inventory data, condition assessment, deterioration model, cost model and priority ranking. The evaluation of these components with their limitation, weaknesses and improvements are reviewed.

Chapter 3 Web GIS-based Bridge Database

This chapter discusses a framework linking Bridge Management System (BMS) to GIS visualization module by developing a map-based visualization interface. The visualization module displays selected relevant information about the bridge such as bridge identification the geospatial location, structure classification, roadway classification, the average daily traffic, the age of bridge, and the condition rating for the deck, superstructure and substructure.

Chapter 4 Bridge Repair Priority Ranking System (BRPRS)

This chapter presents the development of a priority ranking system for MR&R activities. Traditionally, Maintenance, Rehabilitation and Replacement (MR&R) projects are selected based on worst first. However, with BRPRS, the bridge engineers or bridge owners may specify the selection and prioritization process based upon their bridge requirements such as condition, detour length, traffic volume, scour critical, emergency vehicle route, age, and other criteria within recommended limits.

Chapter 5 Forecasting Model

This chapter includes three modules: The first module is the development of a deterioration model based on artificial intelligence (AI) techniques using a case-based reasoning (CBR) method. The second module is the development of a MR&R cost model based on current and predicted future conditions and evaluating repair alternatives including the cost estimate and scheduling. The third module is preparing the 120 year preservation strategy for each bridge in the network.

Chapter 6 Conclusion

This chapter summarizes the research work, contribution and recommendations for future study.

Chapter 2: Literature Review

2.1 Introduction

In the past few decades, federal and some state agencies have developed a Bridge Management System (BMS). Numerous studies worldwide have been conducted to develop more effective BMS applications that can link data collection to decision making.

Public transportation agency officials at all Federal, State, and Municipality levels understand that the public will hold them accountable for infrastructure investment decisions. In the span of ten years from 1997 to 2007, $1.75 trillion was invested in new construction, Maintenance, Rehabilitation, and Replacement (MR&R) of existing transportation networks (FHWA, 2007). Governmental Accounting Standards Board (GASB) Statement No. 34 is aimed to increase accountability for State and Local Governments and encourage the implementation of infrastructure asset management (Dornan, 2002).

The Federal-aid Highway Act of 1976 was intended to ensure safety on the Nation’s highway infrastructure. However, prior to 1976 most federal funds were used for new construction, where the MR&R activities were minimal and neglected; subsequently, the aging transportation system is deteriorated which requires effective BMS to clear the MR&R backlog (Basak, 2011).

Recent bridge management systems have been developed using the guidelines of infrastructure asset management methods (Tariq, 2009). Infrastructure asset management is a collective strategy for decision making to sustain assets at desired levels of service by prioritizing the maintenance, rehabilitation and replacement as needed (Aktan et al., 1996).

The purpose of this chapter is to provide an overview of previous and current research on bridge management systems and review the decision making process and forecasting methods. This research uses today's technology such as geographic information systems (GIS), wireless communication, cloud storage, data accessibility through the web, instant updating, which will advance BMS to the next level.

2.2 Bridge Inventory Data

(1) Inventory Items

Bridge data collection is the key aspect for a Bridge Management System; it will provide essential information to help improve safety, accountability for decision making, extend the service life of bridges, and reduce bridge failure. In 1968 the

Federal-Aid Highway Act formed a program for a state department of transportations to begin collecting inventory data on federal-aid highway bridges (Basak, 2011). The National Bridge Inventory (NBI) is the aggregation of structure inventory and appraisal data which was initially developed in 1971 to observer bridge operations and safety. The NBI inventory data consisting of 116 items provides information for each bridge, these items are specified in the Recording and Coding Guide for the structure inventory and appraisal of the Nation's Bridges (FHWA-PD-96-001). This information must be updated by state DOTs and submitted to the FHWA on an annual basis. Table 2-1 shows the list of the coding guide items (FHWA, 1995). The quality and performance of any bridge management system are heavily dependent on the database storage and its performance (Atzeni et al., 1999).

As of part of this research in addition to NBI inventory data a Local Factor data has been integrated to provide complete information for decision making. Local factor data is an important element in network level bridge management. These factors which are not included in the NBI database are as follows:

1. Year the bridge was last paved.
2. Type of utility supported by the bridge.
3. Bridge rail type and if meets toady's standard
4. In case of bridge closure, the impact on local economic, environmental and societal concerns
5. School bus route
6. Emergency vehicle route

7. Mobility
8. Year deck rating of NBI 6
9. Toll Plaza Bridge (bridge closure would affect toll revenue).

Table 2-1 NBI Coding Guide Items (FHWA, 1995)

NBI Coding Items									
1	State Code	25	Reserved	49	Structure Length	73	Reserved	97	Year of Improvement Cost Estimate
2	Highway Agency District	26	Functional Classification of Inventory Route	50	Curb or Sidewalk Widths	74	Reserved	98	Border Bridge
3	County (Parish) Code	27	Year Built	51	Bridge Roadway Width, Curb-to-Curb	75	Type of Work	99	Border Bridge Structure Number
4	Place Code	28	Lanes On and Under the Structure	52	Deck Width, Out-to-Out	76	Length of Structure Improvement	100	STRAHNET Highway Designation
5	Inventory Route	29	Average Daily Traffic	53	Minimum Vertical Clearance Over Bridge Roadway	77	Reserved	101	Parallel Structure Designation
6	Features Intersected	30	Year of Average Daily Traffic	54	Minimum Vertical Underclearance	78	Reserved	102	Direction of Traffic
7	Facility Carried by Structure	31	Design Load	55	Minimum Lateral Underclearance on Right	79	Reserved	103	Temporary Structure Designation
8	Structure Number	32	Approach Roadway Width	56	Minimum Lateral Underclearance on Left	80	Reserved	104	Highway System of the Inventory Route
9	Location	33	Bridge Median	57	Reserved	81	Reserved	105	Federal Lands Highways
10	Inventory Route, Minimum Vertical Clearance	34	Skew	58	Deck	82	Reserved	106	Year Reconstructed
11	Kilometer Point	35	Structure Flared	59	Superstructure	83	Reserved	107	Deck Structure Type
12	Base Highway Network	36	Traffic Safety Features	60	Substructure	84	Reserved	108	Wearing Surface/Protective System
13	LRS Inventory Route, Sub-Route Number	37	Historical Significance	61	Channel and Channel Protection	85	Reserved	109	Average Daily Truck Traffic
14	Reserved	38	Navigation Control	62	Culverts	86	Reserved	110	Designated National Network
15	Reserved	39	Navigation Vertical Clearance	63	Method Used to Determine Operating Rating	87	Reserved	111	Pier or Abutment Protection (for Navigation)
16	Latitude	40	Navigation Horizontal Clearance	64	Operating Rating	88	Reserved	112	NBIS Bridge Length
17	Longitude	41	Structure Open, Posted, or Closed to Traffic	65	Method Used to Determine Inventory Rating	89	Reserved	113	Scour Critical Bridges
18	Reserved	42	Type of Service	66	Inventory Rating	90	Inspection Date	114	Future Average Daily Traffic
19	Bypass, Detour Length	43	Structure Type, Main	67	Structural Evaluation	91	Designated Inspection Frequency	115	Year of Future Average Daily Traffic
20	Toll	44	Structure Type, Approach Spans	68	Deck Geometry	92	Critical Feature Inspection	116	Minimum Navigation Vertical Clearance
21	Maintenance Responsibility	45	Number of Spans in Main Unit	69	Underclearances, Vertical and Horizontal	93	Critical Feature Inspection Date		
22	Owner	46	Number of Approach Spans	70	Bridge Posting	94	Bridge Improvement Cost		
23	Reserved	47	Inventory Route, Total Horizontal Clearance	71	Waterway Adequacy	95	Roadway Improvement Cost		
24	Reserved	48	Length of Maximum Span	72	Approach Roadway Alignment	96	Total Project Cost		

(2) Bridge Inspection Process

At the height of bridge construction from the 1950s to 1960s, bridge inspection and bridge maintenance were almost nonexistent. The National Bridge Inspection Standards (NBIS) were established in 1971 to require that all bridge inspection processes, frequency of inspections, qualification of the bridge inspectors, bridge inspection report and the maintenance of bridge inventory meet the National Bridge Inspection Standards (Rossow, 2012). All bridges longer than 20 feet (6.1 meters) must be inspected per (NBIS; 23 CFR 650 subpart C) and reported by the states and federal agencies to the Federal Highway Administration. The sudden collapse of the I-35W Interstate Bridge (Mississippi River bridge) in Minneapolis on August 2007 created a major concern on the existing condition of United States bridges and its policy to help state DOT's to address structurally deficient bridges (Kirk et al., 2007). This initiated the investigation by the Office of Inspector General (OIG) to assess the FHWA's management of bridge safety and oversight of the bridge program (Basak, 2011). Based on the NBI database bridge inspections, it is evident that high percentages (more than 1/3) of the bridges in the United States are in poor condition, structurally deficient and functionally obsolete (Parsons, 1992). The FHWA requires all bridge inspectors to be certified and has developed a three-week comprehensive training program on bridge inspection, based on the Bridge Inspector's Reference Manual (BIRM), which includes a three day course refresher of the National Bridge Inspection Standards (NBIS), one week course, “Engineering Concepts for Bridge Inspectors,” , two weeks “Bridge Inspector’s Training Course, Part II - Safety Inspection of In-Service Bridges” and three weeks “Fracture Critical Inspection Techniques for Steel Bridges” (Ryan et al., 2006).

(3) Condition Assessment

The accuracy of condition assessment is a very important element to any BMS and it all depends on the quality of the inspection (Maria et al., 2011). Bridge condition represents the physical condition of individual bridge elements and the overall condition of bridge components such as deck, superstructure, and substructure (Ahlborn, 2010).

Most state DOTs collect bridge condition data on a two -year cycle. The conditions are measured visually or by using instruments based on the guidelines and standards established by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) Guide for Commonly Recognized (CoRe) Structural Elements (Ryan et al., 2006).

NBI condition ratings for various bridge components are designed based on the NBI guidelines and are listed in Appendix A. The AASHTO Guide for Commonly Recognized (CoRe) Structural Elements is an alternative to NBI condition rating. The AASHTO rating should be converted to NBI rating using FHWA’s computer program translator. The FHWA National Bridge Elements (NBEs) are intended to provide consistency countrywide to standardize element condition.

Table 2-2 General NBI Condition Rating (FHWA 1995)

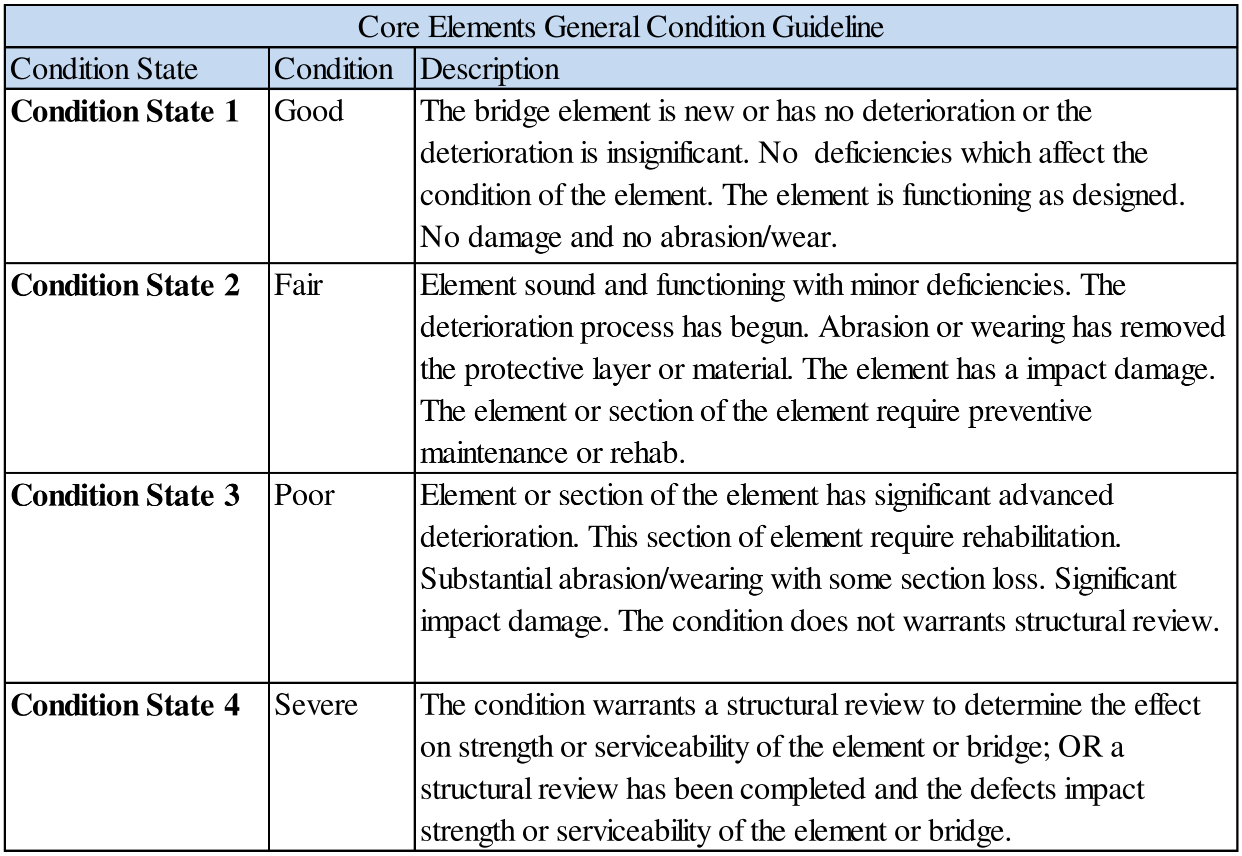
Code	Condition	Description of Condition
N	Use for all culverts	
9	**Excellent Condition**	
8	**Very Good Condition**	No problems noted
7	**Good Condition**	Some minor problems
6	**Satisfactory Condition**	Structural elements show some minor deterioration
5	**Fair Condition**	All primary structural elements are sound but may have minor section loss, cracking, spalling or scour
4	**Poor Condition**	Advanced section loss, deterioration, spalling or scour
3	**Serious Condition**	Loss of section, deterioration, spalling or scour have seriously affected primary structural components Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present
2	**Critical Condition**	Advanced deterioration of primary structural elements. Fatigue cracks in steel 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
1	**Immenent 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.
0	**Failed Condition**	out of service - beyond corrective action

The advantage of this system is it uses a standardized description of bridge elements at a greater level of detail. The NBI rating is only for the overall condition of deck, superstructure, substructure, and culvert, whereas CoRe Elements provides detailed condition data on all bridge component elements. For example, the NBI condition rating for a deck includes multiple distress condition which describes the “general” condition of the bridge. The challenge with this is how to decide what the “general” condition is when the deck has only localized problems.

CoRe Elements are subdivided into Sub-Elements to provide more and better information on performance, maintenance cost, and physical condition. The core element condition data is adopted by Pontis for bridge inspection (Thompson and Shepard, 2000). The condition descriptions consider material composition, the severity of the element, and its extent. AASHTO Commonly Recognized Elements (CoRe) are used by bridge owners nationwide to evaluate structural bridge components (PUB 590, 2006).

Most State Departments of Transportation including NHDOT use the Pontis software application to collect and store condition data for each bridge's component elements.

Table 2-3 Core Elements General Condition Guideline (AASHTO, 2010)



Core Elements General Condition Guideline		
Condition State	Condition	Description
Condition State 1	Good	The bridge element is new or has no deterioration or the deterioration is insignificant. No deficiencies which affect the condition of the element. The element is functioning as designed. No damage and no abrasion/wear.
Condition State 2	Fair	Element sound and functioning with minor deficiencies. The deterioration process has begun. Abrasion or wearing has removed the protective layer or material. The element has a impact damage. The element or section of the element require preventive maintenance or rehab.
Condition State 3	Poor	Element or section of the element has significant advanced deterioration. This section of element require rehabilitation. Substantial abrasion/wearing with some section loss. Significant impact damage. The condition does not warrants structural review.
Condition State 4	Severe	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.

Bridge inspection is based on element condition assessments performed by trained DOT bridge inspectors. Structural elements are load carrying items in highway bridges and in bridge maintenance. Over the years, improvements have been made to obtain clear, accurate, and complete element conditions within defined condition states. The condition state for each element deterioration and the defect is measured quantitatively as a percentage of the total quantity of the element in each condition state. Table 2-3 represents the general condition state guideline. For example, element 14 (Concrete Deck with Membrane and Bituminous Overlay) may have 5% in condition state 1(good), 75% in condition state 2(fair), 20% in condition state 3(poor) and 0% in condition state 4 severe (Ryan et al. 2006).

List of element defects is shown in Appendix D.

The bridge elements are divided into the following sections: Deck Elements (element 1 to 99), superstructure Elements (element 100 to 199), substructure and culvert Elements (element 200 to 299), miscellaneous Elements (element 300 to 599), and defects (element 1000 to 7000) (MDOT, 2015).

For example, element #12 Reinforced Concrete Deck is shown in Table 2-4.

1Element # 12 – Reinforced Concrete Deck

Definition: This element defines all reinforced concrete bridge decks and slabs regardless of wearing surface or protection systems used.

Unit of Measurement: Square Feet

Quantity Calculation: The quantity for this element includes the area of the deck from edge to edge, including any median areas and accounting for any flares or ramps present.

Table 2-4 Condition State Definitions Element # 12 – Reinforced Concrete Deck (Iowa DOT, 2014)

Element # 12 Reinforced Concrete Deck				
Defects	Condition State 1	Condition State 2	Condition State 3	Condition State 4
	GOOD	FAIR	POOR	SEVERE
Delamination/Spall /Patched Area (1080)	None	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.	Spalling is greater than 1” deep or greater than 6” in diameter. Patched areas are unsound or showing distress but do not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge: OR a structural review has been completes and the defects impact strength or serviceability or the element or bridge.
Exposed Rebar (1090)	None	Present without measurable section loss.	Present with measurable section loss, but does not warrant structural review	
Efflorescence/Rust Staining (1120)	None	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining	
Cracking (RC and Other) (1130)	Insignificant cracks or moderate-width cracks that have been sealed	Unsealed moderate width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Abrasion/Wear (PSC/RC) (1190)	No abrasion or wearing	Abrasion or wearing has exposed course aggregate but the aggregate remains secure in the concrete	Course aggregate is loose or has popped out of concrete matrix due to abrasion or wear.	
Damage (7000)	Not applicable	The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.

Bridges normally can be divided into three major components, deck, superstructure and substructure as shown in Figure 2-1 (Ryan et al. 2006) and Figure 2-2.

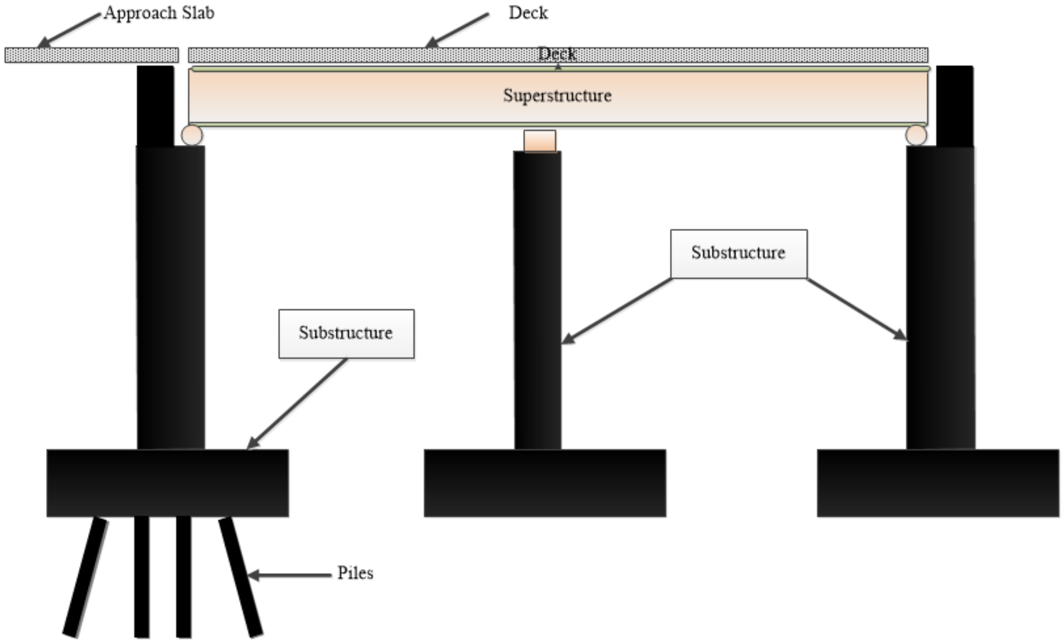


Figure 2-1 Bridge Components

Figure 2-2 illustrates the most commonly used bridge components in the United States. For instance, a bridge deck can be subdivided into concrete, timber, or steel deck. Deck joints and bridge rails or barriers are also part of the bridge deck. The individual type of deck can be further refined into different materials and method of construction. This information is vital for developing a work report and maintenance repairs, as outlined in Chapter 5

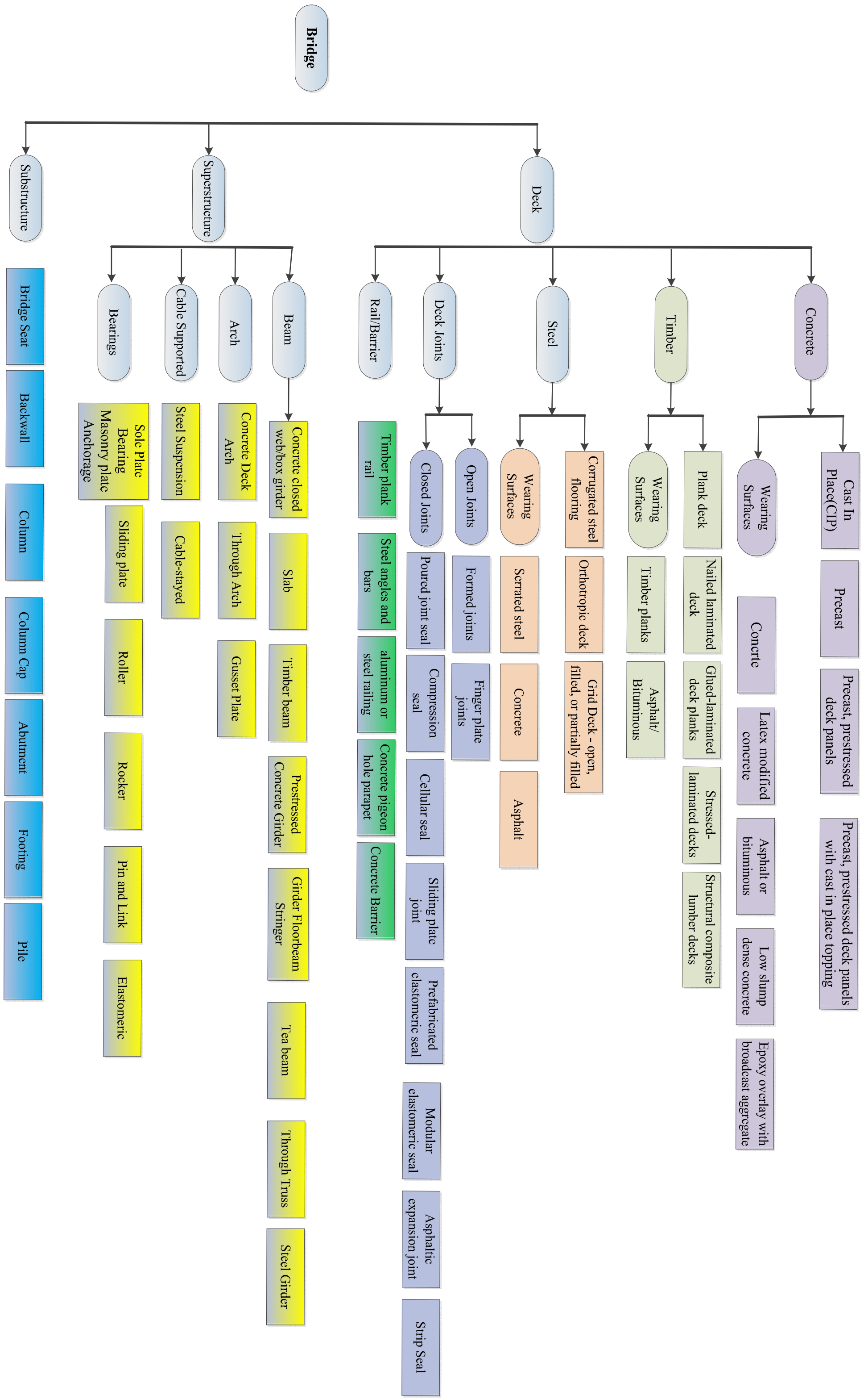


Figure 2-2 Bridge Components

2.3 Bridge Asset Management

Throughout the last thirty years, an increasing effort has been applied in asset management (Arne et al, 2003). Prior to 1980 bridge management systems were almost nonexistent. In 1980, AASHTO developed a *Guide for Bridge Maintenance Management* and later, in 1987, AASHTO developed a *Manual for Bridge Maintenance.* The aforementioned were used by some state DOT's to manage MR&R operations. In 1990 The First International Conference on Bridge Management System emphasized the deteriorating conditions of the existing bridges in developing countries and expressed major concerns on the safety of the aging bridges worldwide (Tariq, 2009). In 1995 The Intermodal Surface Transportation Efficiency Act (Public Law 102-240; ISTEA) regulation required all state DOTs to develop and implement a Bridge Management System ((Liu, 2010). Figure 2-3 shows the history of BMS prior to 1995. (Liu, 2010). An extensive amount of research has been conducted in developing a bridge management system to ensure that bridges are designed and constructed more cost effectively and extending their useful life at the lowest cost possible (Harding et al.,1996).

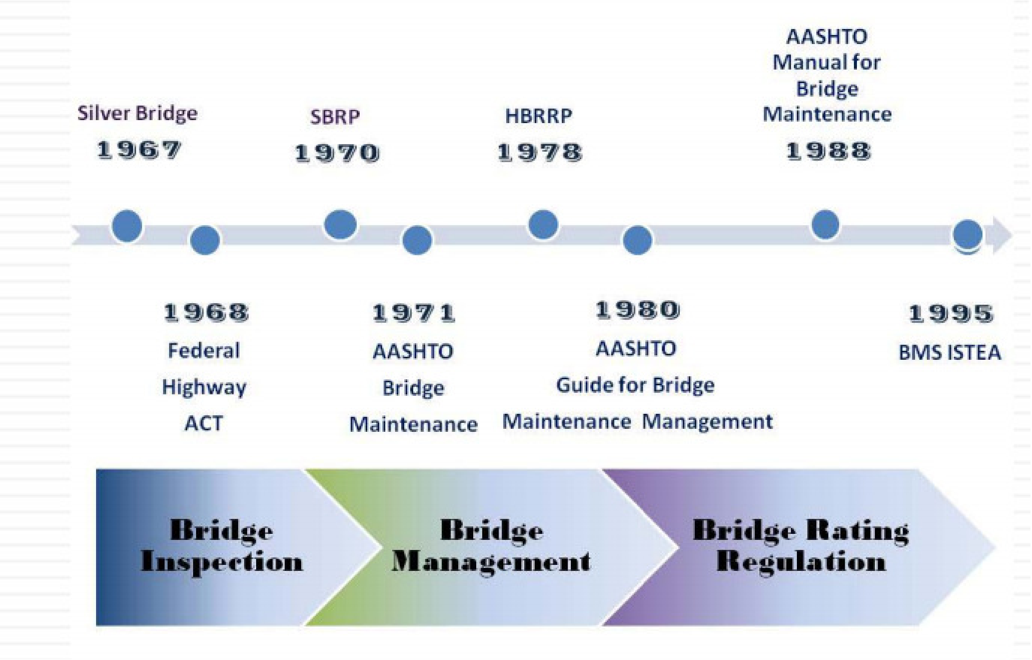


Figure2-3 History of bridge management system prior to 1995 (Liu, 2010)

Many studies worldwide have been conducted involving BMS, defining BMS and the needs to implement an effective BMS have been emphasized by the following selected authors:

BMS is the process of decision making to manage bridges from their birth including planning, designing, construction and, maintenance to extend the life of bridges that are vital to public transportation systems (Hudson et al. 1987).

A Bridge Management System can be described as a well-thought-out strategy for making the decision on bridge maintenance, rehabilitation and replacement in a most efficient way (James et al., 1991)

The goal of Bridge Management System is to identify and apply the best possible comprehensive methods that produce an acceptable level of safety at the lowest possible life-cycle cost (Frangopol et al.,2000).

BMS are resources for managing bridge data to support decision making that guarantees long-term well-being and managing the maintenance, rehabilitation and replacement with limited funding (Youngxin, 2006)

Due to limited funding and budgetary constraints to maintain the existing bridges at a desired level of service, most bridge owners have implemented existing BMSs or developed one based on their need (Yianni, 2017). A successful BMS can provide bridge owners with a tool to help meet their goal of maximizing the useful life of bridges at a lower cost. AASHTO Guidelines for Bridge Management System outlines the components as shown in Figure 2-4.

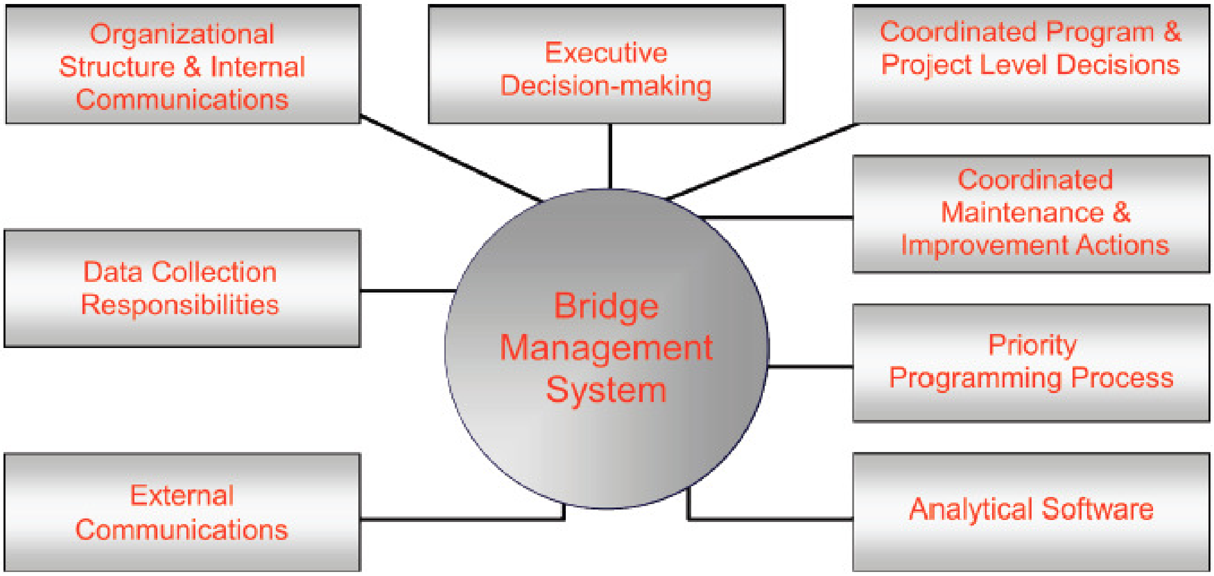


Figure 2-4 BMS Framework (AASHTO Guidelines for Bridge Management System, NCHRP Report 20-7, Task 46)

Based on AASHTO (1993) Guidelines for Bridge Management Systems the major components of BMS are 1. Database, 2. Maintenance cost estimate, 3. Deterioration and 4. Decision making and optimization.

1. The database is the foundation for BMS containing bridge identification, location, description, condition assessments, historical data and maintenance records. The up to date condition data is collected from bridge agencies.

2. A deterioration model is used to predict the deterioration rate and the future condition of bridge elements under different environmental conditions and

the extent of maintenance and repair. The most common deterioration models predict the future conditions using a deterministic or probabilistic method. Deterministic models forecast the future asset conditions by fitting a straight-line or a curve (Sanders et al., 1994) based on a relationship between the bridge age and the related conditions. Regression analysis is widely used for deterministic models. Probabilistic models use a random variable and the Markov based model to calculate the deterioration rate (Bryant, 2014).

3. The estimated cost of MR&R alternatives is provided by bridge agencies to prepare budget plans.
4. Decision making and optimization modules analyze the available data such as deterioration rate combined with the estimated cost and effectiveness information for various strategies to prepare optimal MR&R alternatives for bridge components. The optimization process normally consists of "top-down" and "bottom-up" methods (Small et al., 1999). The top-down method is where all the directions come from the top by established goals for the entire bridge network and apply to selected individual bridges. The bottom-up method allows upper management the opportunity to communicate with individual team members regarding the goals for each bridge to achieve optimal maintenance for the network.

2.4 Current BMS Software

The need for effective bridge management system prompted FHWA through the National Cooperative Highway Research Program (NCHRP) to initiate a research project on multi-objective optimization for bridge management systems (Jaeho, 2007). The NCHRP Report 300 (Performance measures for research, development, and technology program) paved the way for the development of modern BMS software, linking performance measures to the strategic goals of the transportation agencies and identifying the major components of BMS (NCHRP Report 300).

The 2009 report by the Office of Inspector General (OIG) of the U. S. Department of Transportation (DOT) accepted FHWA's recommendation to promote State use of a bridge management system (BMS) and provide training and technical assistance accordingly (FHWA 2010). On the network level, a BMS handles large amounts of data, requiring most bridge owners to use sophisticated computerized management systems to support their decision making (Mirzaei et al., 2012).

There are currently numerous BMSs packages in service around the world to address the significant cost of maintaining transportation networks and prevent the consequences of failure. These BMSs are developed by the national or regional bridge owners or by outside consultants (Yianni, 2017). The 2014 International Association for Bridge Maintenance and Safety – IABMAS report compiled a list of countries using BMS software versus the first version as shown in table 2-5 and compared the number of BMSs in their first version to those which have been updated as shown in figure 2-5 (Mirzaei et al., 2014).

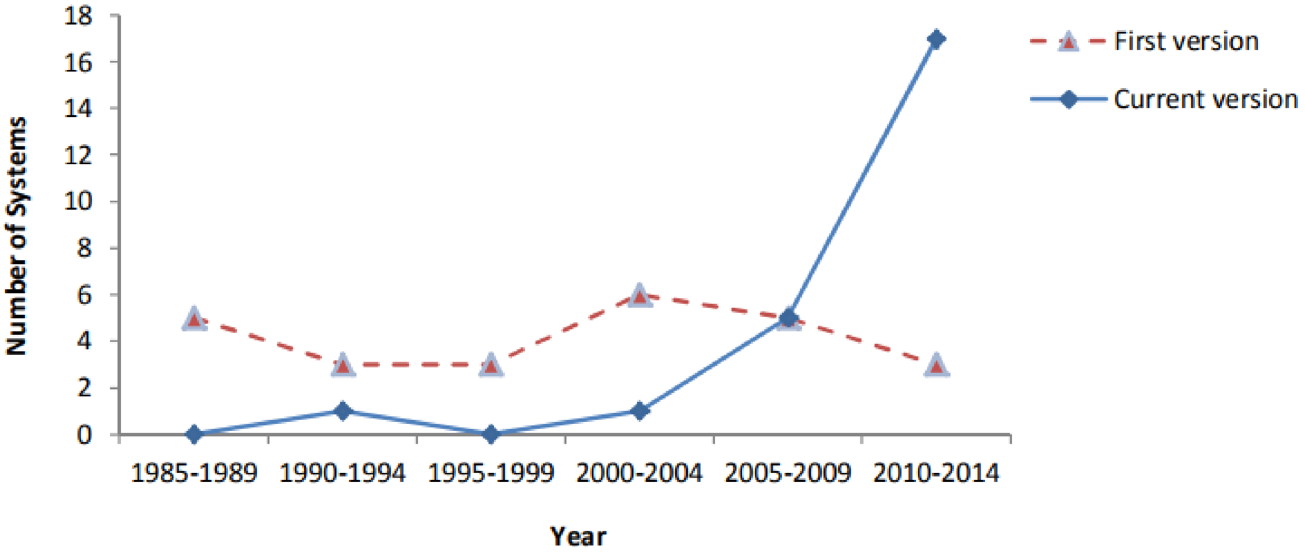
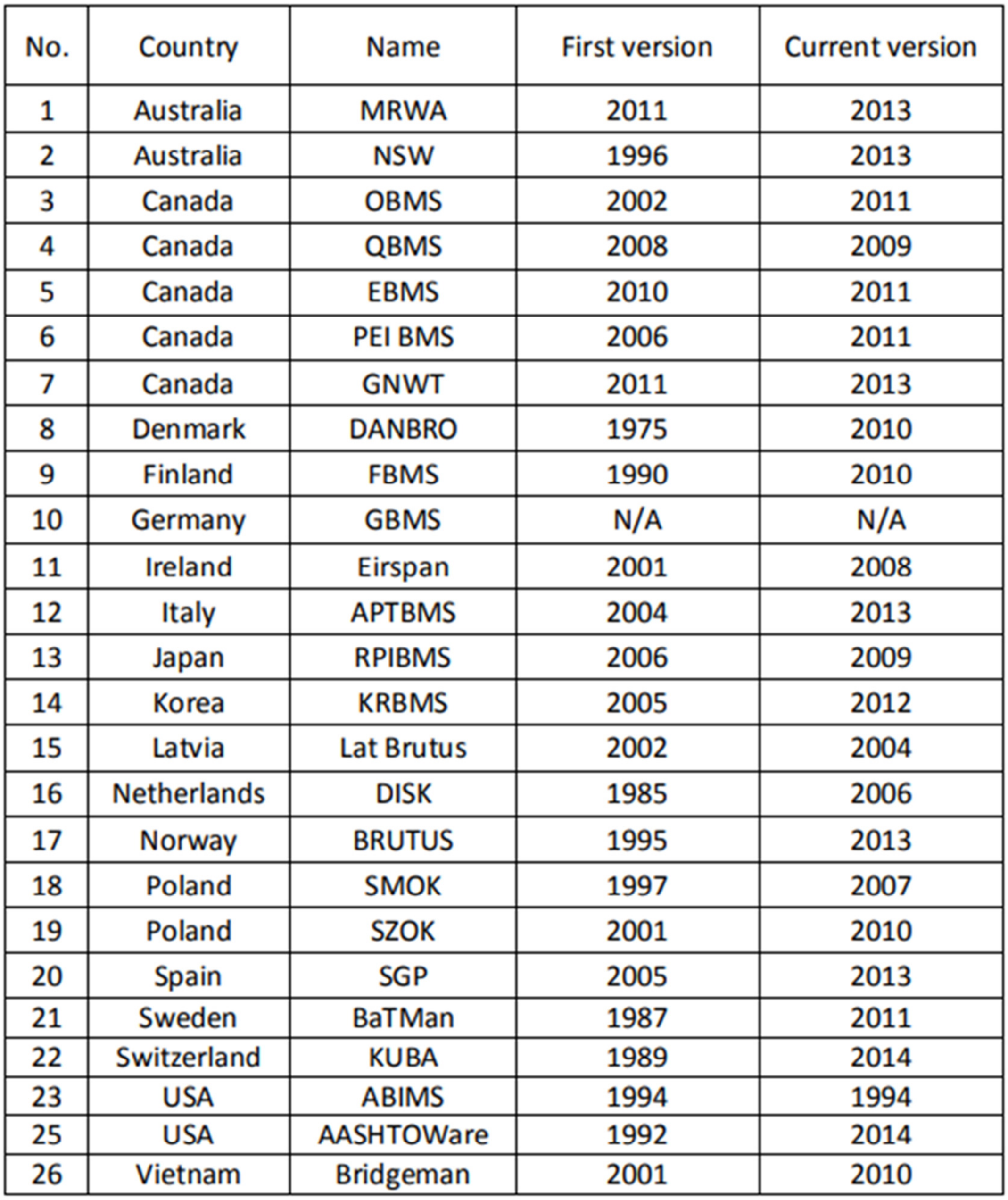


Figure 2-5 Years of first and current versions IABMAS 2014 (Mirzaei et al., 2014)



No.	Country	Name	First version	Current version
1	Australia	MRWA	2011	2013
2	Australia	NSW	1996	2013
3	Canada	OBMS	2002	2011
4	Canada	QBMS	2008	2009
5	Canada	EBMS	2010	2011
6	Canada	PEI BMS	2006	2011
7	Canada	GNWT	2011	2013
8	Denmark	DANBRO	1975	2010
9	Finland	FBMS	1990	2010
10	Germany	GBMS	N/A	N/A
11	Ireland	Eirspan	2001	2008
12	Italy	APTBMS	2004	2013
13	Japan	RPIBMS	2006	2009
14	Korea	KRBMS	2005	2012
15	Latvia	Lat Brutus	2002	2004
16	Netherlands	DISK	1985	2006
17	Norway	BRUTUS	1995	2013
18	Poland	SMOK	1997	2007
19	Poland	SZOK	2001	2010
20	Spain	SGP	2005	2013
21	Sweden	BaTMan	1987	2011
22	Switzerland	KUBA	1989	2014
23	USA	ABIMS	1994	1994
25	USA	AASHTOWare	1992	2014
26	Vietnam	Bridgeman	2001	2010

Table 2-5 list countries with the current BMS software versus the first version IABMAS 2014 (Mirzaei et al., 2014).

2.4.1 AASHTOWare Bridge Management Software (BrM)

Pontis was first developed by Cambridge Systematics in 1989 and has been revised several times per requests by the Federal Highway Administration, the American Association of State Highway and Transportation Officials (AASHTO), and State Departments of Transportation (Smadi et al., 2008). Currently, over 50 state DOTs and other bridge owners nationally and worldwide are using this software. PONTIS is a comprehensive intricate, complete software package with extensive documentation. PONTIS improves and expands the bridge inspection process by requiring the use of more detailed bridge element data to evaluate condition rating, and providing statistical and probabilistic capabilities for alternative MR&R (Gutkowski, et al.,1998). Pontis is one of the products in the AASHTO BRIDGEWare collection. The other AASHTO BRIDGEW products are Virtis which is primarily used for load rating of bridges, and Opis, used for bridge design. Pontis can be used as a standalone product or it can be combined with Virtis and Opis using a BRIDGEWare (Cambridge, 2005).

Pontis can support the entire bridge management life cycle, including the following (Cambridge, 2005):

- Inventory data: integrating all NBI inventory items and importing external information.

- Inspection: entering bridge element inspection data, producing inspection reports, Inventory, and Appraisals.
- Developing bridge component deterioration levels and providing estimated costs based on agency historical estimate costs and engineers experience. Developing bridge preservation strategies and provide long term recommendations for improvements. Based on the bridge condition and performance the program can evaluate different investment scenarios.
- Project development: Preparing project specifications based on inspection reports, providing project rankings and updating project status and completion reports.

One of the Pontis features is its ability to support a high level agency customization. State DOTs and other bridge owners can customize Pontis functions to meet their needs (Robert et al.,2003). However, in order to install and implement the Pontis software, a computer must meet the minimum requirements. New Zealand could not adopt Pontis due to the fact that their data did not meet the program minimum requirements (Jaeho, 2007). According to Robert et al.,2003 approximately 50% of licensed bridge agencies are using Pontis for primary bridge for generating inspection reports. As of 2003, there were 46 agencies licensed to use Pontis. Figure 2-6 is based on 34 confirmed licensed users indicating the level of functionality used by the different bridge agencies.

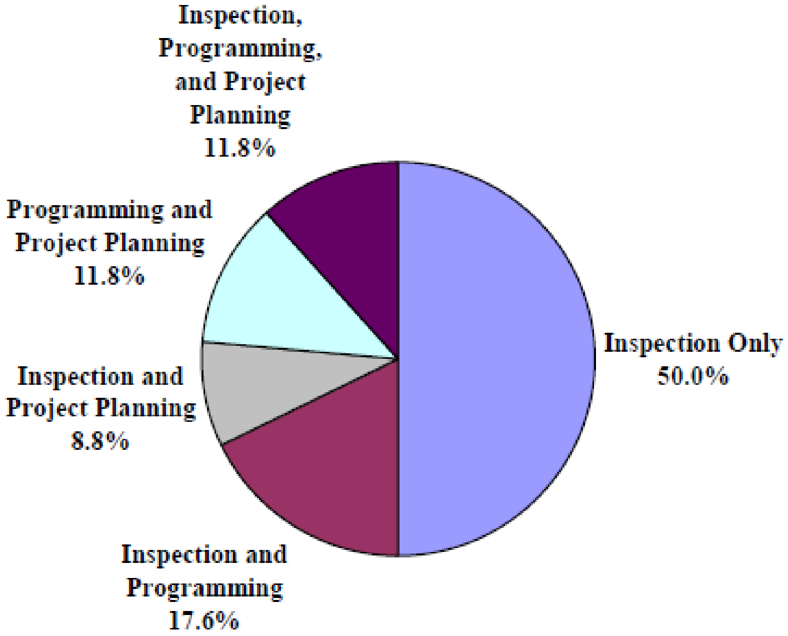


Figure 2-6 Pontis Functionality use by the different bridge agencies (Robert et al.,2003).

The Pontis workflow framework as shown in figure 2-7, was reproduced based on information disseminated through Cambridge Systematics, Inc. "Pontis Release 4.4 User's Manual". The software imports an NBI data file, updates inventory information and enters inspection data to produce NBI files for submission to FHWA and exporting to other systems. Pontis develops a deterioration model based on using a Markov chain model (Cambridge, 2005).

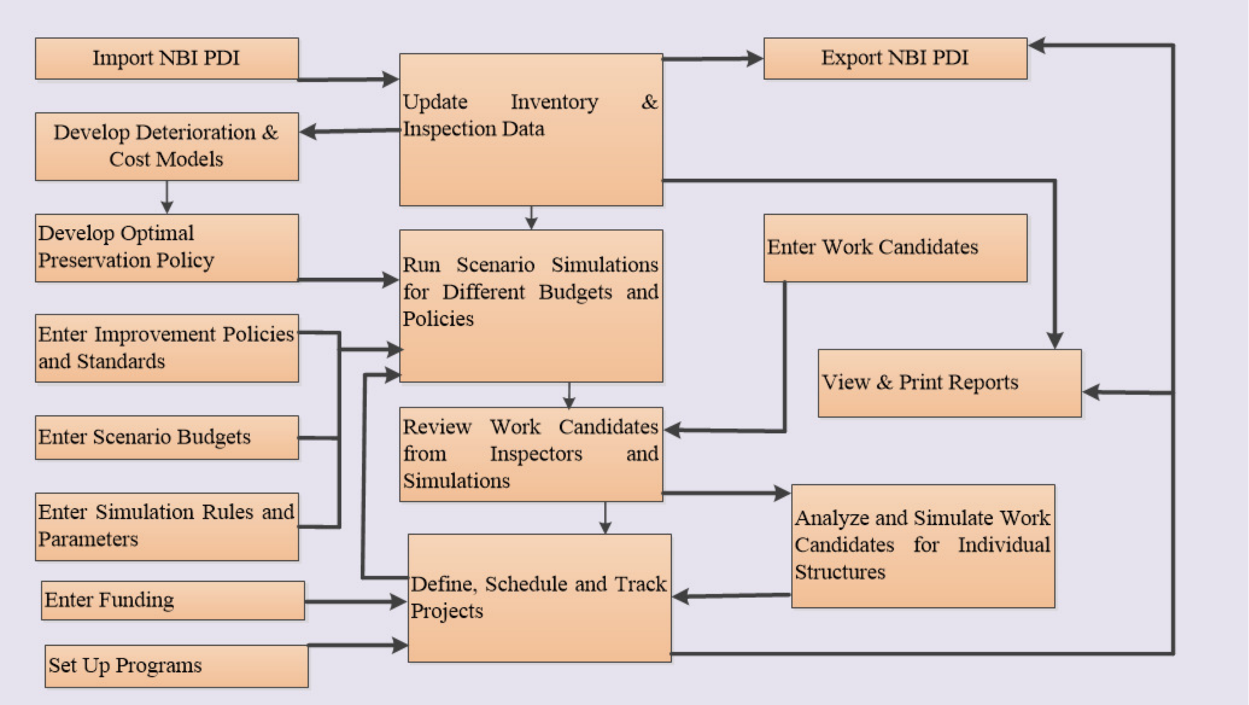


Figure 2-7 Pontis Work Flow Framework (Cambridge, 2005) BrM

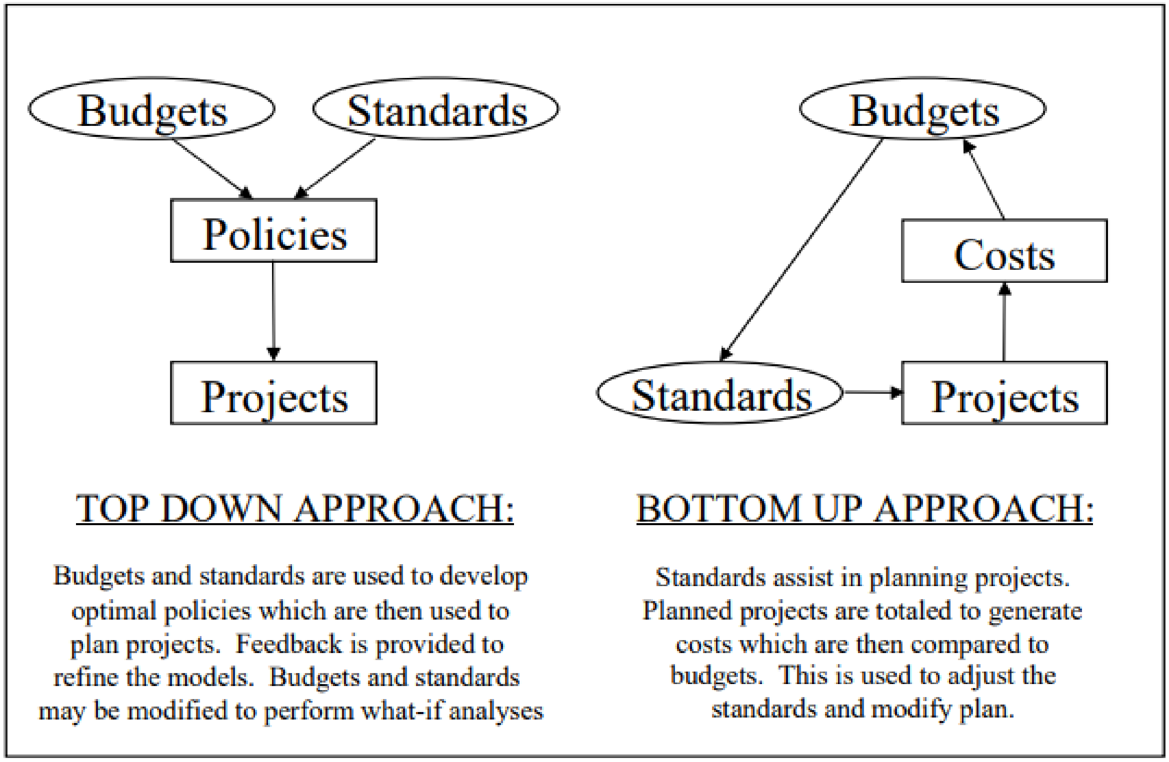
The latest version of AASHTOWare Bridge Management System BrM 5.2.2 was released and implemented in 2015, this software is a web application which can be installed on a web server and specializes in the following (AASHTO, 2015):

- Providing the informational tool to decision makers to help protect the existing infrastructure investments, ensuring safety and maintaining mobility.
- Storing inventory data items and bridge inspection information
- Providing a forecasting model to analyze short and long term project scheduling and budgeting.

- Producing preservation strategies appropriate for network-wide applications that address each bridge structure, making recommendations for the MR&R.
- Analyzing the effect of different project alternatives based on a network performance level or for individual bridge structures.
- Selecting and developing projects for MR&R projects.

2.4.2 BRIDGIT

BRIDGIT was developed and released in early 1990's by AASHTO-sponsored National Cooperative Highway Research Program (NCHRP) Projects 12-28(2) (Small et al., 1999). This software is designed for multi-user PC-based systems to analyze different funding scenarios and produce long term funding for maintenance, repair, and rehabilitation (MR&R) and meet the Federal Highway Administration (FHWA) requirements (Hawk, 1999). BRIDGIT and its rival Pontis have many of similarities, however; Pontis is based on a 'top down' approach while BRIDGIT employed a 'bottom-up' approach as shown in Figure 2-8 (Small et al., 1999).Due to its limitation, the software was superseded by its competitor Pontis,



TOP DOWN APPROACH:

Budgets and standards are used to develop optimal policies which are then used to plan projects. Feedback is provided to refine the models. Budgets and standards may be modified to perform what-if analyses

BOTTOM UP APPROACH:

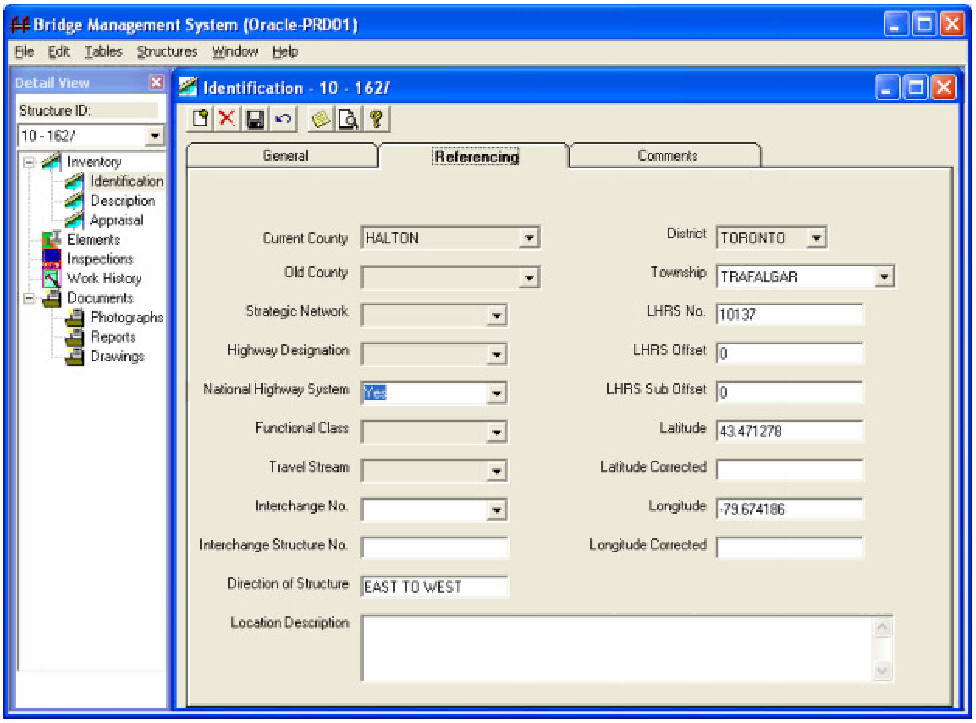
Standards assist in planning projects. Planned projects are totaled to generate costs which are then compared to budgets. This is used to adjust the standards and modify plan.

Figure 2-8 Bridge Management System Philosophies (Small et al, 1999).

2.4.3 Ontario Bridge Management System (OBMS)

The Ontario Bridge Management System (OBMS) was developed in 1998 and released in 2000 for managing the Ontario Ministry of Transportation (MTO) bridges and has been revised several times (Zimoch et al.,2012). The OBMS software is designed to handle a large bridge network, the program process is based on bridge element condition rating and using a Markovian deterioration model, to evaluate the preservation strategy and produce a project cost estimate based on the Ministry's itemized cost database (Thompson, 2001). The OBMS inventory data consists of three components: identification, description, and appraisal. The identification section is composed of location with a photograph of the bridge, bridge type, and other general information. The OBMS can produce a 10 to 60 year long term life-cycle cost analysis for bridge maintenance, rehabilitation and replacement activities (Thompson et al.,2003).

The OBMS software program attribute table includes: Inventory, identification, description, appraisal, elements, inspection, work history, documents (photograph, reports and drawings) as shown in Figure 2-9 (OBMS 2.50)



Structure ID: 10 - 162/

Current County: HALTON
Old County:
Strategic Network:
Highway Designation:
National Highway System: Yes
Functional Class:
Travel Stream:
Interchange No.:
Interchange Structure No.:
Direction of Structure: EAST TO WEST
Location Description:

District: TORONTO
Township: TRAFALGAR
LHRS No.: 10137
LHRS Offset: 0
LHRS Sub Offset: 0
Latitude: 43.471278
Latitude Corrected:
Longitude: -79.674186
Longitude Corrected:

Figure 2-9 Ontario Bridge Management System (OBMS) software application (OBMS 2.5).

2.4.4 Danish Bridge Management System (DANBRO)

DANBRO (DANish Bridges and Roads) BMS software application was developed by Ramboll in 1998 and currently is used by a number of countries around the world. Presently DANBRO is managing over 2500 bridges in Denmark, 10,000 bridges in Thailand and other countries including Colombia, Honduras, Croatia, Malaysia Saudi Arabia and Mexico (Yianni et al.,2017, Lauridsen et al., 1999).

DANBRO support bridge inspection and uses condition rating of 0 (structure element with no damage) to 5 (failed condition) the process requires that the bridge inspector not only identifies and rates the structural element but also makes a recommendation for repair and provide a cost estimate based on estimated data entered by the bridge agency (Telford, 1999).

DANBRO includes six modules (1) the basic information module which provides inventory items, condition rating and inspection data; (2) an experience module determines the life cycle costs based on deterioration and cost data (3) a price catalogue module provides MR&R estimate costs based on itemized unit prices (4) an optimization module produces the most cost efficient maintenance alternative based on following:

a. Repair the bridge structure to a rating of level of 5 (excellent condition).

b. Make a partial repair to preserve the bridge at the existing condition or better.
c. Do nothing and let the bridge components deterred to a structurally deficient state.
d. Do nothing and close the bridge

(5) The budget and cost modules provide short and long term budgets for MR&R activities and (6) the maintenance module contains maintenance history (REHABCON).

2.5 Bridge Deterioration Modeling

In bridge asset management knowledge of deterioration, rates are crucial for forecasting and long term planning. Bridge deterioration is the progression of bridge components deteriorating over time due to normal operation not including natural disaster and impact damage (Abed et al., 1995). The deterioration process due to normal aging under different environmental condition consists of very complex occurrences of physical and chemical changes in bridge components. Each bridge component- deck, superstructure, and substructure consists of many different elements and each element has its own unique deterioration rate (Thompson, 2001a). The quality of decision making depends greatly on the ability to predict the future condition of bridge components accurately. Since 1970 many deterioration models have been developed, however, they are not reliable to forecast future bridge conditions (Morcous et al., 2002b). In the early 1970s, the deterioration models were developed to provide a tool for decision-makers by predicting the future condition of a pavement, this approach has been employed to develop a deterioration model for BMS (Agrawal, 2010). Bridge element deterioration is caused by many different factors comprising of age, material quality environment, design characteristics, construction methods and traffic conditions. The usual indication of the bridge element deterioration can be documented by delamination/spall in concrete, exposed rebar, efflorescence/rust staining in concrete, and corrosion-cracking-distortion in steel girders. Forecasting models are a means of connecting observable defects caused by deterioration to the various factors initiating deterioration, which in turn can predict the future condition of bridge components and indicate corrective actions (Goyal, 2015).

The transportation systems center (TSC) in Cambridge, Massachusetts conducted a study on the relationship between bridge component deterioration and the elements causing the deterioration. The study identified the most influential elements consisting of design type, material, construction method/quality, age, average daily traffic and the environmental conditions (Busa et al.,1985). Madanat et al.,1995 and Hudson et al., in 1998 described the deterioration rate as largely affected by design and construction quality, routine maintenance activities, material properties and the environmental conditions.

Figure 2-10 illustrate the bridge deterioration model grouped into four main categories: mechanistic models, deterministic models, stochastic models, artificial intelligence (AI) models and sub-categories and methodology used in each of the categories.

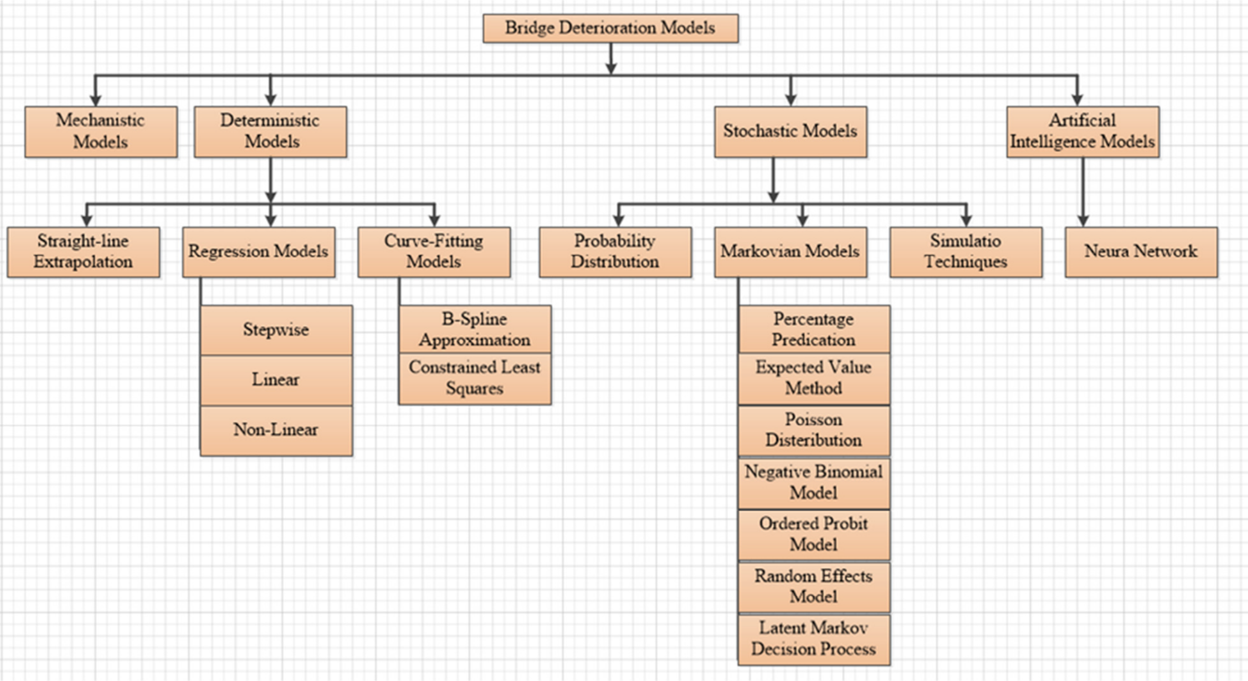


Figure 2-10 Bridge deterioration models categories (Morcous, 2000)

2.5.1 Mechanistic Models

A mechanistic model deterioration approach is based on a high-level of detail aimed at specific bridge elements which predict the micro-response of bridge components caused by an impact of applied loads (Morcous et al., 2007). The mechanistic model takes a complex system and splits it into the individual elements, subsequently analyzes each element. For example, in the mechanistic model the induvial factors such as material, environment and maintenance that affect the bridge deterioration will be analyzed to predict the service life of the bridge structure.

Komp 1987, Kayser and Nowak, 1989 and Sobanjo 1992 described the mechanism of the corrosion process of a steel superstructure which identifies the loss of capacity in steel members due to corrosion. The deterioration process due to corrosion loss is predicted by an exponential function.

$$C = At^B \tag{2.1}$$

Where A, B are variables defined based on the environment where the structure is located, C is the average corrosion penetration measured in microns and t is the number of years. This equation can be used to predict the steel superstructure strength.

2.5.2 Deterministic Models

Deterministic models are based on the relationship among the factors affecting bridge deterioration (design, construction, maintenance, environment, age…) and the condition of the elements by using available statistical descriptors and techniques, such as mean, standard deviation, and regression curve fitting. These models can repeatedly calculate the outcome of the same input data (Jiang et al., 1989). Subsequently, the deterioration model is developed by utilizing the available historical data of a structural element of the same type/material under the same environmental conditions to predict the average condition on the network level regardless of the existing condition and the historical condition of the structure. These models calculate the deterioration rate deterministically by ignoring the random error predictions.

Deterministic models as shown in Figure 2-10 consist of straight-line extrapolation, regression models, and curve-fitting.

2.5.2.1 Straight-Line Extrapolation

This model is simply based on straight-line extrapolation. The model requires two or more variables such as inspection histories including when the structure was new and the existing condition; this provides two points (initial bridge condition and the existing). The straight-line extrapolation is used to predict the material condition rating based on the assumption that traffic loading and maintenance history are linear (Shahin,1994).

The earliest deterministic model was developed in 1987 for the North Carolina DOT, based on two criteria; first, the average age of bridge with a corresponding condition rating and second, the average age of bridges when the condition rating dropped by one NBI rating point (Chen and Johnston, 1987).

This method is only accurate enough for predicting short-term conditions. The linear extrapolation deterioration model for bridge structures has not been widely adopted.

2.5.2.2 Regression Model

Regression models often link two or more variables one dependent (ie. response) and one or more independent variables. Each variable is described in terms of its mean and variance (Shahin 1994).

The simplest form is a linear regression Shahin (2005) which expresses the linear relationship by the following formula:

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i \tag{2.2}$$

Where Yi is the condition rating of bridge structure i , Xi is the age of bridge structure, εi is the prediction error and β_0. β_1 are the regression parameters, Curve-fitting methods are mathematical functions based on constructing a polynomial that best fits bridge condition data. The polynomial function then is used to predicate a deterioration rate.

The limitations of a deterministic model consist of neglecting the stochastic nature of the deterioration process by ignoring the relationship between deterioration of different bridge components such as bridge deck and deck joints (Sianipar and Adams, 1997).

2.5.3 Stochastic Deterioration Models

Stochastic models are more popular, and their uses are increasing in the field of engineering and other applied sciences. Stochastic models have significantly contributed to the field of modeling infrastructure deterioration. Stochastic models predict the deterioration over time based on random variables and probabilistic distributions. Morcous et al. (2010) indicate based on Ditlevsen (1984) that structural deterioration progression is an intricate process with a high amount of uncertainty in the structures “micro-response” this is a significant advantage for deterministic models.

2.5.3.1 Probability Distribution

A probability distribution describes the probabilities associated with all of the values of a random variable. These models can be classified either as state-based or time-based models (Mauch and Madanat, 2001) State-based models predict the probability that an infrastructure asset will deteriorate (change in condition state as it ages) based on explanatory variables such as design, construction, traffic loading, environmental factors, and maintenance history that contribute to deterioration. Time-based models predict the probability distribution of the time it takes for an infrastructure to change its condition-state, based on explanatory variables such as design, construction, traffic loading, environmental factors, and maintenance history that contribute to deterioration. These types of models have been used often in pavement forecasting to predict the time it takes for a new pavement to show signs of stress (Patterson and Chesher, 1986).

2.5.3.2 Simulation Techniques

Simulation techniques can be used to analyze the behavior of the structures. his deterioration model is useful when adequate analytical models are not available. For instance, the deterioration can be simulated if enough on statistics transition times are available for an element to change its condition. The output of the simulation will be a probabilistic deterioration profile which indicates the time it takes the element to change its condition state to the next level.

2.5.3.3 Markovian Models

Much of the research in the deterioration model has focused on Markov Chains and the stochastic techniques used in research. In BrM(Pontis), Markov chain is used in the development of the CoRe element deterioration model. The model integrates all five AASHTO condition states for each bridge element. All factors (design, construction, material, environment, maintenance…) that contribute to deterioration, are classified into one of four categories of the environment: benign, low, moderate, or severe. In turn each environment is based on the level of the external factors on the performance of the bridge element over time, subsequently, a deterioration matrix is made for each structural element in a selected environment (Thompson et al., 1998).

Deterioration is usually assumed to be a Markov process (Frangopol et al., 2004, Barlow and Proschan 1965). The Markov approach can be categorized in two classes vary discretely or continuously with respect to time and space (Andrews and Moss, 2002). The two fundamental assumptions are: 1) the current state depends on only the next preceding state and 2) the time it takes to move from one condition state to another follows an exponential distribution. For the Markov approach to be applicable, the system must satisfy the unique property of Markov models known as “memoryless”, property, which means the next active condition state depends only on the current state and ignores all previous states (Bryant, 2014) . This property can be expressed by:

$$P(X_{n+1}|X_{0,\ldots\ldots,}X_n) = P(X_{n+1}|X_n) \qquad (2.3)$$

Where X_n represents the current state and X_{n+1} represents the next state; $X_{0,\ldots\ldots,}X_n$ are the states between 0 and n.

Markov Transition Probabilities: Markov chains are used as performance prediction models for infrastructure assets by identifying the discrete condition states and adding the probability of moving from one condition state to another over multiple discrete time intervals. Transition probabilities are illustrated by matrix of order (n * n) called the transition probability matrix *(P)*, where n is the number of possible condition states. Each element *(pij)* describes the rate of leaving state *i* and arriving in state *j*. during a unit time interval called the transition period.

$$P(t) = P(0) * P^t \qquad (2.4)$$

$$P(t) = \begin{bmatrix} P1,1 & P1,2 & \ldots & P1,n \\ P2,1 & P2,2 & \ldots & P2,n \\ \ldots & \ldots & \ldots & \ldots \\ Pn,1 & Pn,2 & \ldots & Pn,n \end{bmatrix}$$

2.5.4 Artificial Intelligence Model

The artificial intelligence (AI) technique is gaining substantial popularity in research on forecasting models (Chen and Burrell, 2001). Artificial neural networks (ANN) are non-linear statistical data modeling methodology used to analyze complex relationships between inputs and outputs or to find patterns in data. The (AI) is consisting of several different methods that have been exploited in a variety of applications. Artificial neural networks (ANNs), case based reasoning (CBR), and machine learning (ML) are AI techniques that are used extensively as powerful tools for solving engineering problems.

Sobanjo (1997) recommended the use of ANN to model bridge deterioration using bridge age as an input and the bridge condition would be the output. A multi-layer ANN was used to relate the bridge super structure's age (years) to its corresponding NBI condition rating. Figure 2-11 illustrates the network configuration. In this study 50 bridge superstructures were used to train and test the network; 75% of the data was used for training, while the remaining data was used for testing. The use of this ANN resulted in 79% of the predicted values were within a 15% prediction error.

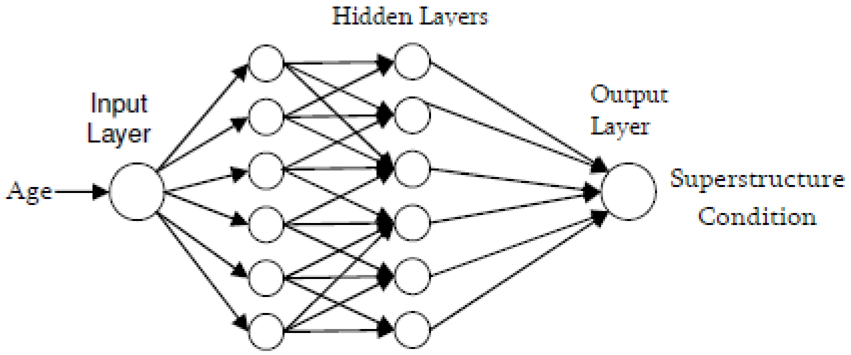


Figure 2-11 Multi-layer Neural Networks (Sobanjo, 1997)

2.5.4.1 Case Based Reasoning (CBR)

Case-based reasoning (CBR) is an AI model developed in 1980s the approach is solving new problems based on the solutions of similar past problems. The CBR field has grown rapidly over the past three decades and is a powerful technique for computer reasoning. Case-based reasoning is a problem solving model that in many respects is fundamentally different from other major AI approaches (Aamodt , 1994). CBR approach uses the detailed knowledge of previous experiences, tangible problem circumstances, instead of relying only on general knowledge of a problem. The primary knowledge source is not generalized rules but a memory of stored cases detailing previous experiences. A new problem is solved by finding a comparable past case, and applying it to the new problem. Every time a new experience is stored and it is immediately made available for future problems.

Much of the original inspiration for the CBR approach came from the role of reminding in human reasoning a theory of reminding and learning in computers and people (Schank, 1982 and Kolodner, 1984). CBR is used in everyday normal life, for example, an auto mechanic who repairs a car by remembering another car exhibited similar symptoms or a medical doctor treating a new patient for specific disease uses a previous case with another patient in previous years with the same disease. The primary source of knowledge in CBR systems are the cases that can be exploited even if they are partially matching the current problem. This knowledge can be improved by adding new cases and without facing the problems of knowledge acquisition or rule coverage as in Rule-based expert systems (ES) (Roddis and Bocox 1997).

Morcous (2000) developed Case-based reasoning for modeling concrete bridge decks using data obtained from the Quebec Ministry of Transportation. The system was developed based on the assumption that two bridges that have similar structures and operate under similar conditions will have the same performance. A library of cases with known parameters and performance was compiled. The performance of a new case can be predicted by retrieving a similar case from the case library.

2.6 Internet Technology and Geographic Information System (GIS)

The development of Internet technology since the creation of the World Wide Web has by far surpassed that of other communication technologies including newspapers, radio, and television (Howard and Jones, 2001). Geographic Information Systems (GIS) are widely accepted around the world as powerful tools for storing, visualizing, manipulating, and analyzing spatial data. This technology was developed in the early 1970s and GIS had a significant influence on the capabilities of geographic analysis (Dragićević, 2004). The GSI based information can be shared and transferred from anywhere anytime with users making choices for access to the geography related information. The integration of Web-based systems continually updates as the public uses the system and provides additional information (Kingston et al., 2000).

"A geographic information system (GIS) is a computer system for capturing, storing, checking, and displaying data related to positions on Earth's surface. By relating seemingly unrelated data, GIS can help individuals and organizations better understand spatial patterns and relationships" (National Geographic Society,2017).

GIS application includes cartographic data, photographic data, digital data, and data in spreadsheets. Cartographic data has been implemented in map form, this includes information such as the location of roads, towns, rivers and mountains. Cartographic data also includes survey data such as location of bridges or culverts and mapping information which can be directly entered into a GIS. Photographic interpretation is a major part of GIS. Photo interpretation involves analyzing aerial photographs and evaluating the topographies that appear, topological data includes the mathematical rules defining the connectivity between spatial objects (Laurini and Thompson, 1992 and National Geographic Society,2017).

In the past most Web-GIS based applications were used on environmental studies, in the recent years there has been growing interest on infrastructure monitoring and management. Shi et al. (2005) presented development of a bridge structural health monitoring and information management system by employing GIS, database and other related technologies.. Chen et al. (2010) developed an Integrated Remote Sensing and Visualization (IRSV) bridge management system which aims to provide a tool for bridge managers to comprehend bridge data from four essential perspectives: geospatial, temporal, relational and per-bridge attributes.

2.7 Summary

This chapter presented an overview of previous and current research on Bridge Management System (BMS), a review of the decision making process, and the forecasting methods. The literature review revealed the components most suitable for the proposed BMS model. The National Bridge Inventory (NBI) data was found to be the most comprehensive and accepted method for bridge assessment. Although Markovian models are the most commonly used deterioration methods in many BMSs such as Pontis and Bridigit, they are still based on assumptions and have some limitations:

- Transition probabilities in the Transition Probability Matrix (TPM) are challenging to accurately calculate and quite often require manipulation by expert judgment (Frangopolet al., 2004).
- The Markov modeling approach suffers from a rapid expansion of states when interactions between elements are considered. The number of model states follows $S^n$where S is the number of states and n is the number of elements or assets (Yianni, 2017). The model size increases exponentially with the increasing number of condition states. Using data from 4,000 NHDOT bridges would create 9^{4000} states which is too large for computing.

Chapter 3: Bridge Repair Priority Ranking System (BRPRS)

3.1 General

DOTs, cities, and towns in the United States have limited or constrained funding to maintain their bridges and improve the transportation infrastructure as desired by the public. Bridge Repair Priority Ranking System (BRPRS) prepares a network bridge project management strategy within management specified budget limits. The objective is to refine the decision-making process to attain the maximum network service life, at the lowest possible cost to sustain a bridge network at the highest possible network condition index. Subsequently, the priority ranking system provides data for network managers for presentation to respective government budget approval process as well as the voting public. This chapter presents the site specific bridge parameters, weighting factors, and cost comparative factors to provide a bridge network priority ranking system that includes preservation, general maintenance, rehabilitation, and replacement projects. Bridge network managers face the challenge of having many bridges in the same relative condition with limited funding sufficient to rehabilitate one or two bridges per fiscal year. BRPRS will justify bridge management decisions which result in improved budget decision making and defense while improving the network bridge condition index and reducing potential infrastructure failures and their consequences. The goal for BRPRS is to extend the useful life of bridges in the most cost effective manner by evaluating financial plans to identify funding levels required to sustain bridge networks at selected service levels. Traditionally maintenance, rehabilitation, and replacement (MR&R) projects are selected on a "worst first" approach. This method is acceptable if an unlimited budget is available to provide sufficient funding to sustain the bridge network at a high level of performance. This is typically not the case as municipalities and state transportation agencies have a limited resource to manage their infrastructure. Consequently, there is a need for prioritization to use available funds to assure the highest network level of performance as evaluated by bridge infrastructure managers specified parameters. Bridge prioritization is based on ranking all the available bridges in a network, with an overall score developed using the pre-defined set of criteria pertinent to individual bridge site conditions selected by a network manager.

3.2 Bridge Ranking and Prioritization Techniques Background

In the past several attempts have been made to develop BMSs that are based on a priority ranking methodology for MR&R activities. The "worst first" routine is no longer being viewed as the best option for selecting bridges, this view may be suitable for small networks with adequate funding, however, for large networks with limited funding this method does not maximize the network condition index nor reduce the life cycle cost, therefore a BMS based on this methodology cannot provide optimal solutions (Jiang, 1990). Project priority ranking systems have been used by several state departments of transportations to evaluate and select bridge projects for their preservation, capital improvement programs and replacement projects in preparing long and short term budget plans. (Kulkarni et al., 2004). Most BMS programs provide some type of ranking system on a network level. BrM (Pontis) provides bridge ranking based on the benefit-to-cost ratio, the average health index or the sufficiency rating for each project (Cambridge, 2005).

3.2.1 Sufficiency Rating (SR)

The sufficiency-rating (SR) approach is still used by some state DOTs for ranking bridges. Sufficiency rating (SR) was developed by the Federal Highway Administration (FHWA, 1995) to rate and rank bridge inventories. The SR is used by FHWA as of priority-ranking technique to determine the eligibility of bridges for MR&R activities and overall assessment of a bridge's condition. An SR calculation scale is expressed as a percentage from 0 to 100, with 0 representing a completely deficient bridge and 100 a new or rehabilitated bridge. SR categorizes bridges into three groups for MR&R recommendation. (1) bridges with SR ratings between 80 and 100 should receive preservation treatments and no additional maintenance (2) bridges with SR between 50 and 80 are eligible for rehabilitation and (3) bridges with SR between 0 and 50 are eligible for replacement. Bridge deficiencies are described in one of two categories: structurally deficient or functionally obsolete (Xanthakos, 1996).

The drawbacks of the SR method are (Sianipar, 1997): (1) overlooks the Average Daily Traffic (ADT); (2) SR is determined on the basis of a single standard; and (3) the method provides no room for optimization. Based on SR method narrow bridges that have a low capacity are subjected to low sufficiency ratings, although these bridges may be in good or better condition. (Elbehairy, Hegazy, and Souki 2006). The SR is not capable of providing a MR&R strategy for each bridge.

3.2.2 Benefit-to-Cost Ratio Analysis

The benefit-to-cost ratio (B/C) considers all of the benefits and costs associated with a project. Agency benefits are defined as "the present worth of future cost savings to the agency bridge expenditures" (FHWA, 1989b). Benefit/cost ratios are used to compare the use of monies between projects. Numerous projects on the network level may be prioritized by evaluating the B/C ratio for each project. In comparing all the projects, those projects with the highest B/C ratio would be ranked as the most efficient (Sallman et al., 2012). Farid et al. (1993) reported that the B/C ratio is difficult to use for assessing user costs and forecasting future conditions. The B/C ratio assumes the benefits gained from improvement projects are constant. This, however, is not always correct; this assumption does not take into account project timelines within the limits of the analysis period.

3.2.3 Level-of-service-deficiency rating

The Level-of-service-deficiency rating was developed by Johnston and Zia, 1983 at North Carolina University for NC DOT. This LOC priority ranking system was developed to resolve the disadvantages of the SR system. The ranking system for this method recognizes that priorities should be the degree of deficiency of bridges meeting the public's needs based three criteria: (1) Load capacity, (2) Clear deck width and (3) Vertical roadway clearance. The NC DOT's priority ranking system is based on the level of service goals (Johnston and Zia, 1983) where

$$DP = CP + WP + VP + LP \qquad (3\text{-}1)$$

Where DP is the total deficiency points on a scale of 0 to 100, 0 representing no deficiency. CP, WP, VP, and LP are need functions for load capacity, clear deck width, vertical clearance and remaining service life. The weights factors assigned to these variables are CP (70), WP (12), VP (12) and LP (6).

The disadvantage of this system is that it does not forecast activities (i.e., project levels of major maintenance, rehabilitation, or replacement) and does not predict the optimal timing for any repair alternative (Mohamed, 1995).

3.2.4 Health Index

The Bridge Health Index was developed by the California Department of Transportation (CALTRANS). The purpose was to create a unified condition index that would solely reflect the structural condition of the bridge (Roberts and Shepard, 2000). The heath index determines the remaining bridge asset value and compares it to its replacement value or to its best possible condition versus the current condition. The equations to compute the HI are as follows:

$$HI=(\Sigma CEV/\Sigma TEV) * 100 \qquad (3\text{-}2)$$

$$TEV=TEQ * (EWF*ERC) \qquad (3\text{-}3)$$

$$CEV=\Sigma(QCS_i*WF_i) * (EWF*ERC) \qquad (3\text{-}4)$$

Where:

HI=Health Index
CEV=Current Element Value
TEV=Total Element Value
TEQ=Total Element Quantity
EWF=Element Weighting Factor
ERC=Element Replacement Cost per Unit of Element
QCS=Quantity in a Condition State
WF=Weighing Factor for the Condition State, as shown in table 3-1

Table 3-1 Condition State Weighting Factors

WF for each Condition State Based on No. of Possible Condition States					
Number of Condition States	Condition State 1 WF	Condition State 2 WF	Condition State 3 WF	Condition State 4 WF	Condition State 5 WF
5	1	0.75	0.5	0.25	0
4	1	0.6667	0.3333	0	NA
3	1	0.5	0	NA	NA

Liu and Frangopol (2006) and Lee and Sanmugarasa (2011) also presented a methodology to consider conflicting criteria such as life-cycle failure and socio-economic implications in a multi-objective optimization. The approach integrates time-dependent structural reliability prediction, highway network performance assessment, and life-cycle cost analysis. Individual bridge failure and their effects on the overall performance of the highway network are evaluated probabilistically. The MR&R activities are prioritized to deteriorating bridges through simultaneous and balanced minimization of three objective functions, i.e., maintenance cost, bridge failure cost, and user cost (Liu and Frangopol, 2006). Traditional risk estimation considering probability and consequence of failure is also a common approach in which bridges will be prioritized based on their risk scores in a descending order (Prasad and Coe 2007). The consequence of failure is an analysis of the impact of bridge failure to the community and to the bridge structure itself.

The probability of bridge failure is expressed as a function of the structural capacity of the bridge. Condition, load bearing capacity, material, and criticality factors are also included in the evaluation of probability. For each bridge, the degree of failure is evaluated under the features including structural damage, the potential for damage, loss of service and loss of life. The disadvantage of this system is in handling large-scale networks it is difficult assigning quantities for the subjective factors which have the potential to increase the complexity of decision-making and its associated cost of errors (Rashidi et al., 2016).

3.3 Bridge Repair Priority Ranking System (BRPRS)

Due to limited funding for bridge management and its significant role in transportation services MR&R strategies have to be prioritized. As a part of this BMS a Bridge Repair Priority Ranking System (BRPRS) is integrated with the forecasting model outlined in Chapter 4. Bridge engineers or bridge owners using BRPRS can specify the selection and prioritize repair schedules based on their requirements such as condition, detour length, traffic volume, scour critical, bus route, age, and other criteria. Priority ranking techniques are based on calculating a value for each bridge and then sorting all bridges in descending order of their parameters.

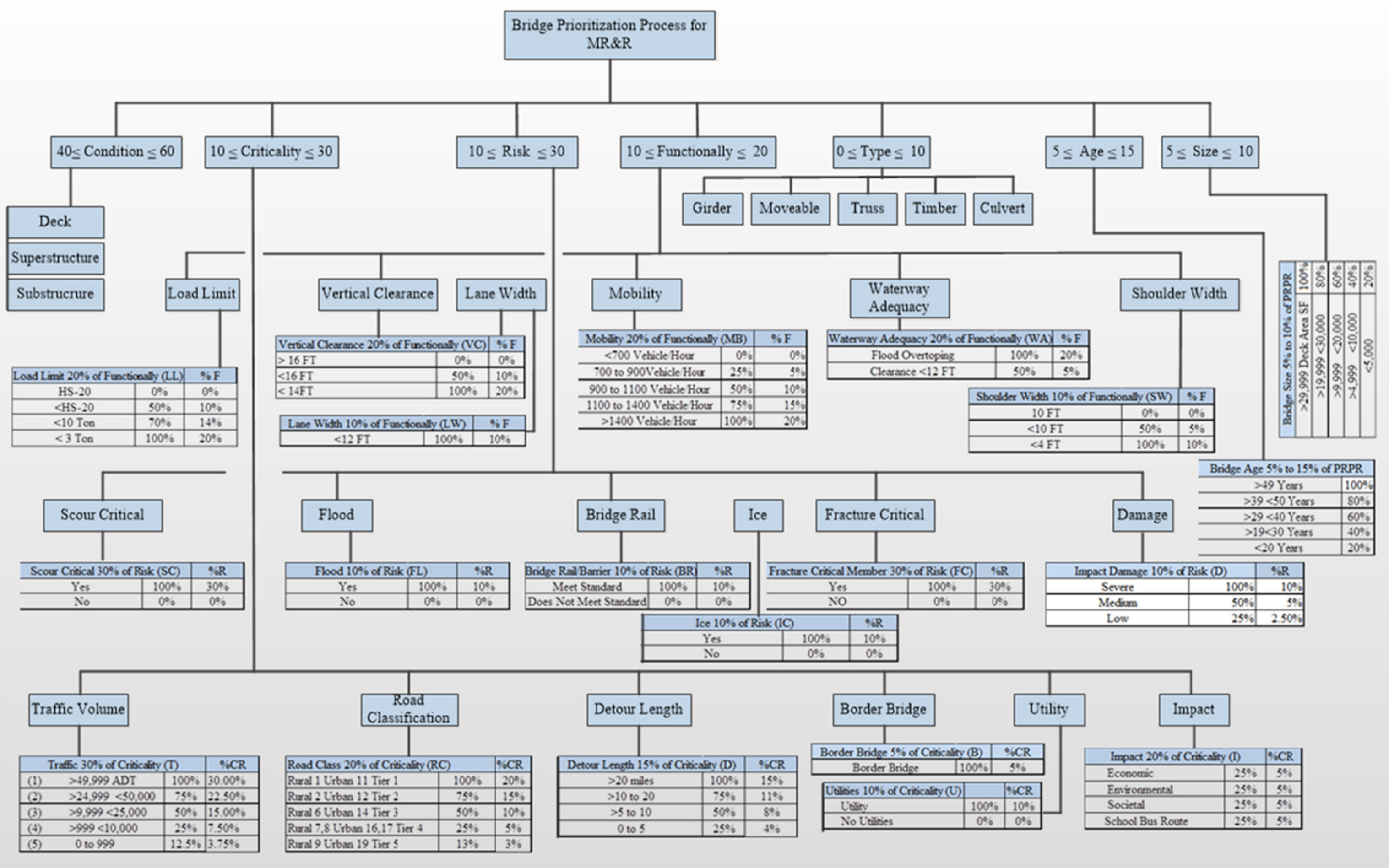


Figure 3-1 Bridge Prioritization Framework

The bridge prioritization process (Figure 3-1) is based on a set of criteria for performance measures which will be used to prioritize projects in the ranking system. These criteria are based on fundamental values and concepts in the following categories:

1. Condition
2. Criticality
3. Risk
4. Functionally
5. Type
6. Age
7. Size

This study ranks bridges in two different categories. The categories include:

1. Rehabilitation and Replacement
2. Preservation and Preventive Maintenance

The data for these categories can be determined using the inventory and condition items listed in Chapter 2 and Appendix D.

3.4 Ranking System for Rehabilitation and Replacement

Rehabilitation is described as major work required to restore the structural integrity of a bridge, as well as the work necessary to correct major safety defects as defined in the Code of Federal Regulation (CFR) 23 Clause 650.403.

The rating scoring system includes user specified site conditions pertaining to a respective individual bridge in a network. The priority ranking index is from 0 (least candidate for rehabilitation and replacement) to 100 (most preferred candidate for rehabilitation and replacement).

The ranking system formula is:

$$\boldsymbol{PRPR} = \{[\boldsymbol{\alpha}(\boldsymbol{C})] + [\boldsymbol{\beta}(\boldsymbol{CT})] + [\boldsymbol{\gamma}(\boldsymbol{R})] + [\boldsymbol{\delta}(\boldsymbol{F})] + [\boldsymbol{\varepsilon}(\boldsymbol{BT})] + [\boldsymbol{\theta}(\boldsymbol{A})] + [\boldsymbol{\mu}(\boldsymbol{S})]\} \qquad (3\text{-}5)$$

Where

PRPR= priority ranking points for rehabilitation (ranging from 0 to 100)

C= condition rating points based on NBI rating system

CT= criticality based on traffic volume, road class, detour length, border bridge, utility, and impact

R= risk based on scour critical, flood, ice, fracture critical member and bridge rail type

F= functionally based on load limit, vertical clearance, lane width, shoulder width, waterway adequacy, and mobility

BT= bridge type: girder, movable, culvert, timber, truss….

S= size

A=age

The coefficient variables (α, β, γ, δ, ε, θ, μ) are a percentage of each criterion in the rating equation and are agency specified. It is recommended that the rating score total 100 points to denote the highest priority. Bridge managers can adjust the distribution percentages of each category and their respective parameters based on their highway network. Table 3-2 shows the recommended range of category weighting factors.

Table 3-2 Ranking Criteria Distribution

Criteria	Variable Coefficient	Weighting Factor	Default Setting	If condition rating of deck, superstructure and substructure is equal to or less than 4 (NBI rating ≤4) a total of 5 to 10 points per each bridge components that is ≤4 should be added to the total score, the maximum total score should not exceed 100.
Condition	α	40% to 60%	40%	
Criticality	β	10% to 30%	18%	
Risk	δ	10% to 30%	15%	
Functionally	γ	10% to 20%	12%	
Type	ε	0% to 10%	5%	
Age	θ	5% to15%	5%	
Size	μ	5% to10%	5%	Emergency vehicles route bridge have an additional 10 points
Total		100%	100%	Toll Plaza bridge have an additional 5 points

3.4 Condition

Federal law requires state transportation agencies to inspect public road bridges periodically and to report their findings to the Federal Highway Administration (FHWA). In the United States, most highway transportation networks are inspected on a two year cycle. The conditions are measured visually or with instruments based on the guidelines and standards established by the Federal Highway Administration (FHWA) and The American Association of State Highway and

Transportation Officials (AASHTO) Guide for Commonly Recognized (CoRe) Structural Elements. NH bridges are inspected by certified DOT bridge inspectors through training to conduct all bridge inspections. These bridge inspections meet the requirements of the National Bridge Inspection Standards Regulations (NBIS). The condition assessments are described in Chapter 2.

The bridge condition criteria are worth 40% to 60% of the total PRPR. A bridge condition assessment is normally divided into three sections or components: (1) Deck, (2) Superstructure, and (3) Substructure

In this study, the default condition distribution rate is α = 40%. The unified condition ***C***, which is based on NHDOT's requirement, consists of the Deck Condition score at 20%, while the Superstructure and Substructure Condition score account for 40% each, as shown in Table 3-3. The scoring system ***S*** is based on the NBI rating. The NBIS regulation applies to all publicly owned structures defined as highway bridges longer than twenty feet and located on public roads.

$$\boldsymbol{C = [0.2S(Deck) + 0.4S(Superstructure) + 0.4S(Substructure)]} \quad (3\text{-}6)$$

Where

$$\boldsymbol{S = \{(NBI\ Condition\ Rating - 9)(-1)(\tfrac{X}{9})\}} \quad (3\text{-}7)$$

Where $40 \le X \le 60$

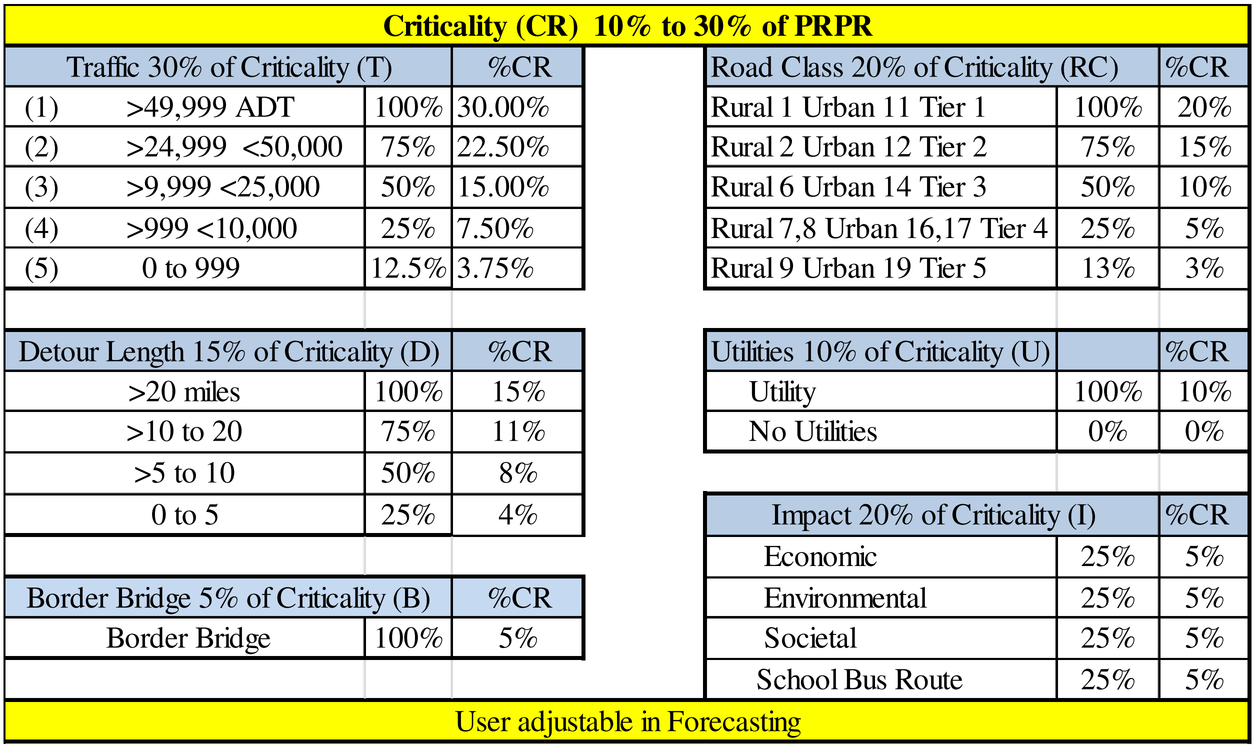
Table 3-3 Condition Scoring

Condition						
NBI Condition		**Deck**	**Superstructur**	**Substructur**	**Culvert**	**S**
Rating		20%	40%	40%	100%	**Score**
9	Excellent Condition	9	9	9	9	**0.00**
8	Very Good Condition	8	8	8	8	**4.44**
7	Good Condition	7	7	7	7	**8.89**
6	Satisfactory Condition	6	6	6	6	**13.33**
5	Fair Condition	5	5	5	5	**17.78**
4	Poor Condition	4	4	4	4	**22.22**
3	Serious Condition	3	3	3	3	**26.67**
2	Critical Condition	2	2	2	2	**31.11**
1	Imminent Failure Condition	1	1	1	1	**35.56**
0	Failed Condition	0	0	0	0	**40.00**

3.5 Criticality

Criticality is based on a set of criteria that is important to the public. These criteria include traffic volume, road classification, detour length when a bridge is closed to traffic, border bridge (if a bridge is connecting two states), utilities on the bridge, and the economic, environmental, the societal impact caused by a bridge closure. Table 3-4 describes the percentage of each section of criticality. Criticality recommended distribution factor is 10% to 30% of PRPR (β=10% to 30%)

Table 3-4 Criticality Recommended Scoring



Criticality (CR) 10% to 30% of PRPR

Traffic 30% of Criticality (T)			%CR
(1)	>49,999 ADT	100%	30.00%
(2)	>24,999 <50,000	75%	22.50%
(3)	>9,999 <25,000	50%	15.00%
(4)	>999 <10,000	25%	7.50%
(5)	0 to 999	12.5%	3.75%

Detour Length 15% of Criticality (D)		%CR
>20 miles	100%	15%
>10 to 20	75%	11%
>5 to 10	50%	8%
0 to 5	25%	4%

Border Bridge 5% of Criticality (B)		%CR
Border Bridge	100%	5%

Road Class 20% of Criticality (RC)		%CR
Rural 1 Urban 11 Tier 1	100%	20%
Rural 2 Urban 12 Tier 2	75%	15%
Rural 6 Urban 14 Tier 3	50%	10%
Rural 7,8 Urban 16,17 Tier 4	25%	5%
Rural 9 Urban 19 Tier 5	13%	3%

Utilities 10% of Criticality (U)		%CR
Utility	100%	10%
No Utilities	0%	0%

Impact 20% of Criticality (I)		%CR
Economic	25%	5%
Environmental	25%	5%
Societal	25%	5%
School Bus Route	25%	5%

User adjustable in Forecasting

$$\boldsymbol{CR} = [(\mathbf{0.3} * \boldsymbol{T}) + (\mathbf{0.2} * \boldsymbol{RC}) + (\mathbf{0.15} * \boldsymbol{D}) + (\mathbf{0.05} * \boldsymbol{B}) + (\mathbf{0.1} * \boldsymbol{U}) + (\mathbf{0.2} * \boldsymbol{I})] \quad (3\text{-}8)$$

3.6 Risk

The bridge risk criteria are factors that may cause bridge failure. In the United States, bridge scour has been the number one cause of bridge failures. The risk criteria for this study are scour critical, flood, ice, fracture critical member (Fracture critical bridge is defined by the FHWA as *a steel member in tension, or with a tension element, whose failure would probably cause a portion of or the entire bridge to collapse*.), bridge rail types (bridge railings are one of the very important components bridge safety systems and play an important role in preventing and mitigating crashes) and impact damage. The recommended distribution factor is 10% to 30% of PRPR (γ=10% to 30%) as indicated in table 3-5.

$$\boldsymbol{R} = [(\mathbf{0.3} * \boldsymbol{SC}) + (\mathbf{0.3} * \boldsymbol{FC}) + (\mathbf{0.1} * \boldsymbol{FL}) + (\mathbf{0.1} * \boldsymbol{IC}) + (\mathbf{0.1} * \boldsymbol{BR}) + (\mathbf{0.1} * \boldsymbol{D})] \tag{3-9}$$

Table 3-5 Risk Recommended Scoring

Risk (R) 10% to 30% of PRPR						
Scour Critical 30% of Risk (SC)		%R		Fracture Critical Member 30% of Risk (FC)		%R
Yes	100%	30%		Yes	100%	30%
No	0%	0%		NO	0%	0%
Flood 10% of Risk (FL)		%R		Ice 10% of Risk (IC)		%R
Yes	100%	10%		Yes	100%	10%
No	0%	0%		No	0%	0%
Bridge Rail/Barrier 10% of Risk (BR)		%R		Impact Damage 10% of Risk (D)		%R
Meet Standard	100%	10%		Severe	100%	10%
Does Not Meet Standard	0%	0%		Medium	50%	5%
				Low	25%	2.5%
User adjustable in Forecasting						

3.7 Functionally

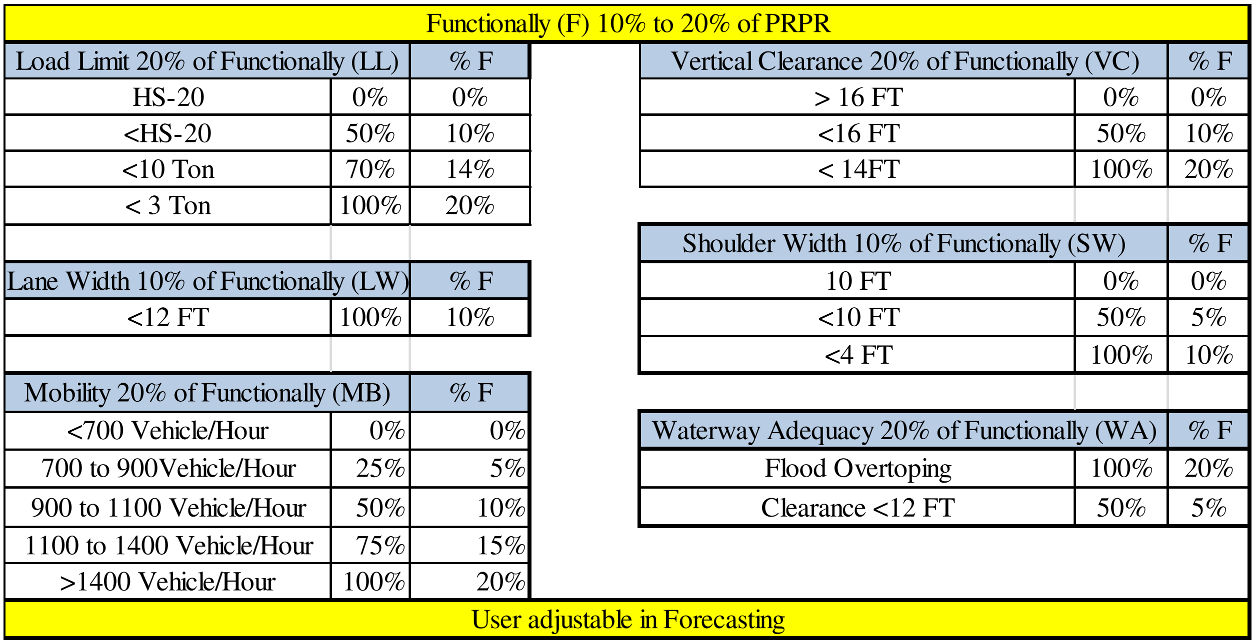
Functionally obsolete bridges are those that do not have adequate vertical clearances, lane widths, shoulder widths, or those that may be occasionally flooded or fail to meet current traffic demand or current geometric standards. The Federal Highway Administration defines functionally obsolete as, *does not meet current design standards (for criteria such as lane width), either because the volume of* *traffic carried by the bridge exceeds the level anticipated when the bridge was constructed and/or the relevant design standards have been revised.*

In this study, the functionally criteria are based on load limit, vertical clearance, lane width, shoulder width, waterway adequacy, and mobility. The scoring detail is shown in Table 3-6.

The recommended distribution factor is 10% to 20% of PRPR (γ=10% to 20%) .

$$\boldsymbol{F} = [(\mathbf{0.2} * \boldsymbol{LL}) + (\mathbf{0.2} * \boldsymbol{VC}) + (\mathbf{0.1} * \boldsymbol{LW}) + (\mathbf{0.1} * \boldsymbol{SW}) + (\mathbf{0.2} * \boldsymbol{MB}) + (\mathbf{0.2}\boldsymbol{WA})] \tag{3-10}$$

Table 3-6 Functionally Recommended Scoring



Functionally (F) 10% to 20% of PRPR

Load Limit 20% of Functionally (LL)		% F
HS-20	0%	0%
<HS-20	50%	10%
<10 Ton	70%	14%
< 3 Ton	100%	20%

Lane Width 10% of Functionally (LW)		% F
<12 FT	100%	10%

Mobility 20% of Functionally (MB)		% F
<700 Vehicle/Hour	0%	0%
700 to 900Vehicle/Hour	25%	5%
900 to 1100 Vehicle/Hour	50%	10%
1100 to 1400 Vehicle/Hour	75%	15%
>1400 Vehicle/Hour	100%	20%

Vertical Clearance 20% of Functionally (VC)		% F
> 16 FT	0%	0%
<16 FT	50%	10%
< 14FT	100%	20%

Shoulder Width 10% of Functionally (SW)		% F
10 FT	0%	0%
<10 FT	50%	5%
<4 FT	100%	10%

Waterway Adequacy 20% of Functionally (WA)		% F
Flood Overtoping	100%	20%
Clearance <12 FT	50%	5%

User adjustable in Forecasting

3.8 Bridge Type

The most common bridge types in New England are girder, truss, arch, timber, culvert, rigid frame, cable supported, and movable.

Girder Bridges

Girder Bridge is the most common basic bridge type constructed in the United States. The most common basic type of superstructure used in the construction of girder type bridges are I beam girders and box girders. The material normally includes structural steel, prestressed concrete, and/or composite of steel, and reinforced concrete. Based on maintenance history and performance, this type of bridge is worth 100% of $[(\varepsilon*0.8)*100]$.

Movable Bridges:

Movable bridges and drawbridges are commonly used over navigated water to allow passage for boats, ships, and barges. The various types of movable bridges include:

Drawbridge: A bridge that is hinged at one end to allow the deck and superstructure to be raised.

Bascule Bridges: Theses type of bridges use a counterweight to swing the superstructure and deck (single leaf and double leaf) upward.

Vertical Lift Bridge: The bridge superstructure/deck is raised by the counterweight cables which are supported by the two towers.

Swing Bridges: The bridge deck/superstructure swings around a fixed structure.

Movable bridges are important to roadway and waterway traffic. The score value for priority ranking system is 100% of [(ε*1)*100].The bridge type value points for common bridges in New England are shown in Table 3-7.

Table 3-7 Bridge Type Scoring

Bridge Type 0% to 10% of PRPR	
Girder	80%
Moveable	100%
Culvert	20%
Timber	50%
Truss	100%
Cable Supported	100%
Arch	75%
User adjustable in Forecasting	

3.9 Bridge Size

The bridge size distribution factor μ= 5% see table 3-2.

Table 3-8 Bridge Size Scoring

Bridge Size 5% to 10% of PRPR	
>29,999 Deck Area SF	100%
>19,999 <30,000	80%
>9,999 <20,000	60%
>4,999 <10,000	40%
<5,000	20%
User adjustable in Forecasting	

3.10 Bridge Age

Table 3-9 Bridge Age Scoring

Bridge Age 5% to 15% of PRPR	
>49 Years	100%
>39 <50 Years	80%
>29 <40 Years	60%
>19<30 Years	40%
<20 Years	20%
User adjustable in Forecasting	

Municipal bridges that are on a school bus route should have score value of 0% to 5 % points. Emergency vehicles route bridges for fire departments and hospitals should receive 5% to 10% points.

An example of calculating priority ranking system value is shown in Appendix E.

3.11 Priority Ranking System for Bridge Preservation

The complete Bridge Preservation is covered in Chapter 4. The Priority Ranking System for Bridge Preservation is based on the following Categories.

1. Bridge Condition
2. Criticality

The ranking system formula is:

$$\boldsymbol{PRPP} = [\mathbf{0.7} * \boldsymbol{CR}] + [\mathbf{0.3} * \boldsymbol{CT}] \tag{3-11}$$

Where

PRPP= Priority ranking points for preservation ranging from 0 (least candidate for preservation) to 100 (most preferred candidate for preservation).

Table 3-10 Preservation Bridge Prioritizations

Criteria	Recommended Distribution Rate	Default Setting
Condition	70% to 80%	70%
Criticality	20% to 30%	30%
Total	100	100

3.12 Case Study

In order to demonstrate the application of the developed priority ranking method, a sample network consisting of 170 New Hampshire Turnpikes bridges has been chosen. Majority of the data for these bridges are extracted from BrM (points) the remaining required data is provided by NHDOT. Table 3-10 represent the bridge condition index (BCI) and priority ranking for selected 23 NH Turnpike bridges utilizing 2016 inspection reports the complete list of all 170 NH TPK bridges ranked based on aforementioned are provided in Appendix E . The NHDOT BCI is based on the following formula:

$$BCI = [(NBI\,deck * 0.2) + (NBI\,\mathrm{super} * 0.4) + (NBI\,subs * 0.4)] * (100/9) \qquad (3\text{-}12)$$

The NBI condition rating is described in Chapter 2. Table 3-11 provides the condition of individual components. The major components are rated in NBI format while the core elements conditions are rated from 0 to 4. The color code is used to enhance visual observation in that if a major component such as deck is in poor or serious condition, it will stand out visually.

Table 3-11 Bridge Condition Rating

Bridge Condition Rating			
Description	**BCI**	**NBI**	**CS**
Very Good	85 to 100	9	1
Good	75 to 85	7,8	1
Fair	55 to 75	5,6	2
Poor	35 to 55	4,3	3
Serious	0 to 35	0,1,2	4

3.13 Ranking Analysis

In order for BRPRS (Bridge Repair Priority Ranking System) to be effective, there needs to be a fine balance between the condition of the bridge and the other criteria that affect the traveling public. The BRPRS, in altering the distribution rate outside of the recommended range, should not compromise the condition of the bridge, nor should it be solely based on the condition. The current method of bridge management is insufficient to meet the demands of the traveling public; the "worst first" routine is no longer being viewed as the best option. The BRPRS is most effective when the condition range is between 40% and 60% which allows other user factors to be considered. The criteria such as traffic volume, detour length, bridge rail, fracture critical member, lane width, and mobility that interrupt the nation's economy, lifestyle, and the safety of motorists should be a significant part in decision making. The two other criteria that should remain constant are toll plaza bridges and emergency vehicle route bridges. These two criteria should receive an additional 5 to 10 points in the priority rating. The detour bypass around toll plazas can be costly due to revenue loss. Emergency vehicle route bridge closure can have a significant impact on the community and can be costly to the bridge owner in providing a safe reliable detour.

Ranking analysis performed for this study utilizes the following two different approaches:

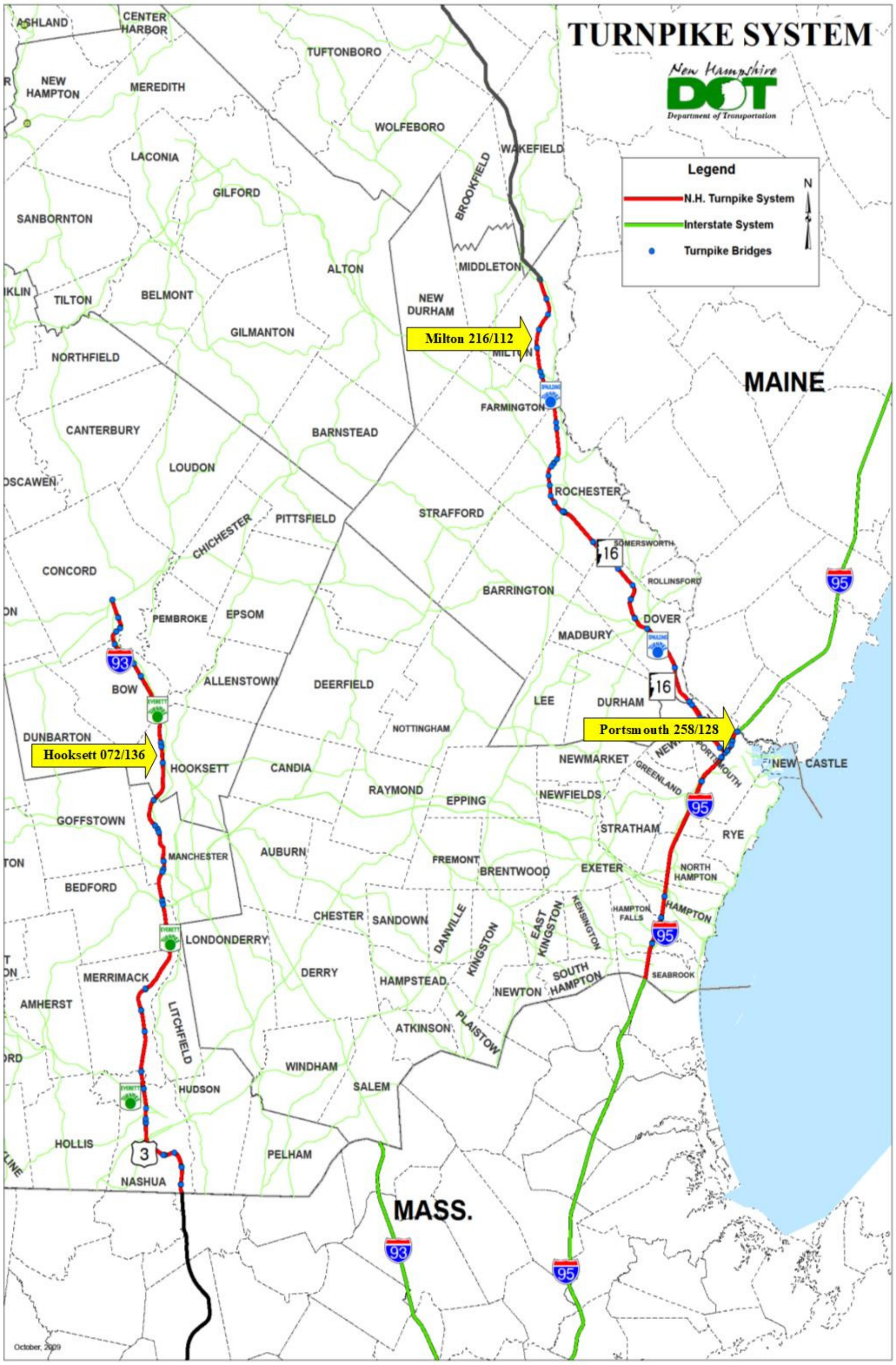
A. Choosing 3 bridges based on their level of importance from the list of 170 New Hampshire Turnpikes bridges and varying the decision variables outside of the recommended range.

B. Choosing 20 bridges from the list and examining how different values of categories impact the BRPRS under a given set of assumptions.

Choosing the following 3 bridges as shown in Figure 3-2 based on their level of importance:

1. Portsmouth 258/128 I-95 Bridge over Piscataqua River Road, BMRR. This bridge connects New Hampshire to Maine. The total bridge length is 4503 feet long, 3 lanes in each direction, AADT of 86,000, condition NBI 6, and it was built in 1971. This bridge is of the utmost importance within the Turnpike system. In this study, the bridge is classified as very important.
2. Milton 216/112 Spaulding Turnpike over NH Route 75. This bridge has a total length of 140 feet, a total width of 46.7 feet, AADT 14,000, condition NBI 7.2, and was built in 1980.This bridge is classified as an average bridge within the Turnpike system.
3. Hooksett 072/136 Access Road over I-93 NB off Ramp. This bridge has a total length of 68 feet, a total width of 30.7 feet, AADT 3,000, condition NBI 6.4, and was built in 1978. The level of importance of this bridge is classified as below average within the Turnpike system.

Table 3-12 illustrates 11 different scenarios of the distribution percentage of each category. The category percentages are sorted by condition percentage from 0% to 100% for all 3 bridges.



Hooksett 072/136

Figure 3-2 bridge location

Table 3-12 Variable Distribution Rate

	Categories							Portsmouth	Milton	Hooksett
Scenario	**Condition**	**Criticality**	**Risk**	**Functionally**	**Type**	**Age**	**Size**	**BRPRS**	**BRPRS**	**BRPRS**
Scenario 1	0%	50%	20%	10%	5%	5%	10%	99.00	46.00	17.00
Scenario 2	10%	40%	20%	10%	5%	5%	10%	90.11	40.80	17.16
Scenario 3	20%	30%	20%	10%	5%	5%	10%	81.22	35.60	17.31
Scenario 4	30%	30%	15%	10%	5%	5%	5%	72.33	33.40	16.47
Scenario 5	40%	25%	10%	10%	5%	5%	5%	63.44	30.20	17.12
Scenario 6	50%	20%	10%	5%	5%	5%	5%	54.56	27.50	17.78
Scenario 7	60%	15%	5%	5%	5%	5%	5%	45.67	24.30	18.44
Scenario 8	70%	10%	5%	5%	0%	5%	5%	36.78	18.10	15.09
Scenario 9	80%	10%	5%	0%	0%	0%	5%	28.89	15.40	12.25
Scenario 10	90%	10%	0%	0%	0%	0%	0%	20.00	13.20	11.40
Scenario 11	100%	0%	0%	0%	0%	0%	0%	11.11	8.00	11.56

Figure 4-8 shows the impact of different scenarios in which the condition percentage varies from 0% to 100%. In scenario 1, the condition distribution percentage is 0%, where the BRPRS is not based on condition category, but depends on other categories (Criticality, Risk, Functionally, Type, Age and Size).

The Very Important high investment (Portsmouth) bridge with the high consequence of failure is significantly sensitive to variation of the condition category percentage. When the condition distribution percentage is 0%, the BRPRS is at its highest level and it can easily reach 100 points. This is due to other categories being at the high percentage for such a bridge. As the condition category percentage increases, the BRPRS will decrease to a point where it exclusively depends on condition only. As shown in the Figure 3-3, the designed BRPRS warrants the very important bridges with extreme replacement costs and high consequence of failure to remain at the top of the list for MR&R and this ensures that these types of bridges are well maintained. Maintaining bridges in good condition has proven to extend service life and to be more cost effective versus allowing deterioration.

The average bridge is less impacted by variation in the condition category. When the condition percentage is 0%, the BRPRS can range from 40 to 70 points. The distribution percentage of other categories (Criticality, Risk, Functionally, Type, Age, and Size), as outlined in this Chapter is intended to distinguish similar average bridges by ranking them.

The Less Important bridges are hardly impacted by variation in condition category. Their percentage in other categories (Criticality, Risk, Functionally, Type, Age, and Size) is so low that the BRPRS scoring remains fairly constant, ranging from 10 (new bridge) to 40 (NBI condition <3) and they are not well maintained due to limited funding.

All 3 bridges' conditions are within 1 NBI rating when the condition percentage is at 100% (as seen in the graph). The BRPRS is most effective when the condition category is within 40% to 60%.

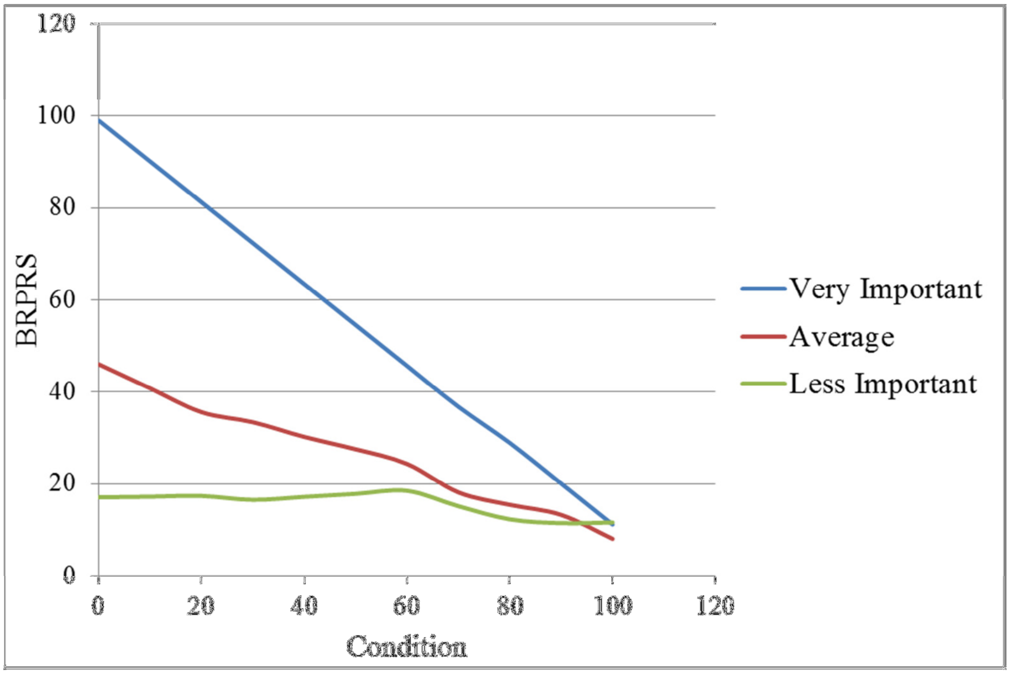


Figure 3-3 Variable Condition Distribution Rate

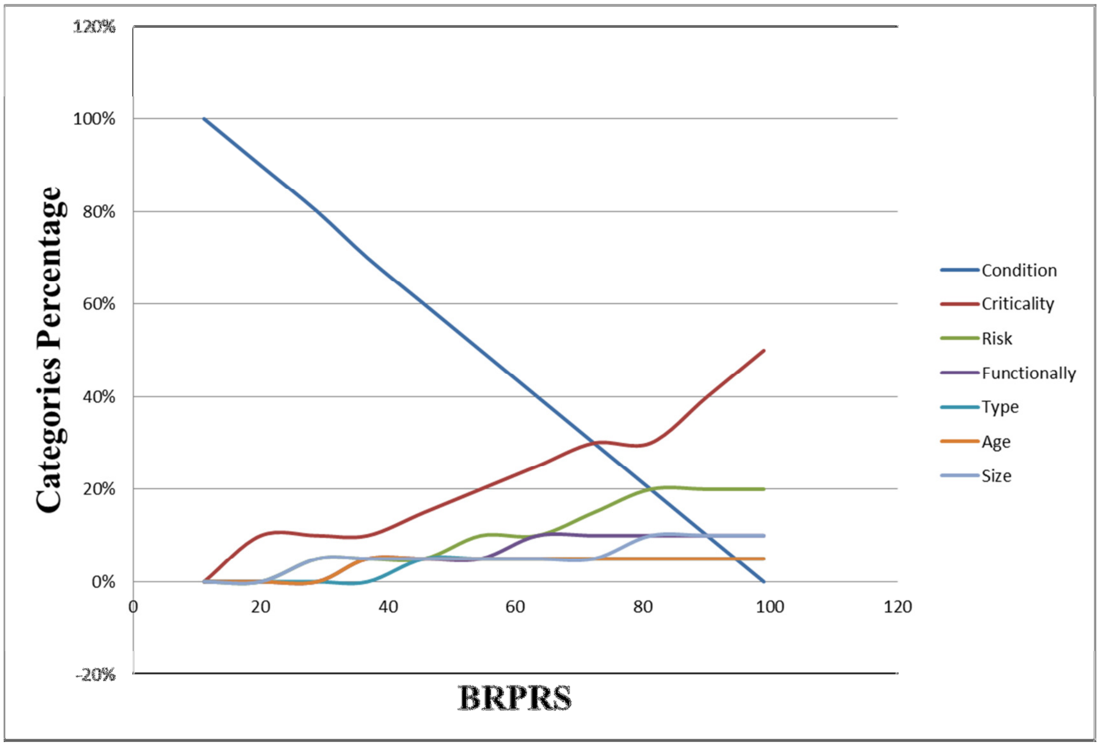


Figure 3-4 Variable Categories Distribution Rate

Figure 3-4 shows the percentage of each priority ranking system categories (condition, criticality, risk, functionally, bridge type, age, and size) in relations to BRPRS. The condition Parameter as discussed earlier has an inverse relationship with BRPRS, however, the other Parameters percentage increases as the BRPRS increases. While the bridge type can remain constant the transportation agencies can adjust the distribution factors of other priority ranking system categories based on their interest to justify the selection for MR&R project.

B. The NH Turnpikes System Data for the 170 bridge network was used to establish bridge priority ranking system for MR&R. Figure 3-9 represent the baseline for this analysis. 20 bridges were selected from the list with varying percentage distribution of each category, as shown in table 3-14. In this analysis in Risk category, the impact damage is eliminated due to lack of accurate accident records for impact damage.

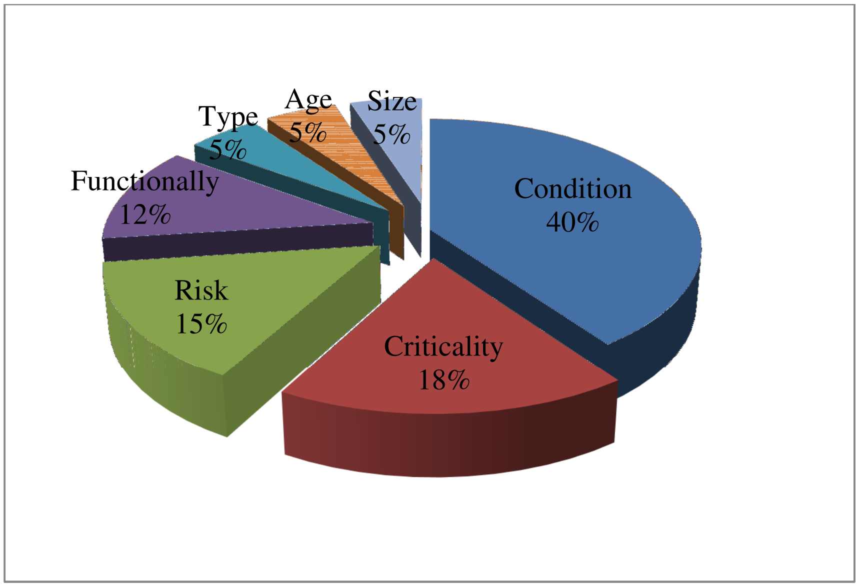


Figure 3-9 Default Priority Distribution

Table3-13 NH Turnpikes BRPRS

Town	BR #	Description	BCI	BRPRS
Portsmouth	**258/128**	I-95 over Piscataqua River Road, BMRR	72.22	63
Dover/ Newington	**201/025**	SB Sp. Tpk. over Little Bay	80.00	60
Dover/ Newington	**201/024**	NB Sp. Tpk over Little Bay	85.19	58
Hampton	**120/102**	I-95 over Taylor River	33.33	51
Manchester	**099/067**	F.E. Everett Turnpike NB over Black Brook	54.07	47
Nashua/ Hudson	**157/059**	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	45
Dover	**106/133**	Sp. Tpk. NB over Cocheco River	64.44	44
Dover	**105/133**	Sp. Tpk. SB over Cocheco River	69.63	43
Manchester	**099/066**	F.E. Everett Turnpike SB over Black Brook	48.89	43
Merrimack	**107/131**	Baboosic Road over FEET	48.89	43
Merrimack	**106/042**	F.E. Everett Turnpike SB over Pennichuck Brook	61.85	41
Merrimack	**107/042**	F.E. Everett Turnpike NB over Pennichuck Brook	61.85	41
Concord	**201/096**	F.E. Everett Turnpike SB over Hall St.	54.07	40
Nashua	**101/118**	F.E. Everett Turnpike NB over Nashua River	59.26	34
Concord	**203/090**	F.E. Everett Turnpike NB over B & M RR	85.19	34
Portsmouth	**190/118**	I-95 over Hodgson Brook	82.59	33
Nashua	**100/112**	F.E. Everett Turnpike SB over Canal Road	90.37	29
Nashua	**101/112**	F.E. Everett Turnpike NB over Canal Road	72.22	27
Bow	**158/137**	F.E. Everett Turnpike Over Dow Road	72.22	26
Hooksett	**071/138**	I-93 over Ramp A and B	87.78	25

The first 3 bridges in Table 3-13 with the highest BRPRS are the most important bridges in Turnpike's system and all 3 bridges have a high capital replacement cost. These bridges demonstrate the need to adjust weight factors in each bridge network being addressed. For example, NB Spaulding Turnpike over Little Bay Bridge with BCI 85.19 is ranked higher than I-95 over Taylor River Bridge with BCI of 33.33. The Spaulding Turnpike over Little Bay Bridges is far more important (major route connecting NH seacoast to northern country) and has a higher capital replacement cost than Taylor River Bridge.

Altering the decision variable outside of the recommended range, as shown in Table 3-15, illustrates ten different scenarios with different outcomes.

Table 3-14 Variable Distribution Rate B

Criteria	Scenario									
	1	2	3	4	5	6	7	8	9	10
Condition	60%	70%	80%	90%	30%	20%	10%	40%	40%	40%
Criticality	10%	10%	10%	10%	30%	35%	30%	40%	60%	10%
Risk	10%	5%	5%	0%	15%	20%	20%	5%	0%	10%
Functiona	5%	0%	0%	0%	10%	10%	25%	0%	0%	25%
Type	5%	5%	0%	0%	5%	5%	5%	5%	0%	5%
Age	5%	5%	5%	0%	5%	5%	5%	5%	0%	5%
Size	5%	5%	0%	0%	5%	5%	5%	5%	0%	5%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Scenario 1

Because the weighted percentage for Type, Age, and Size are low, the distribution rate will remain unchanged for Scenario 1 and 2. Increasing the condition weighted factor to 60% will reduce the distribution factor of Criticality, Risk, and Functionally to a combine of 25%, as shown in Table 3-14. In the Criticality group, the impact criteria will be eliminated and the effect of traffic volume, road classification, and the detour length will be reduced. The Risk group criteria will be reduced slightly. In the Functionality group, the shoulder width impact will be eliminated. This scenario is within the highest limit of recommendation with some impact on other groups.

Table 3-15 Scenario 1

Scenario 1									Condition	60%
Criticality			Risk					Functionally		
Traffic Volume	3		Scour Critical			3		Load Limit		1
Road Class	2		Flood			3		Vertical Clearance		1
Detour Length	3		Ice			3		Lane Width		1
Interstate	1		Fracture Critical member			3		Shoulder Width		0
Utility	1		Bridge Rail			3		Waterway Adequacy		1
Impact	0		Total			10		Mobility		1
Total	10							Total		5
Type	5		Age	5		Size	5			

Table 3-18 illustrates that the ranking scores have decreased and the top 4 bridges still have the highest BRPRS. The I-95 Bridge over Taylor River with a low NBI condition rating of 3 has gained the advantage over the more important bridge- NB Spaulding Turnpike over Little Bay which has an NBI condition rating of 7.67.

Table 3-16 Scenario 1Result

Scenario 1				
Town	BR #	Description	BCI	BRPRS
Portsmouth	**258/128**	I-95 over Piscataqua River Road, BMRR	72.22	46
Dover/ Newington	**201/025**	SB Sp. Tpk. over Little Bay	80.00	43
Hampton	**120/102**	I-95 over Taylor River	33.33	43
Dover/ Newington	**201/024**	NB Sp. Tpk over Little Bay	85.19	41
Manchester	**099/067**	Feet NB over Black Brook	54.07	39
Manchester	**099/066**	Feet SB over Black Brook	48.89	37
Merrimack	**107/131**	Baboosic Road over FEET	48.89	37
Dover	**106/133**	Sp. Tpk. NB over Cocheco River	64.44	36
Dover	**105/133**	Sp. Tpk. SB over Cocheco River	69.63	34
Merrimack	**106/042**	FEET SB over Pennichuck Brook	61.85	34
Merrimack	**107/042**	FEET NB over Pennichuck Brook	61.85	34
Concord	**201/096**	FEET SB over Hall St.	54.07	34
Nashua/ Hudson	**157/059**	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	34
Nashua	**101/118**	FEET NB over Nashua River	59.26	30
Portsmouth	**190/118**	I-95 over Hodgson Brook	82.59	26
Bow	**158/137**	FEET Over Dow Road	72.22	25
Concord	**203/090**	FEET NB over B & M RR	85.19	25
Nashua	**101/112**	FEET NB over Canal and Service Road	72.22	24
Nashua	**100/112**	FEET SB over Canal and Service Road	90.37	23
Hooksett	**071/138**	I-93 over Ramp A and B	87.78	21

Scenario 2

Increasing the condition weighting factor to 70% will reduce the distribution factor of Criticality, Risk, and Functionally groups to a combine of 15% and the Type, Age, and Size criteria will remain unchanged, as shown in Table 3-16.

The Criticality group weighting factor is the same as Scenario 1, however, the Risk factor will be reduced by more than 50% and the Functionally impact will be eliminated. Thus, the BRPRS (Bridge Repair Priority Ranking System) will not be impacted by load limit, vertical clearance, lane width, waterway adequacy, and mobility. The BRPRS scoring continues to drop and bridges with worse condition move up moderately. The I-95 bridge over Taylor River moves up to the number 1 spot.

Table 3-17 Scenario 2

Scenario 2				
Town	BR #	Description	BCI	BRPRS
Hampton	**120/102**	I-95 over Taylor River	33.33	41
Portsmouth	**258/128**	I-95 over Piscataqua River Road, BMRR	72.22	37
Dover/ Newington	**201/025**	SB Sp. Tpk. over Little Bay	80.00	35
Manchester	**099/067**	Feet NB over Black Brook	54.07	34
Manchester	**099/066**	Feet SB over Black Brook	48.89	34
Merrimack	**107/131**	Baboosic Road over FEET	48.89	34
Concord	**201/096**	FEET SB over Hall St.	54.07	33
Dover/ Newington	**201/024**	NB Sp. Tpk over Little Bay	85.19	32
Dover	**106/133**	Sp. Tpk. NB over Cocheco River	64.44	32
Merrimack	**106/042**	FEET SB over Pennichuck Brook	61.85	31
Merrimack	**107/042**	FEET NB over Pennichuck Brook	61.85	31
Dover	**105/133**	Sp. Tpk. SB over Cocheco River	69.63	31
Nashua/ Hudson	**157/059**	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	29
Nashua	**101/118**	FEET NB over Nashua River	59.26	27
Bow	**158/137**	FEET Over Dow Road	72.22	24
Portsmouth	**190/118**	I-95 over Hodgson Brook	82.59	23
Concord	**203/090**	FEET NB over B & M RR	85.19	22
Nashua	**101/112**	FEET NB over Canal and Service Road	72.22	21
Nashua	**100/112**	FEET SB over Canal and Service Road	90.37	20
Hooksett	**071/138**	I-93 over Ramp A and B	87.78	18

Scenario 3

Increasing the condition weighted factor to 80% will reduce the distribution factor of Criticality, Risk, and Functionally groups to a combine of 15% and eliminates

Type and Size criteria. The Criticality group weighted factor is the same as Scenario 1 however, the Risk factor will be reduced by more than 50% and the Functionally impact will be eliminated. Thus, the BRPRS will not be impacted by load limit, vertical clearance, lane width, waterway adequacy, mobility, bridge type, and bridge size. The BRPRS scoring continues to drop and the gap between bridges with worse condition and important bridges is getting wider.

Table 3-18 Scenario 3

Scenario 3				
Town	BR #	Description	BCI	BRPRS
Hampton	**120/102**	I-95 over Taylor River	33.33	39
Portsmouth	**258/128**	I-95 over Piscataqua River Road, BMRR	72.22	28
Dover/ Newington	**201/025**	SB Sp. Tpk. over Little Bay	80.00	26
Manchester	**099/067**	Feet NB over Black Brook	54.07	29
Manchester	**099/066**	Feet SB over Black Brook	48.89	29
Merrimack	**107/131**	Baboosic Road over FEET	48.89	29
Concord	**201/096**	FEET SB over Hall St.	54.07	28
Dover/ Newington	**201/024**	NB Sp. Tpk over Little Bay	85.19	24
Dover	**106/133**	Sp. Tpk. NB over Cocheco River	64.44	26
Merrimack	**106/042**	FEET SB over Pennichuck Brook	61.85	25
Merrimack	**107/042**	FEET NB over Pennichuck Brook	61.85	25
Dover	**105/133**	Sp. Tpk. SB over Cocheco River	69.63	25
Nashua/ Hudson	**157/059**	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	21
Nashua	**101/118**	FEET NB over Nashua River	59.26	25
Bow	**158/137**	FEET Over Dow Road	72.22	17
Portsmouth	**190/118**	I-95 over Hodgson Brook	82.59	17
Concord	**203/090**	FEET NB over B & M RR	85.19	19
Nashua	**101/112**	FEET NB over Canal and Service Road	72.22	18
Nashua	**100/112**	FEET SB over Canal and Service Road	90.37	13
Hooksett	**071/138**	I-93 over Ramp A and B	87.78	12

Scenario 4

Increasing the condition weighted factor to 90% and the Criticality with 10%, will eliminate the other criteria, as shown in Table 3-19.

The Criticality group has a minor impact on BRPRS and will be based mostly on condition. This scenario is almost based on worst first. The most important bridges’ rankings drop significantly.

Table 3-19 Scenario 4 Criteria

Scenario 4							Condition	90%
Criticality			Risk				Functionally	
Traffic Volume	3		Scour Critical		0		Load Limit	0
Road Class	2		Flood		0		Vertical Clearance	0
Detour Length	3		Ice		0		Lane Width	0
Interstate	1		Fracture Critical member		0		Shoulder Width	0
Utility	1		Bridge Rail		0		Waterway Adequacy	0
Impact	0		Total		0		Mobility	0
Total	10						Total	0
Type	0		Age	0	Size	0		

Table 3-20 Scenario 4

Scenario 4				
Town	BR #	Description	BCI	BRPRS
Hampton	120/102	I-95 over Taylor River	33.33	34
Concord	201/096	FEET SB over Hall St.	54.07	24
Manchester	099/066	Feet SB over Black Brook	48.89	23
Merrimack	107/131	Baboosic Road over FEET	48.89	23
Manchester	099/067	Feet NB over Black Brook	54.07	23
Portsmouth	258/128	I-95 over Piscataqua River Road, BMRR	72.22	20
Dover	106/133	Sp. Tpk. NB over Cocheco River	64.44	20
Merrimack	106/042	FEET SB over Pennichuck Brook	61.85	19
Merrimack	107/042	FEET NB over Pennichuck Brook	61.85	19
Nashua	101/118	FEET NB over Nashua River	59.26	19
Dover	105/133	Sp. Tpk. SB over Cocheco River	69.63	18
Dover/ Newington	201/025	SB Sp. Tpk. over Little Bay	80.00	17
Dover/ Newington	201/024	NB Sp. Tpk over Little Bay	85.19	15
Nashua/ Hudson	157/059	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	13
Concord	203/090	FEET NB over B & M RR	85.19	13
Nashua	101/112	FEET NB over Canal and Service Road	72.22	12
Bow	158/137	FEET Over Dow Road	72.22	12
Portsmouth	190/118	I-95 over Hodgson Brook	82.59	11
Hooksett	071/138	I-93 over Ramp A and B	87.78	6
Nashua	100/112	FEET SB over Canal and Service Road	90.37	5

Scenario 5

Decreasing the condition weighted factor to 30% will result in increasing other factors. In this scenario, the Criticality group (traffic volume, road classification, detour length, interstate, utility, economic, environmental, and societal) have a higher impact on BRPRS. Table 3-21 illustrates the BRPRS numbers increase and important bridges have a higher ranking than bridges with worse conditions.

Table 3-21 Scenario 5

Scenario 5				
Town	BR #	Description	BCI	BRPRS
Portsmouth	258/128	I-95 over Piscataqua River Road, BMRR	72.22	72
Dover/ Newington	201/025	SB Sp. Tpk. over Little Bay	80.00	69
Dover/ Newington	201/024	NB Sp. Tpk over Little Bay	85.19	68
Hampton	120/102	I-95 over Taylor River	33.33	59
Nashua/ Hudson	157/059	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	53
Manchester	099/067	Feet NB over Black Brook	54.07	51
Dover	106/133	Sp. Tpk. NB over Cocheco River	64.44	50
Dover	105/133	Sp. Tpk. SB over Cocheco River	69.63	50
Manchester	099/066	Feet SB over Black Brook	48.89	46
Merrimack	107/131	Baboosic Road over FEET	48.89	46
Concord	201/096	FEET SB over Hall St.	54.07	46
Merrimack	106/042	FEET SB over Pennichuck Brook	61.85	45
Merrimack	107/042	FEET NB over Pennichuck Brook	61.85	45
Concord	203/090	FEET NB over B & M RR	85.19	42
Portsmouth	190/118	I-95 over Hodgson Brook	82.59	38
Nashua	101/118	FEET NB over Nashua River	59.26	37
Nashua	100/112	FEET SB over Canal and Service Road	90.37	30
Nashua	101/112	FEET NB over Canal and Service Road	72.22	28
Bow	158/137	FEET Over Dow Road	72.22	27
Hooksett	071/138	I-93 over Ramp A and B	87.78	26

Scenario 6 and 7

Decreasing the condition weighted factor to 20% and 10% will result in the increasing of the Criticality and Risk groups. In this scenario, the bridge condition has a minor impact on BRPRS. The important bridges have a significant lead on bridges with the worse condition and they will be well maintained while the less important bridges' conditions continue to deteriorate. Due to lack of funding, a fair number of municipal bridges are in this predicament.

Table 3-22 Scenario 6

Scenario 6				
Town	BR #	Description	BCI	BRPRS
Portsmouth	258/128	I-95 over Piscataqua River Road, BMRR	72.22	81
Dover/ Newington	201/025	SB Sp. Tpk. over Little Bay	80.00	79
Dover/ Newington	201/024	NB Sp. Tpk over Little Bay	85.19	77
Hampton	120/102	I-95 over Taylor River	33.33	65
Nashua/ Hudson	157/059	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	59
Manchester	099/067	Feet NB over Black Brook	54.07	56
Dover	106/133	Sp. Tpk. NB over Cocheco River	64.44	55
Dover	105/133	Sp. Tpk. SB over Cocheco River	69.63	55
Manchester	099/066	Feet SB over Black Brook	48.89	50
Merrimack	107/131	Baboosic Road over FEET	48.89	50
Merrimack	106/042	FEET SB over Pennichuck Brook	61.85	49
Merrimack	107/042	FEET NB over Pennichuck Brook	61.85	49
Concord	201/096	FEET SB over Hall St.	54.07	48
Concord	203/090	FEET NB over B & M RR	85.19	46
Portsmouth	190/118	I-95 over Hodgson Brook	82.59	43
Nashua	101/118	FEET NB over Nashua River	59.26	40
Nashua	100/112	FEET SB over Canal and Service Road	90.37	34
Nashua	101/112	FEET NB over Canal and Service Road	72.22	31
Bow	158/137	FEET Over Dow Road	72.22	28
Hooksett	071/138	I-93 over Ramp A and B	87.78	28

Table 3-23 Scenario 7

Scenario 7				
Town	BR #	Description	BCI	BRPRS
Portsmouth	258/128	I-95 over Piscataqua River Road, BMRR	72.22	90
Dover/ Newington	201/025	SB Sp. Tpk. over Little Bay	80.00	85
Dover/ Newington	201/024	NB Sp. Tpk over Little Bay	85.19	84
Hampton	120/102	I-95 over Taylor River	33.33	62
Nashua/ Hudson	157/059	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	61
Manchester	099/067	Feet NB over Black Brook	54.07	58
Dover	106/133	Sp. Tpk. NB over Cocheco River	64.44	56
Dover	105/133	Sp. Tpk. SB over Cocheco River	69.63	56
Manchester	099/066	Feet SB over Black Brook	48.89	51
Merrimack	107/131	Baboosic Road over FEET	48.89	51
Merrimack	106/042	FEET SB over Pennichuck Brook	61.85	51
Merrimack	107/042	FEET NB over Pennichuck Brook	61.85	51
Concord	201/096	FEET SB over Hall St.	54.07	49
Concord	203/090	FEET NB over B & M RR	85.19	48
Portsmouth	190/118	I-95 over Hodgson Brook	82.59	43
Nashua	101/118	FEET NB over Nashua River	59.26	40
Nashua	100/112	FEET SB over Canal and Service Road	90.37	35
Hooksett	071/138	I-93 over Ramp A and B	87.78	32
Nashua	101/112	FEET NB over Canal and Service Road	72.22	32
Bow	158/137	FEET Over Dow Road	72.22	29

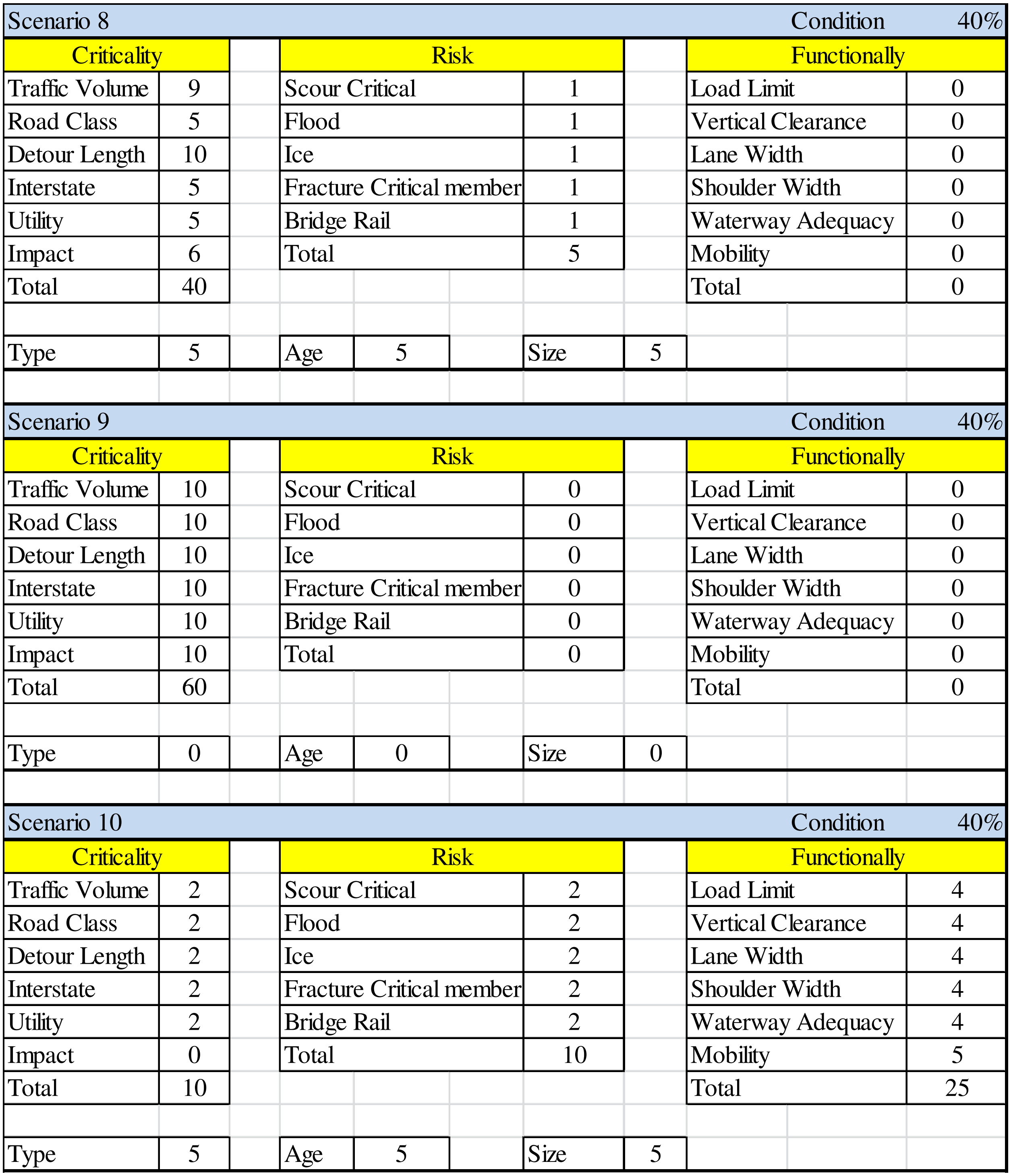
Scenario 8 and 9

In Scenario 8 to 10 the condition weighted factor remains at 40% while the factors can be variable, as shown in the Table 3-24. Scenario 8 has more emphasis on Criticality, while Scenario 9 has a higher impact on Risk and Functionally.

Scenario 10

In this scenario, the bridge condition has the weighing factor of 40% however, the condition is not a controlling factor since it is less than 50%. Second to condition is functionally with weighing factor of 25% and the other major category such as criticality and risk each has a 10% weighing factor. As shown in table 4-23, scenario 10 utilizes all important parameters that contribute to the priority ranking. With exception of condition the three major factors (criticality, risk and functionally (CRF)) combine 45% weighing factor which is greater than condition weighing factor therefore, CRF has the controlling influence on the outcome of priority ranking. Within CRF the functionally has a significant impact on ranking; the functionally is subdivided into load limit, vertical clearance, lane width, shoulder width, waterway adequacy and mobility, whereas these factors influence the decision making on MR&R activities. Bridges that are structurally deficient or functionally obsolete will be rank higher than important bridges.

Table 3-24 Scenarios 8, 9, and 10



Scenario 8				Condition	40%
Criticality		Risk		Functionally	
Traffic Volume	9	Scour Critical	1	Load Limit	0
Road Class	5	Flood	1	Vertical Clearance	0
Detour Length	10	Ice	1	Lane Width	0
Interstate	5	Fracture Critical member	1	Shoulder Width	0
Utility	5	Bridge Rail	1	Waterway Adequacy	0
Impact	6	Total	5	Mobility	0
Total	40			Total	0
Type	5	Age	5	Size	5

Scenario 9				Condition	40%
Criticality		Risk		Functionally	
Traffic Volume	10	Scour Critical	0	Load Limit	0
Road Class	10	Flood	0	Vertical Clearance	0
Detour Length	10	Ice	0	Lane Width	0
Interstate	10	Fracture Critical member	0	Shoulder Width	0
Utility	10	Bridge Rail	0	Waterway Adequacy	0
Impact	10	Total	0	Mobility	0
Total	60			Total	0
Type	0	Age	0	Size	0

Scenario 10				Condition	40%
Criticality		Risk		Functionally	
Traffic Volume	2	Scour Critical	2	Load Limit	4
Road Class	2	Flood	2	Vertical Clearance	4
Detour Length	2	Ice	2	Lane Width	4
Interstate	2	Fracture Critical member	2	Shoulder Width	4
Utility	2	Bridge Rail	2	Waterway Adequacy	4
Impact	0	Total	10	Mobility	5
Total	10			Total	25
Type	5	Age	5	Size	5

Scenario 8				
Town	BR #	Description	BCI	BRPRS
Portsmouth	258/128	I-95 over Piscataqua River Road, BMRR	72.22	63
Dover/ Newington	201/025	SB Sp. Tpk. over Little Bay	80.00	62
Dover/ Newington	201/024	NB Sp. Tpk over Little Bay	85.19	60
Hampton	120/102	I-95 over Taylor River	33.33	63
Nashua/ Hudson	157/059	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	51
Manchester	099/067	Feet NB over Black Brook	54.07	47
Dover	106/133	Sp. Tpk. NB over Cocheco River	64.44	49
Dover	105/133	Sp. Tpk. SB over Cocheco River	69.63	48
Manchester	099/066	Feet SB over Black Brook	48.89	43
Merrimack	107/131	Baboosic Road over FEET	48.89	43
Merrimack	106/042	FEET SB over Pennichuck Brook	61.85	41
Merrimack	107/042	FEET NB over Pennichuck Brook	61.85	41
Concord	201/096	FEET SB over Hall St.	54.07	48
Concord	203/090	FEET NB over B & M RR	85.19	44
Portsmouth	190/118	I-95 over Hodgson Brook	82.59	36
Nashua	101/118	FEET NB over Nashua River	59.26	35
Nashua	100/112	FEET SB over Canal and Service Road	90.37	25
Hooksett	071/138	I-93 over Ramp A and B	87.78	23
Nashua	101/112	FEET NB over Canal and Service Road	72.22	23
Bow	158/137	FEET Over Dow Road	72.22	26

Scenario 9				
Town	BR #	Description	BCI	BRPRS
Hampton	120/102	I-95 over Taylor River	33.33	71
Portsmouth	258/128	I-95 over Piscataqua River Road, BMRR	72.22	64
Dover/ Newington	201/025	SB Sp. Tpk. over Little Bay	80.00	63
Dover/ Newington	201/024	NB Sp. Tpk over Little Bay	85.19	62
Nashua/ Hudson	157/059	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	50
Concord	203/090	FEET NB over B & M RR	85.19	50
Concord	201/096	FEET SB over Hall St.	54.07	49
Dover	106/133	Sp. Tpk. NB over Cocheco River	64.44	48
Dover	105/133	Sp. Tpk. SB over Cocheco River	69.63	47
Manchester	099/067	Feet NB over Black Brook	54.07	43
Manchester	099/066	Feet SB over Black Brook	48.89	38
Merrimack	107/131	Baboosic Road over FEET	48.89	38
Merrimack	106/042	FEET SB over Pennichuck Brook	61.85	36
Merrimack	107/042	FEET NB over Pennichuck Brook	61.85	36
Portsmouth	190/118	I-95 over Hodgson Brook	82.59	33
Nashua	101/118	FEET NB over Nashua River	59.26	31
Nashua	101/112	FEET NB over Canal and Service Road	72.22	16
Bow	158/137	FEET Over Dow Road	72.22	16
Hooksett	071/138	I-93 over Ramp A and B	87.78	14
Nashua	100/112	FEET SB over Canal and Service Road	90.37	14

Table -25 Scenarios 8, 9 and 10 Outcome

Scenario 10				
Town	BR #	Description	BCI	BRPRS
Portsmouth	**258/128**	I-95 over Piscataqua River Road, BMRR	72.22	63
Dover/ Newington	**201/025**	SB Sp. Tpk. over Little Bay	80.00	57
Dover/ Newington	**201/024**	NB Sp. Tpk over Little Bay	85.19	55
Manchester	**099/067**	Feet NB over Black Brook	54.07	45
Hampton	**120/102**	I-95 over Taylor River	33.33	44
Manchester	**099/066**	Feet SB over Black Brook	48.89	41
Merrimack	**107/131**	Baboosic Road over FEET	48.89	41
Dover	**106/133**	Sp. Tpk. NB over Cocheco River	64.44	41
Nashua/ Hudson	**157/059**	WB Connector over B & M RR and Merrimack River Sagamore Bridge	85.19	40
Dover	**105/133**	Sp. Tpk. SB over Cocheco River	69.63	40
Merrimack	**106/042**	FEET SB over Pennichuck Brook	61.85	39
Merrimack	**107/042**	FEET NB over Pennichuck Brook	61.85	39
Concord	**201/096**	FEET SB over Hall St.	54.07	38
Concord	**203/090**	FEET NB over B & M RR	85.19	31
Nashua	**101/118**	FEET NB over Nashua River	59.26	31
Portsmouth	**190/118**	I-95 over Hodgson Brook	82.59	29
Hooksett	**071/138**	I-93 over Ramp A and B	87.78	28
Nashua	**100/112**	FEET SB over Canal and Service Road	90.37	27
Bow	**158/137**	FEET Over Dow Road	72.22	26
Nashua	**101/112**	FEET NB over Canal and Service Road	72.22	25

4-14 Summary

In this Chapter, a methodology for priority ranking of bridges for MR&R is proposed. The prioritization is based on a multi-criteria type of analysis, a priority ranking is computed for each bridge, the ranking index is expressed as a number from 0 (least candidate for rehabilitation and replacement) to 100 (most preferred candidate for rehabilitation and replacement) which enables the project managers and the decision-makers to understand and compare the overall health of various bridges in the network. The advantage of this system is that it provides flexibility to the bridge owners to adjust the weighing factor based on their own interest, however, the adjustment must be within recommended weighing factor and the changes must be on the network level. This priority ranking system is designed to integrate with the proposed forecasting model outlined in Chapter 4. The drawback of this system is the weighing factor which is based on engineering experience and judgment which can be biased.

Chapter 4: Forecasting Model

4.1 General

A bridge forecasting model is a vital part of decision making within any BMS, it extends the service life of a bridge by keeping the bridge above a minimum acceptable condition at minimum maintenance cost. Today's increasing average truck/vehicle miles per gallon is significantly decreasing transportation infrastructure budgets making it more difficult to sustain desirable network bridge inventories above minimum condition assessments. A forecasting model evaluates MR&R strategies for preparing and defending budgets; bridge managers need decision support systems to help them manage their bridge infrastructure (Mirza and Haider 2003, Vanier 2000).

This Chapter presents a deterioration model, an MR&R cost model, and preservation strategies. The deterioration model is based on artificial intelligence (AI) techniques using a case-based reasoning (CBR) method, the MR&R cost model evaluates the repair alternatives including the cost estimate and scheduling, the preservation strategies provide 120 years of preservation, repair and reconstruct plans for each bridge in a network.

4.2 Deterioration Model

A deterioration model is one of the minimum requirements of any Bridge Management System (AASHTO, 1993). Infrastructure deterioration is caused by climatic exposure, traffic volume, insufficient financial resources, and absence of a network management system. State DOTs and municipalities are recognizing the need to implement effective tools to better manage transportation infrastructure networks, and are now demanding decision-support tools (Vanier, 2000).

In Chapter 2 various deterioration models were discussed, the proposed deterioration model for this research is based on an artificial intelligence (AI) method. AI includes several different methods that have been utilized in a variety of applications during the last few decades. Some of these models are artificial neural networks (ANNs), machine learning (ML), and case based reasoning (CBR), and that have been recognized as powerful tools solving numerous engineering problems.

4.2.1 Case Based Reasoning (CBR)

The AI Case-based reasoning (CBR) model developed in 1980s, addresses new problems based on solutions implemented on past problems. The CBR field has grown rapidly over the past three decades and has become a powerful technique for computer reasoning. The case-based reasoning approach is fundamentally different from other major AI approaches (Aamodt, 1994). CBR approach uses the detailed knowledge of previously experienced, tangible problem circumstances, instead of relying only on general knowledge of a problem. The primary recording knowledge source is not generalized rules but a database of stored detailed descriptions pertaining to previous experiences. A new problem is solved by finding a comparable past case and applying those aspects to address a new problem. Every time a new experience is stored it becomes immediately available for future problems. Much of the original inspiration for the CBR approach came from the role of reminding in human reasoning (Schank, 1982 and Kolodner, 1984). CBR is used in everyday normal life for example an auto mechanic who repairs a car by remembering another car exhibiting similar symptoms or a medical doctor treating a new patient for a specific disease using his/her or recorded experiences with other cases with similar symptoms. These case databases can be exploited even if they are only partially matching the current problem. This knowledge is improved by adding new cases and without facing the problems of knowledge acquisition or rule coverage as in rule-based expert systems (ES) (Roddis and Bocox 1997).

Morcous (2000) developed Case-based reasoning for modeling concrete bridge decks using data obtained from the Quebec Ministry of Transportation. The system was developed based on the assumption that two bridges that have similar structures, operations and managed under similar conditions will have the same performance. A library of cases with known parameters and performances becomes available to enable the performance of a new case to be examined by retrieving a similar case from the case library.

4.2.2 CBR Model

Case-based reasoning systems are based on a four-step process (Aamodt, 1994):

1. Retrieve: Case or cases from the BMS database in a defined single case category are evaluated. The goal of CBR is to retrieve the "most similar" case or a set of similar cases which are called proposed solutions (Leake, 1996).
2. Reuse: Utilization of information and knowledge from selected cases and adapting the solutions to address a new problem.
3. Revise: Test the new solution and revise for future use. Learning in CBR systems is by adding new cases with sufficient detail to expand the information base.
4. Retain: Store the experience gained from all new cases, to continuously upgrade the database to include the use of new materials and procedures for use in future problem solving.

Figure 4-1 illustrates the CBR process based on the aforementioned steps. First, a new problem (new case) is solved by the CBR program by searching the case database library for one or more recorded cases similar to the new problem. Second, the CBR program reuses the retrieved cases and selects the solution of the best-matched problem and recommends a solution to an existing problem. Third, CBR through revised process evaluates this solution between the new problem and the retrieved cases. The revised solution is, then, evaluated for potential success and modified if necessary. Fourth, CBR approach continually expands the case database library by adding a new learned case, and supplementing existing cases when appropriate.

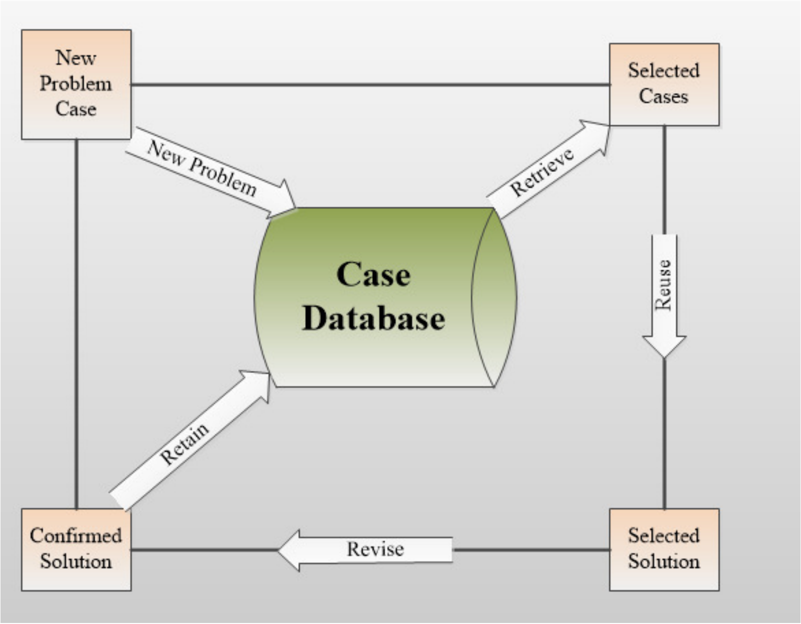


Figure 4-1 CBR process

4.2.3 Bridge components Case Development

The Retrieval process begins with an initial problem description and ends when best matching previous case/cases have been found. It is imperative that the CBR case library and analysis approach follows appropriate knowledge level modeling methods in defined cases, particularly the components of expertise methodology (Steels-90). There have been many CBR systems developed such as CB-BFX (case-based bridge fabrication error solution expert system) a system for resolving fabrication errors in steel highway bridges (Roddis and Bocox, 1997), Integrated Case-Based Reasoning for Structural Design (Wang, J. 1992), is a framework for case-based reasoning in engineering design (Kumar and Krishnamoorthy, 1995) and improving concrete placement simulation with a case-based reasoning input (Graham et al., 2004). Since a problem is solved by retrieving previous suitable cases, a case searches and matching processes should both be effective and reasonably time efficient. The challenge is finding an appropriate configuration for describing case contents, and how it should be organized for effective retrieval and reuse. Bridge structures are very complex and representing them is not a simple task (Haque, 1997).

A similarity measure of classification is developed to identify how close the characteristics of bridge components are to each other based on scoring system values between 0 and 100, where 100 is totally similar and 0 is completely dissimilar. The CBR bridge deterioration model methodology is based on the similarity in the performance among bridges under similar environmental conditions, traffic volume, analogous operating condition, matching bridge type and material, and the equivalent level of preventive maintenance. The bridge components (deck, superstructure, and substructure) case matching process are based on the parameters as illustrated in Figure 4-3A, 4-4 and 4-5. For example, the following are the parameters for a bridge structure:

1. *Bridge Structure Type*, there are many different types of bridges, the most common ones in the State of New Hampshire are girder or beam type, culvert, timber, truss and moveable. Figure 4-2 indicates the percentage of each bridge type and deck surface area; there are only four moveable bridges in New Hampshire.

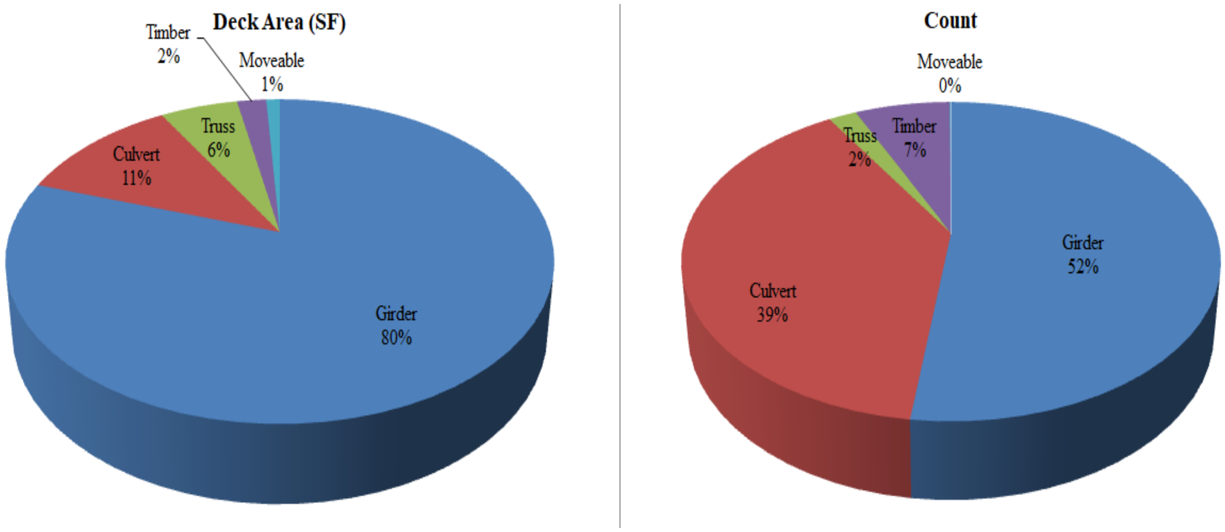


Figure 4-2 NHDOT Bridge Type

2. *Bridge Deck Types*, A bridge deck is the most vulnerable component in a bridge. A severe environment, an increase in traffic volume, and aging are the main reasons for rapid bridge deck deterioration. There are three common materials used in the construction of bridge decks, as shown in Figure 4-3 they include concrete, steel, and timber.

   a. Concrete decks are the most common bridge deck type due to its workability to form in various shapes and sizes and are the most flexible alternative for the bridge designer and the bridge builder; it is most adaptive to a variety of construction techniques. However, concrete being weak in tension, it requires reinforcement thus receptive to corrosive deterioration. As indicated in Figure 4-3 there are several common types of concrete decks including, reinforced cast-in-place (CIP), precast, prestressed deck panels and precast prestressed deck panels with a cast-in-place topping. It is very important to identify the type of rebar used in the bridge deck. Concrete with black rebar deteriorate faster than coated and stainless steel rebar and some fiber reinforced plastics

   b. Steel decks are composed of either solid steel plate or steel grids. There are three common types of steel decks shown in Figure 4-3, which includes; corrugated steel flooring, orthotropic grid deck, and open, filled, or partially filled.

c. Timber decks are considered non-composite this is due to inefficient shear transfer through the attachment devices between the deck and superstructure. There are some steel bridges with timber decking. Timber is relatively easy to fabricate, and timber can also withstand significant loads over a short period of time and are locally available. There are few basic types of timber deck (Figure 4-3); plank decks, glued-laminated deck panels, nailed laminated decks, stressed-laminated decks and structural composite lumber decks.

3. *Wearing surface* is a thin layer, less than 3 inches, placed on the bridge deck to seal and protect the bridge deck from traffic and weather conditions. The basic type of wearing surface classification for each bridge deck types includes (Figure 4-3); bituminous overlay, membrane and bituminous overlay, thin overlay, rigid overlay, timber planks, concrete and serrated steel.
4. *District*; most DOTs are divided into small districts and each district maintains their roads and bridges as does each municipality at different condition levels which can have a significant effect on deterioration rate and must be classified accordingly to maintenance protocol. For example, Turnpike districts wash their bridges every year while other DOT districts

and municipalities never wash their bridges. A primary issue is the application of de-icing chemicals typically used in urban areas.

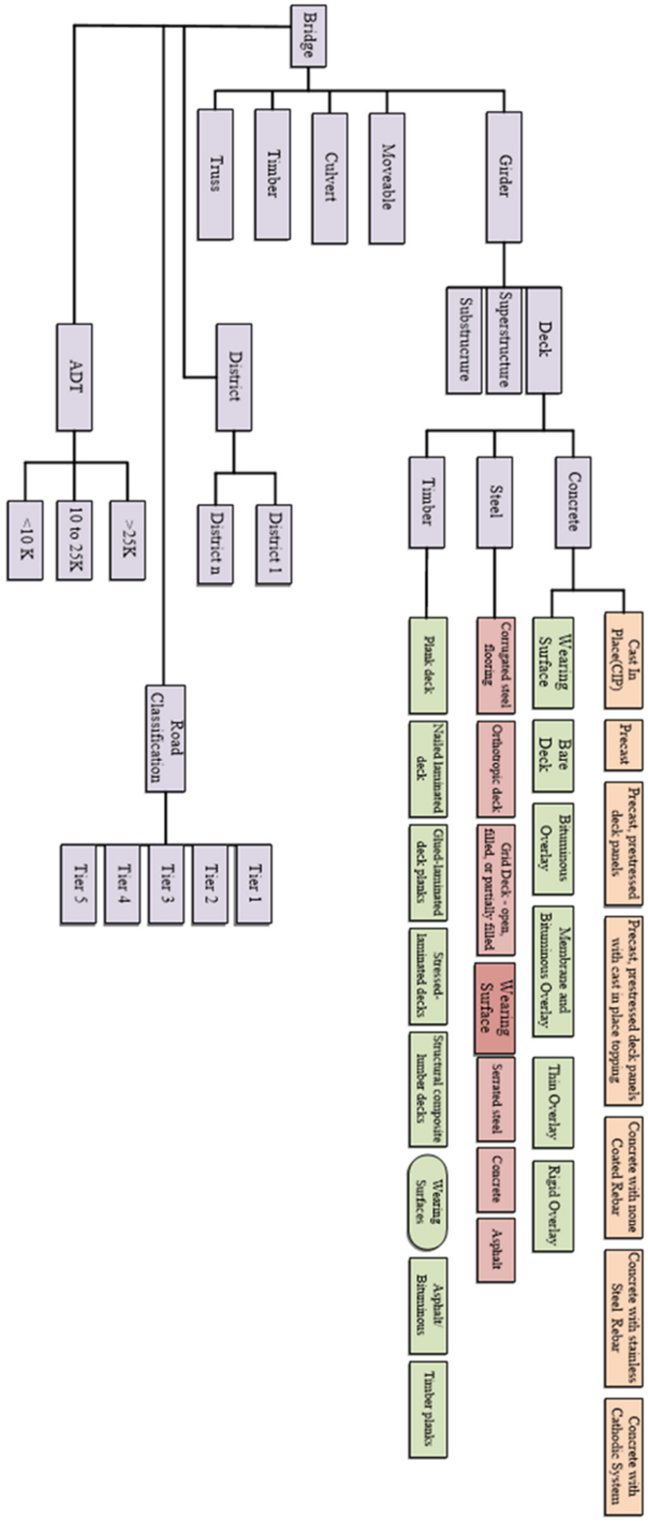


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Figure 4-3 CBR Bridge Deck Matching Case Process

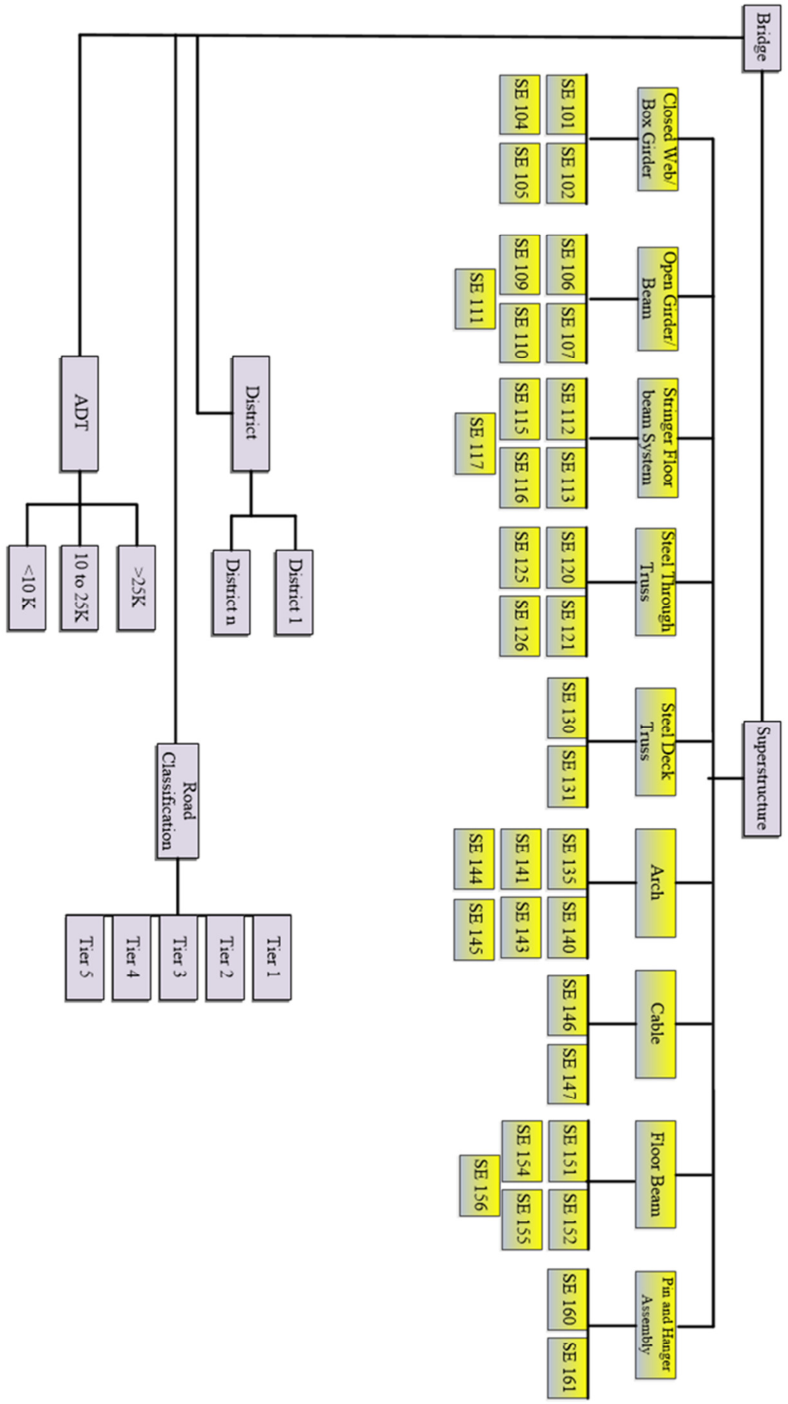


Figure 4-4 CBR Bridge Superstructure Matching Case Process

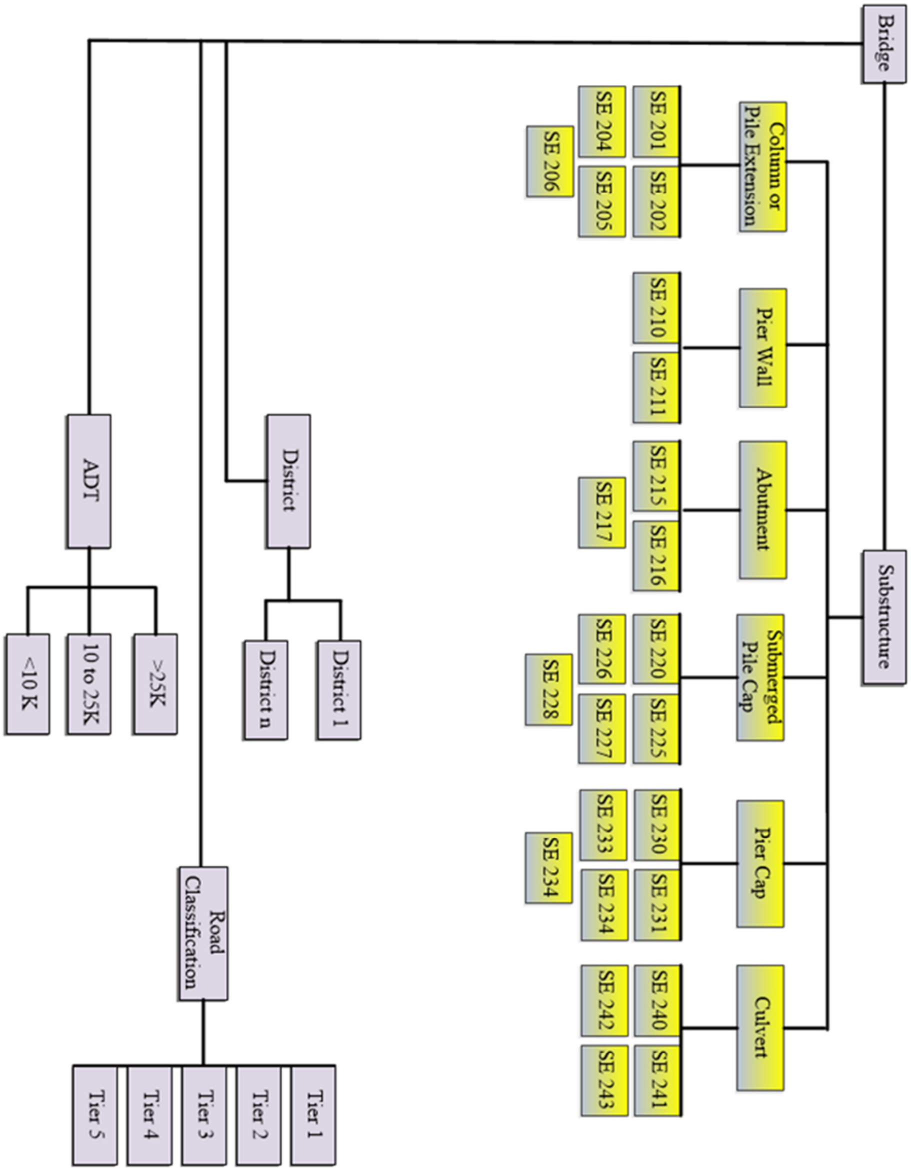


Figure 4-5 CBR Bridge Substructure Matching Case Process

5. *ADT*; the average daily traffic is subdivided into 3 case categories (Figure 4-3). Each category is based on the volume of traffic, case category 1 being ADT>25,000, case category 2 ADT of 10,000 to 25,000 and case category 3 with ADT< 10,000.
6. *Road Classification*; there are various types of roads (interstate, state routes, recreational road, town and city streets, rural highways and unmaintained roads) within each highway network which receives different levels of maintenance classification.

The matching process for superstructure and substructure is like the aforementioned process, the material types as shown in Figure 4-4 and Figure 4-5 must match exactly within a classification. A complete list of all structural elements used to define a classification (SE) is shown in Appendix C.

Inspection history of over 2000 bridges provided by NHDOT is used to define cases based on aforementioned requirements .The inspection history with NBI condition ratings are available from late 1970s to present.

5.2.4 Matching Process

The case matching process is based on a scoring system value between 0 and 100 where 100 is totally similar (problem bridge is similar to the case bridge) and 0 is completely dissimilar. The matching type for bridge deck is illustrated in table 4-1 and the scoring system used to define cases is shown in table 4-2. The case library database for this model consists of over 2000 bridges provided by NHDOT. The case library database includes three categories: A) Statewide Case Bridge which is a group of bridges that have a 70% or more similarities based on criteria shown in table 4-2. B) Average Case Bridge (ACB) includes groups of bridges with 90% similarities and C) Refined Case Bridges are ACB bridges that are within same district and similar roadway system. Table 4-2 is an example of girder bridge type.

Table 4-1 Bridge Deck Matching Type

Deck Type		Bridge Type	
A	Cast in place with none coated rebar		Girder
B	Cast in place with coated rebar		Timber
C	Precast		Culvert
D	Precast Prestressed deck panels		Truss
E	Precast Prestressed deck panels with cast in place toping		Ridged Frame
F	Corrugated steel flooring		
G	Orthotropic deck	ADT	
H	Grid Deck - open, filled, or partially filled	1	>= 25000
I	Plank deck Timber	2	10000 to 25000
J	Nailed laminated deck	3	<10000
K	Glued-laminated deck planks		
L	Stressed-laminated decks	Wearing Surface	
M	Structural composite lumber decks	1	Membrane with Asphalt Bituminous
		2	Concrete
Road Classifacation		3	Timber Planks
Tier 1	Interstates, Turnpikes, and Divided Highways	4	Serrated steel
Tier 2	Statewide Corridors		
Tier 3	Regional Transportation Corridors	District	
Tier 4	Local Connectors	1	Highway Maintenance
Tier 5	Local Roads	n	

Table 4-2 Matching Type Value

Category	Statewide (70)	Average Case (90)	Refined Case (>90)
Matching Type	Point	Point	Point
Bridge Type	30	30	30
Deck Type	30	30	30
Wearing Surface	10	10	10
District	NA	NA	10
Road Class	NA	10	10
ADT	NA	10	10
Total	70	90	100

Table 4-3 Girder Bridge Matching Type

	Category	Statewide (70)					
		Average Case (90)					
		Refined Case (>90)					
	Matching Type	Bridge Type (30)	Deck Type (30)	Wearing Surface (10)	ADT (20)	Road Class (5)	District (5)
Concrete Deck	**State Wide Case A**	Girder	A				
	State Wide Case B	Girder	B				
	State Wide Case C	Girder	C				
	State Wide Case D	Girder	D				
	State Wide Case E	Girder	E				
	Case Bridge A1	Girder	A		1		
	Case Bridge A2	Girder	A		2		
	Case Bridge A3	Girder	A		3		
	Case Bridge B1	Girder	B		1		
	Case Bridge B2	Girder	B		2		
	Case Bridge B3	Girder	B		3		
	Case Bridge C1	Girder	C		1		
	Case Bridge C2	Girder	C		2		
	Case Bridge C3	Girder	C		3		
	Case Bridge D1	Girder	D		1		
	Case Bridge D2	Girder	D		2		
	Case Bridge D3	Girder	D		3		
	Case Bridge E1	Girder	E		1		
	Case Bridge E2	Girder	E		2		
	Case Bridge E3	Girder	E		3		
Steel Deck	**State Wide Case F**	Girder	F				
	State Wide Case G	Girder	G				
	State Wide Case H	Girder	H				
	Case Bridge F1	Girder	F		1		
	Case Bridge F2	Girder	F		2		
	Case Bridge F3	Girder	F		3		
	Case Bridge G1	Girder	G		1		
	Case Bridge G2	Girder	G		2		
	Case Bridge G3	Girder	G		3		
	Case Bridge H1	Girder	H		1		
	Case Bridge H2	Girder	H		2		
	Case Bridge H3	Girder	H		3		
Timber Deck	**State Wide Case I**	Girder	I				
	State Wide Case J	Girder	J				
	State Wide Case K	Girder	K				
	State Wide Case L	Girder	L				
	State Wide Case M	Girder	M				
	Case Bridge I1	Girder	I		1		
	Case Bridge I2	Girder	I		2		
	Case Bridge I3	Girder	I		3		
	Case Bridge J1	Girder	J		1		
	Case Bridge J2	Girder	J		2		
	Case Bridge J3	Girder	J		3		
	Case Bridge K1	Girder	K		1		
	Case Bridge K2	Girder	K		2		
	Case Bridge K3	Girder	K		3		
	Case Bridge L1	Girder	L		1		
	Case Bridge L2	Girder	L		2		
	Case Bridge L3	Girder	L		3		
	Case Bridge M1	Girder	M		1		
	Case Bridge M2	Girder	M		2		
	Case Bridge M3	Girder	M		3		

Table 4-4 illustrates the similarity between the Problem Bridge and case bridges. In this example two bridges the girder type and deck types are the exact match with concrete cast in place combined with uncoated rebar. Most bridge decks in New England are protected with barrier membrane and the minimum of 2 inches of bituminous pavement. Both bridges in this example have membrane and pavement wearing surfaces. If a problem bridge is located in a different district it warrants a 5 point deduction. Both bridges are in the same highway system however, the problem bridge has less traffic then a similar case bridge, this requires a 5 point deduction. Combining all the points the similarity score add up to 90 points in this example.

Table 4-4 Similarity Scoring Example between Case Bridge and Problem Bridge

Matching Type	Case Bridge	Problem Bridge	Points
Bridge Type	Girder	Girder	30
Deck Type	Concrete CIP w uncoated bar	Concrete CIP w uncoated bar	30
Wearing Surface	Membrane, and 2" Pavement	Membrane, and 2" Pavement	10
District	7	5	5
Road Class	1	1	10
ADT	>25000	14000	5
Total			90

4.2.5 Development of Case Bridge Deterioration Model

The bridge deck deterioration rate is used to predict the future decline in the condition of the bridge deck; this information is used to prepare appropriate MR&R strategies (Sobanjo,1997). The Minnesota Department of Transportation analyzed their bridge data to determine on average, how many years a bridge deck remains at the various NBI condition code states (Nelson, 2014).

Every case bridge in the database is linked to an average case bridge. Average case bridges are a group of bridges that have 90 % or more similarities within the case (Figure 4-3). The average number of years that bridge decks remain at certain NBI condition states is used to determine the deterioration rate. The condition rating is based on NBI specifications which were developed by FHWA (1989a). A new bridge deck typically starts at an NBI condition code of 9, and declines throughout its life. The condition rating ranges from 0 to 9, 0 being the bridge deck has failed. A 4 rating is when the bridge is classified as structurally deficient and an NBI 3 rating warrants bridge closure. The NBI condition ratings are described in more detail in Chapter 2.

The process of building the average case bridge involves analyzing each bridge inspection history. The length of time in years that a bridge deck stays at NBI condition rating increments is recorded and combined with other 90% or better similar bridges to obtain an average.

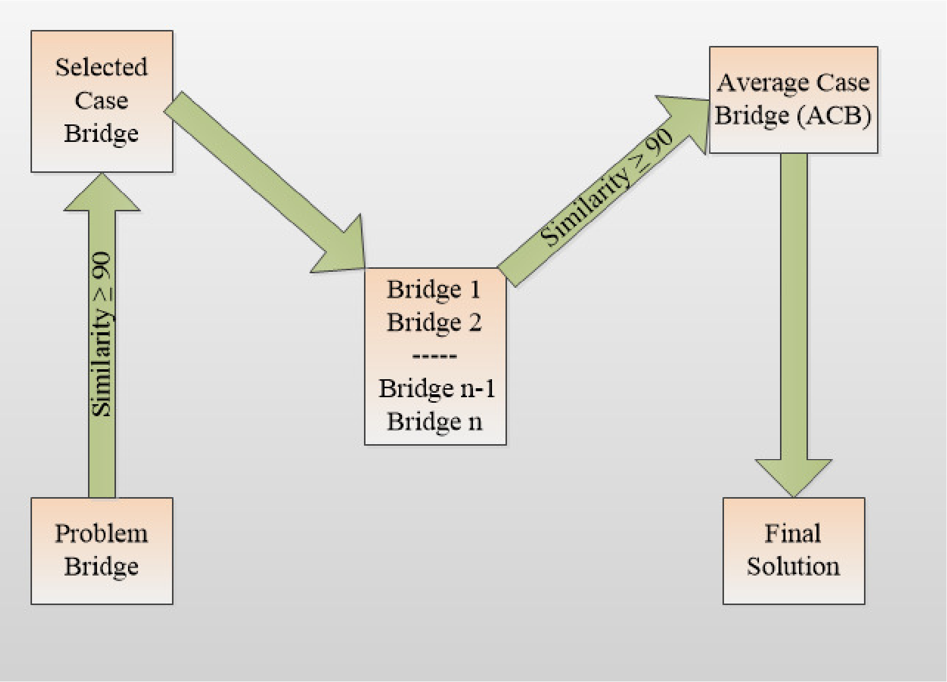


Figure 4-6 Average Case Bridge

Each NBI rating must go through a complete cycle which includes the beginning and end dates for each condition rating cycle. For example, selecting two bridges from the BMS database as shown in table 4-4 the bridge # 5 has NBI deck ratings spanning 26 years from 1991 to 2017 however only the NBI rating of 7 can be recorded since the beginning and end dates are known. Conversely, the inspection data from the culvert cannot be used because the beginning date for NBI rating of 8 is unknown, and the end date for NBI 7 also is unknown.

Table 4-5 Bridge Deck Inspection History

Culvert # 11		Bridge # 5	
Year	NBI Rating	Year	NBI Rating
1979	8	1991	8
1981	8	1993	8
1983	8	1995	7
1985	8	1997	7
1987	8	1999	7
1989	8	2001	7
1991	8	2003	7
1993	8	2005	7
1995	8	2007	7
1997	7	2009	7
1999	7	2011	7
2001	7	2013	7
2003	7	2015	7
2005	7	2017	6
2007	7		
2009	7		
2011	7		
2013	7		
2015	7		
2017	7		

Table 4-5 is an example of ACB (average case bridge) which includes groups of 25 bridges with 90% similarities, all these bridges are girder type bridge with type B deck (concrete cast in place with coated rebar),tier 1 road classification and ADT greater than 25,000. Table 4-6 is an example of SACB (Statewide average case bridges) which includes groups of 103 bridges that are girder bridge with type B deck and have asphaltic membrane with 2 inches of bituminous pavement for wearing surface. There are limited case bridges for NBI deck rating 4, as this is the minimum acceptable NBI rating (structurally deficient); at this level major rehabilitation is needed and most transportation departments initiate rehabilitation.

Table 4-6 Example of Average case Bridge (ACB)

Girder bridge Type B Deck, Membrane, Tier 1 and ADT>25 K							
NBI Rating	**9**	**8**	**7**	**6**	**5**	**4**	
Bridge 1	4	9	18				
Bridge 2	2	4	14				
Bridge 3				10	7	5	
Bridge 4	2	6			7		
Bridge 5	2	4	21				
Bridge 6	2	4	23				
Bridge 7	2	2	23				
Bridge 8	3	12					
Bridge 9	5					6	
Bridge 10	4	4				10	
Bridge 11			19				
Bridge 12		8			6		
Bridge 13		9			6		
Bridge 14	4	11	23				
Bridge 15			23				
Bridge 16	4			12			
Bridge 17				11			
Bridge 18			14	12			
Bridge 19	2	10		11			
Bridge 20			24				
Bridge 21		14					
Bridge 22					10		
Bridge 23				14	8		Average expected lifespan to reach structurally deficient 57.1 Years
Bridge 24			22				
Bridge 25	4				9		
Average	3.1	7.5	20.4	11.7	7.6	7.0	

Table 4-7 Statewide Average case Bridge (SACB) for Type B Deck

Girder bridge with concrete deck, concrete cast in place, (Type B), membrane, 2" pavement. Statewide (70)							
NBI Rating	9	8	7	6	5	4	
Bridge 1	4	8			6	14	
Bridge 2				6			
Bridge 3			24				
Bridge 4		20					
Bridge 5		18					
Bridge 6		6					
Bridge 7							
Bridge 8					12	4	
Bridge 9			20				
Bridge 10	2	16					
Bridge 11				14			
Bridge 12	2	20					
Bridge 13				12			
Bridge 100	2	12	12	13			
Bridge 101	1	7	6	3			Average expected lifespan to reach structurally deficient 61.6 Years
Bridge 102	2	12	16				
Bridge 103	4	24					
Average	**3.25**	**11.51**	**16.54**	**11.58**	**10.00**	**8.71**	

Bridge conditions are assessed by trained DOT bridge inspectors through an inspection process per National Bridge Inspection Standards (NBIS), which involves the use of specific techniques to assess the physical condition of bridges. Visual inspection is conducted on a routine or scheduled basis; however, the reliability and accuracy of the inspection can be within +/- 1 NBI rating. Because the condition assessment of NBI rating of 8 and 7 are similar, same bridge decks can be rated 7 by one bridge inspector and 8 by another. In fact, when reviewing the data provided by NHDOT there were several instances where this occurred. The NBI rating condition 8 is defined as very good condition with no problem noted and NBI 7 rating is defined as good condition with some minor problem. With the exception of cyclical routine preventive maintenance, the NBI condition rating of 8 and 7 does not warrant any type of MR&R activities. The advantage of combining the number of years the bridge deck condition remains at NBI 8 and 7 will result in a more accurate assessment. Analyzing the data provided by NHDOT, as illustrated in Table 4-6, the total years in NBI 8 and 7 is 27.9 years and from Table 4-7 is 28.05 years as shown in Figure 4-5.

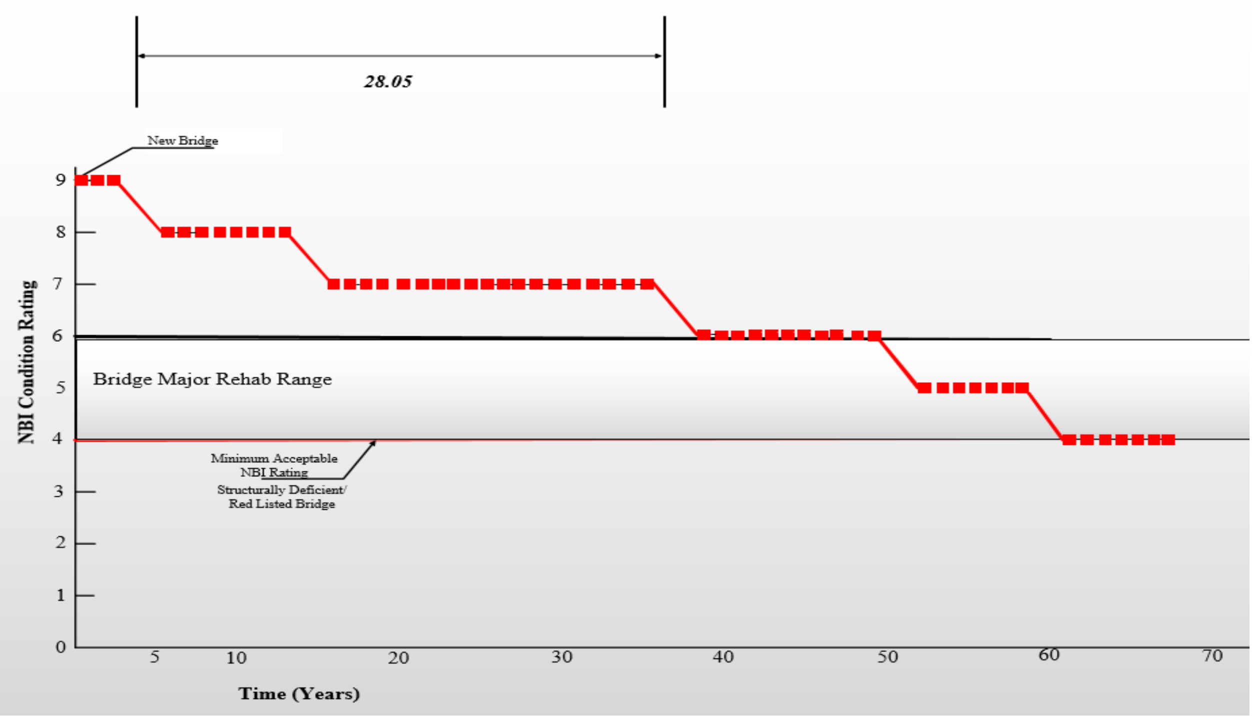


Figure 4-7 Deterioration Rate for Concrete CIP Deck

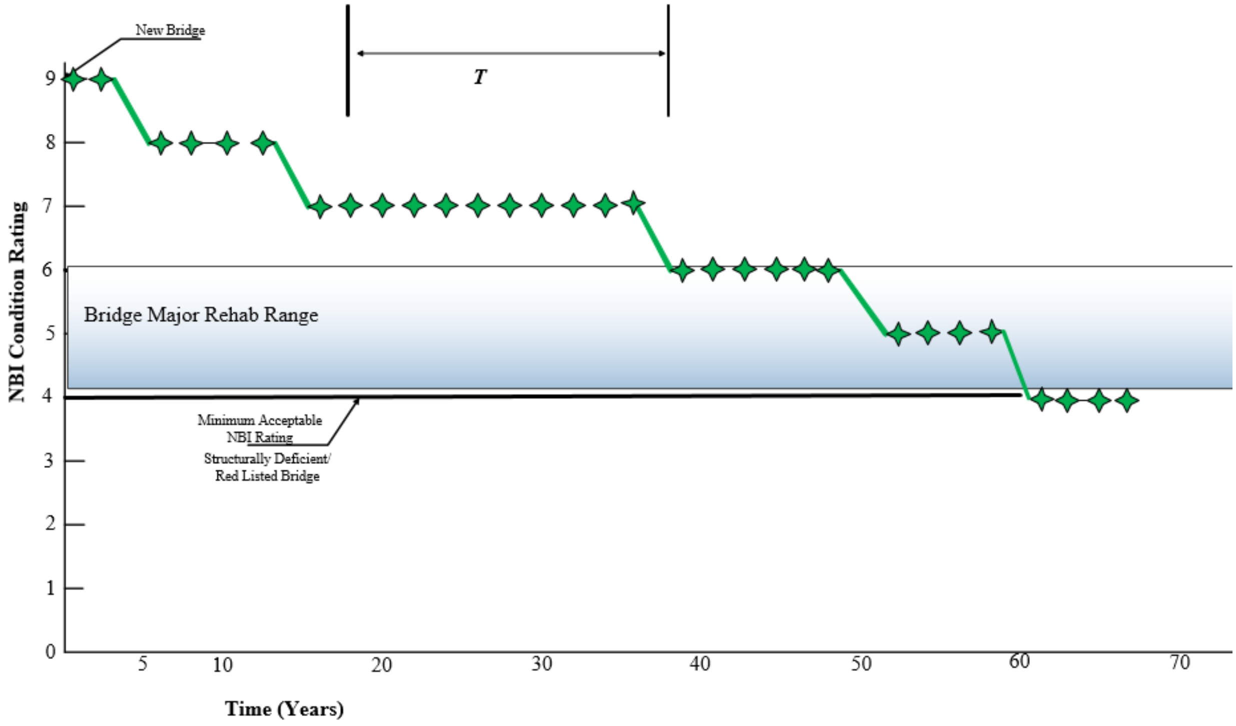


Figure 4-8 Average Case Bridge (ACB) Deterioration Rate

Figure 4-8 demonstrates the deterioration rate for type A case bridge (table 4-1) where T_i is the length of time in years that the bridge deck remains at a specific NBI condition rating.

The deterioration rate of bridge components (deck, superstructure and substructure) is determined by the rate of deterioration between two consecutive NBI ratings calculated by the following equation:

$$D_i = \frac{CC_i - CC_{i+1}}{T_{i+1} - T_i} \qquad (4\text{-}1)$$

Where

D_i	Deterioration rate at NBI *i*
CC_i	Components condition rating at NBI *i*
T_i	Time at NBI *i*

The bridge inspection report is based on NBIS regulations to set the component (deck, superstructure and substructure) NBI ratings (0 to 9 rating). The condition rating for the remaining bridge elements such as Deck Joint and Deck Bearing are described in 4 different condition states: 1) good, 2) fair 3) poor and 4) severe. The deterioration for these elements is assumed to be linear based on the expected lifespan of the element.

The Condition Rating (*CR*) for element *i* at year *t* is estimated by:

$$CR_i = \left(4 - \frac{4-1}{life\ span} * t\right) \qquad (4\text{-}2)$$

Where ***t*** is the length of time in years

For example, deck joint strip seal has a life span of 15 years under severe high traffic volume; the condition prediction for the 10 year service life is

$$CR_{i=\left(4-\frac{4-1}{15}*10\right)=2}$$

The condition rating is fair at a rating of 2.

5.2.6 Case Study

The case library database for this model consists of over 2000 bridges provided by NHDOT. The case library database is made up of a number of ACB (average case bridge) and Statewide Average Case Bridge (SACB) as shown in table 5-1. Average case bridges (ACB) are a group of bridges that have 90% or more similarities based on bridge type, deck type, wearing surface, district, road classification and ADT.(table 4-2). The SACB is a group bridges that have a 70% or more similarities based on criteria shown in table 4-2.

Fifteen (15) problem bridges are randomly selected from NHDOTs database for testing the proposed deterioration model to predict their future deck condition rating. Each bridge is evaluated by the model on an individual basis and classified based on criteria shown in the Figure 4-7 framework. The system retrieval will analysis each bridge one at a time using the matching process to search for the most similar bridge case in the case library database as outlined (Figure 4-9) below:

1. The system retrieval searches the database for ACB (bridge similarity greater than or equal to 90 points) based on the matching process. If a match is found, the system retrieval searches for a Refine Match (RM) based on condition history. The RM search on the identified ACB matches seeks bridges within a 10% differential over a designated number of years. Once RM matches are found the system continues to predict the problem bridge future deterioration rate.
2. If ACB is found and there are no RM bridges then the system proceeds to a final solution.
3. If ACB is not found then the system will search the SACB data file through the matching process to locate a matching set of bridges then proceeds to the final solution.

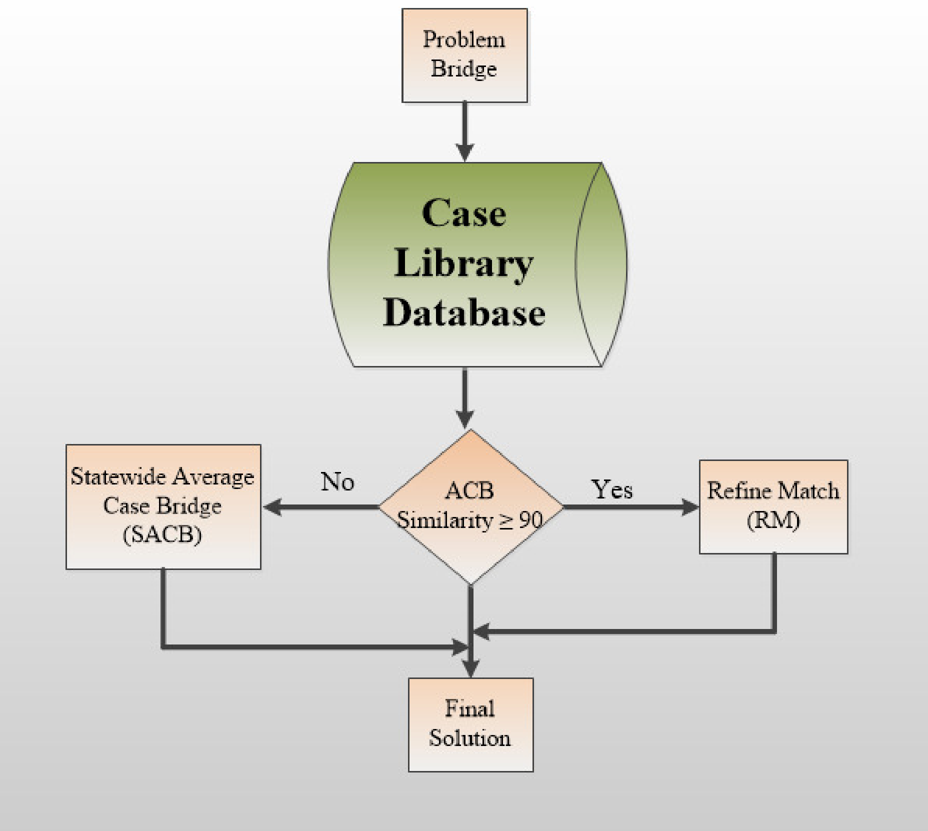


Figure 4-9 Retrieval Process

All 15 bridges were investigated using the ACB, RM and SACB, see table 4-6 the results are based on a degradation prediction period of 5 to10 years. In the refined match group, the search method found matches for 11 out of the 15 problem bridge groups (73% retrieved), these are bridges with similarity greater than or equal to 90 points, the inspection history was also found to be similar within a 10% tolerance. From the 73% retrieved 10 out of 11 cases matched the actual condition. In the average case bridge method (ACB) the retrieval search found 14 out 15 (93%) cases with the similarity greater than or equal to 90 points; the percentage of correct a prediction is at 79%. The final method is Statewide Average Case Bridge (SACB) is comprised of a group of bridges that have 100% matching bridge components and are independent of the district and road classification. Occasionally a problem bridge is located in a rural area that has a low similarity to ACB. The SACB method has 100% retrieval but also has the lowest percentage of correct predictions.

Table 4-8 Case Study Example

	Refine Match		Average Case Bridge (ACB)		Statewide Average Case Bridge	
Matching	Predicted Condition	Actual Condition	Predicted Condition	Actual Condition	Predicted Condition	Actual Condition
Bridge 1	8	8	8	8	8	8
Bridge 2	6	6	7	6	7	6
Bridge 3	7	7	7	7	7	7
Bridge 4			5	5	5	5
Bridge 5	6	5	6	5	6	5
Bridge 6	8	8	7	8	7	8
Bridge 7			7	7	7	7
Bridge 8	5	5	5	5	5	5
Bridge 9	6	6	6	6	6	6
Bridge 10	7	7	7	7	7	7
Bridge 11	6	6	6	6	7	6
Bridge 12	7	7	8	8	8	8
Bridge 13			7	7	7	7
Bridge 14					5	5
Bridge 15	6	6	6	6	7	6
Percent Retrieved	73%		93%		100%	
Percent Correct	91%		79%		67%	

Example: a problem bridge (bridge # 145/060) with the given following information requires a condition rating be determined after 6 years, in 2023.

Bridge Type	Girder	NBI Rating	
Deck Type	Concrete CIP w epoxy coated rebar	1996	9
Wearing	Membrane, and 2" Pavement	1998	8
District	TPK	2000	8
Road Class	1	2002	8
ADT	> 25 K	2004	7
Year Built	1993	2006	7
		2008	7
		2010	7
		2012	7
		2014	7
		2016	7

Using the matching retrieval process for the given information this bridge classifies as a type A case bridge. The ACB type A is used to predict the future condition of the bridge deck. From the ACB data file there are two bridges (bridge 5 and 6) that are very similar to the problem bridge, these two bridges are classified as Refine Match(RM).

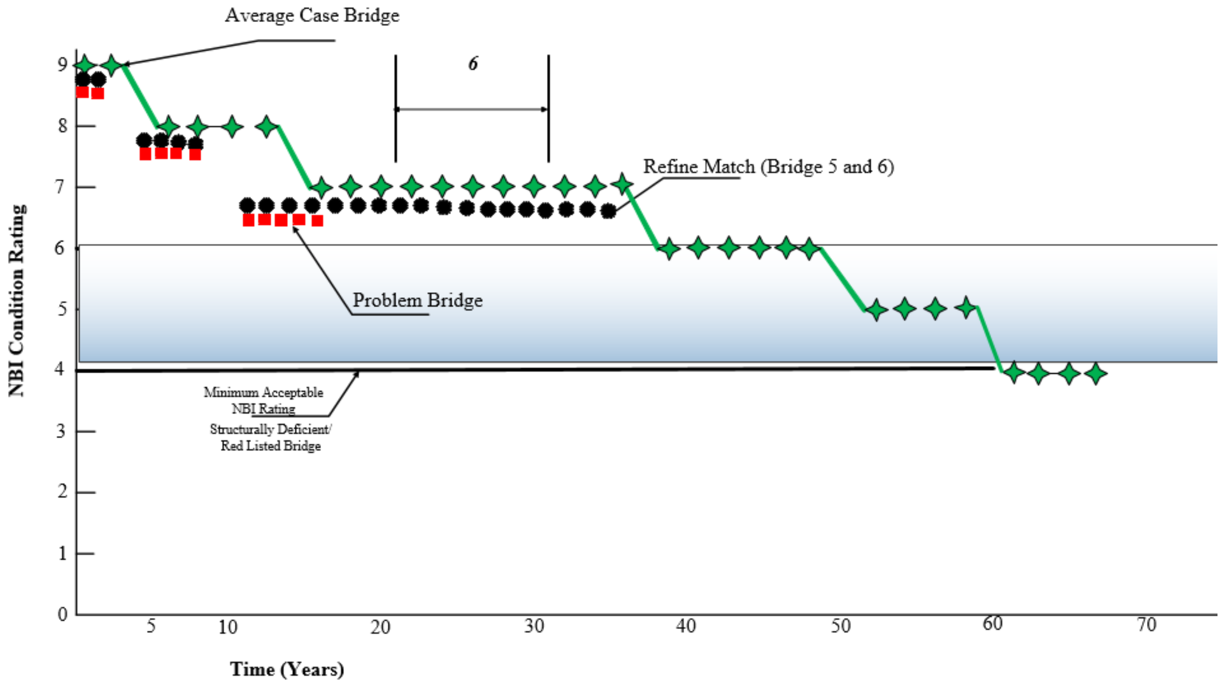


Figure 4-10 CBR Deterioration Model for Concrete CIP Deck

The Problem bridge is deteriorating at a faster rate than the average deterioration rate for the matching case bridges even though the problem bridge mirrors two other bridges in the ACB file. In this case, the governing deterioration rate is the refined match (RM). The predicated condition rate for the problem bridge at age 30 is NBI 7 as shown in Figure 4-10.

Numerous researchers are using the Markov Chain algorithm to forecast bridge sustainability. This approach is incorporated in the American Association of State

Highway and Transportation Officials, AASHTO, Pontis, a Bridge Maintenance System, BMS is FHWA approved and is commercially available. Pontis integrates bridge deterioration rates, alternative bridge component repair alternatives, and default costs to predict bridge maintenance network budgets. Markov based models does not consider preventive maintenance in combination with the history of general maintenance performed on a bridge in projecting a bridge deterioration rate. It must be recognized that bridge preventative maintenance practices have only been promoted in the past few years. In Markov models, the effects of preventive maintenance are not captured and it uses a constant deterioration rate independent of general management options. The proposed CBR module considers a current deterioration rate as a function of traffic volume, management history, and additional condition inspected parameters. The projected deterioration rate is thus selected by taking data from bridges subjected to similar loading conditions and a department's applied general maintenance practices.

In certain situations of an extreme event such as natural disaster or vehicle impact to the bridge structure the following measure shall apply:

1. The proposed module integrates the damage inflicted by a natural disaster to ascertain the current condition index of a bridge from which the deterioration rate is determined. This surpasses age; it simply sets the

deterioration rate as a function of the current condition of similar bridges at that level of deterioration.

2. Any bridge components with a specific damage caused by the extreme event that has been rated in AASHTO Commonly Recognized (CoRe) Elements condition state of 3 (poor) or 4 (severe), or with NBI rating equal or less than 4 shall be inspected by certified bridge engineer or structural reviewer to determine the effect on strength or serviceability of the bridge.

5.3 MR&R Cost Model

Maintaining bridges in good or better condition has proven to extend service life and to be more cost effective than allowing them to deteriorate to a condition requiring major rehabilitation or replacement. To manage bridges efficiently, the cost of maintenance, rehabilitation, and replacement (MR&R) and improvement has to be known. The BMS developed for this study contains detailed costs for various types of preventive maintenance, major rehabilitation, and replacement projects. These various types of MR&R and estimated repair costs can be used to develop 10 or more years of budget plans and preservation strategies. In the proposed BMS model four repair options including cost estimates are used for maintaining bridges. They include the following:

1. Routine Preventive Maintenance (RPM); the following maintenance alternatives are proven options:

    a. Bridge washing
    b. Cleaning and sealing deck joint and joint repair
    c. Cleaning drainage system
    d. Graffiti removal
    e. Clearing channel
    f. Bearing lubrication
    g. Spot painting
    h. Sealing concrete
    i. Minor concrete repair

2. Condition Based Preventive Maintenance (CBPM); these types of activities are for bridge elements that need maintenance as identified in a bridge inspection report. The extent of this work is a bridge network managers decision. Bridge rehabilitation is more costly than bridge preservation but it must also address functional improvement, increased structural capacity, and repair necessary to correct major safety defects. Rehabilitation projects include preservation treatments which do not meet eligibility criteria for preventative maintenance as outlined in Figure 4-11. The CBPM activities may include minor repair to major rehabilitation but are not limited to the following:

    a. Repairing deck wearing surface with membrane replacement
    b. Partial deck repair
    c. Superstructure repair
    d. Substructure repair
    e. Maintaining proper deck drainage

f. Replacing bridge bearings
g. Repairing or replacing bridge approach slabs
h. Repairing bridge beam ends and back wall
i. Bridge painting
j. Repairing or installing new expansion dams on bridge decks
k. Scour protection

The qualification criteria for CBPM as outlined in Figure 4-11 are the following:

a. The NBI condition rating for bridge components or elements should be 4, 5 and 6.
b. The bridge structure is older than 25 years with an exception of some bridges that deteriorate prematurely due to poor construction and/or severe environmental conditions.
c. The total cost of rehabilitation should not exceed 60 percent of a new bridge cost estimate.
d. Superstructure replacement and deck replacement rehabilitation projects should bring the completed bridge to current standards.
e. Steel painting should be given special attention; in the long term, it may be more cost effective to replace the lead or PCB painted steel superstructure. The weathering steel bridge fascia and deck joint areas are normally painted.
f. All the components (deck, superstructure, and substructure) of the completed rehab bridge should have an NBI of 6 or higher, or the section of the bridge not rehabilitated should have an NBI rating 6 or higher and last as long as the rehabilitated sections.

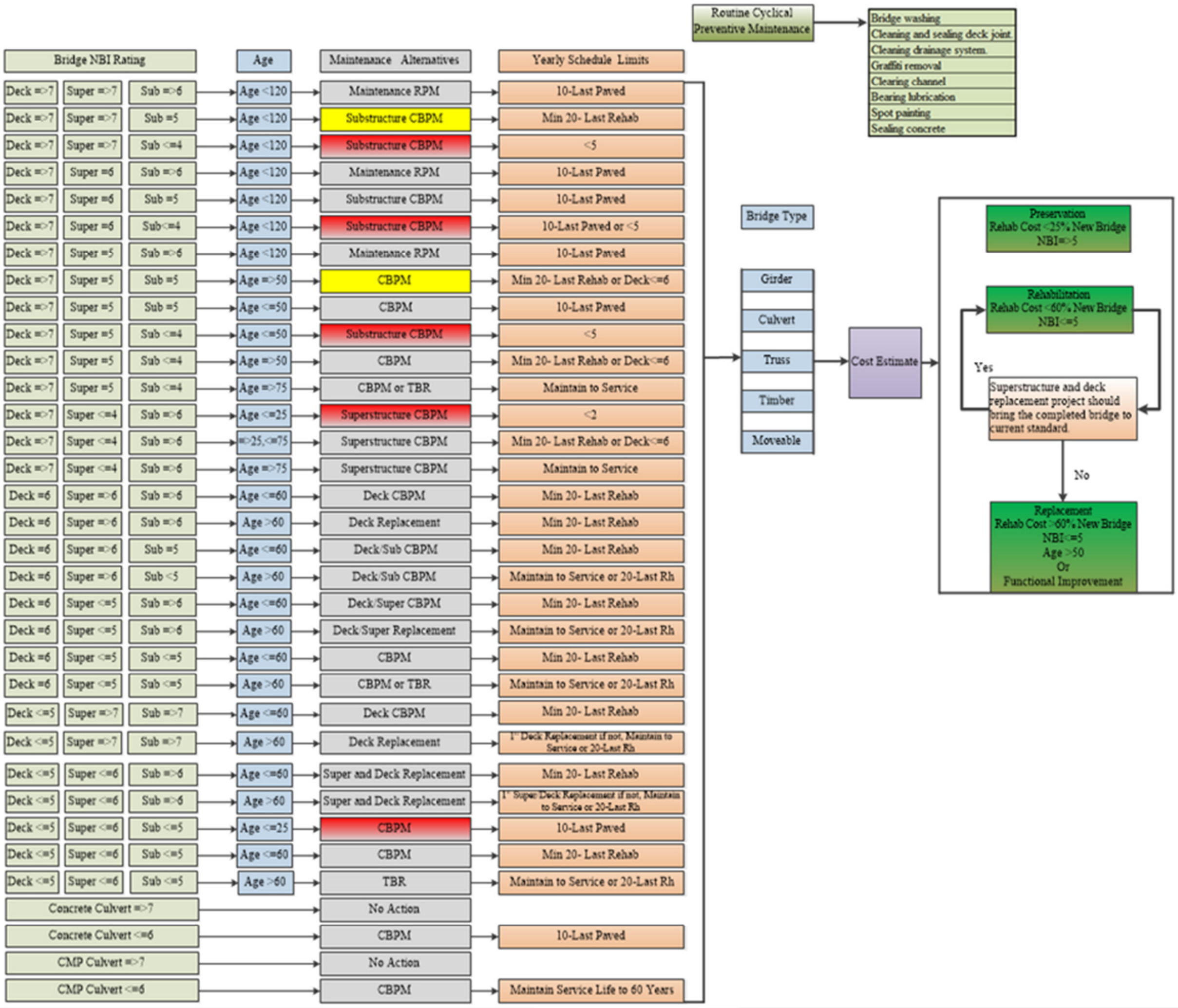
3. Deck Replacement (DR); the deck replacement in certain situations may also include superstructure replacement.
4. Total Bridge Replacement (TBR); Total bridge replacement includes removing an existing bridge and constructing a new bridge per current design and construction standards. Bridges are usually replaced due to age, a

structurally deficient (poor condition NBI rating <= 4, a structural evaluation<=2 and waterway adequacy<=2) and functionally obsolete (bridge roadway width, bridge structural capacity, bridge lane width, vertical clearance). Bridge replacement should meet the following criteria:

a. The NBI condition rating for bridge components should be 0,1,2,3 and 4.
b. Bridges should be older than 50 years. The exception will apply for necessary functional improvement.
c. If the bridge rehabilitation project cost exceeds 60 percent of new bridge costs.
d. The replacement bridge should meet the current geometric standards.
e. The bridge is structurally deficient and rehabilitation costs are too high for the bridge to meet design standards.
f. Functional improvement such as bridge roadway width, capacity expansion, vertical clearance, lane and shoulder width.

The cost model (Figure 4-11) is designed to identify the type of MR&R using NBI component condition ratings and provide bridge repair recommendations with estimated cost repairs. Each component (deck, superstructure, and substructure) is linked to multiple levels of treatment. There are over 1000 condition combinations with different maintenance alternatives covering the entire bridge, including applicable roadway approach work. Some of the maintenance alternatives are highlighted in red indicating that a detailed analysis may be necessary to support scoping decisions. The timeline for MR&R activities is based on condition and budget scheduling with other MR&R projects when maintenance repair is required on an individual bridge. Sometimes this is not adequate to justify a separate contract, it is often advantageous to bundle multiple bridges or combine bridges with concurrent roadway work. This is also to avoid multiple traffic disruptions and working in the same area at less than 10 year intervals. These various types of MR&R and estimated repair costs can be used to develop 10 year budget plans and preservation strategies.

Tables 4-9 to 4-13 consist of a list of the most common items that are used in bridge construction. The itemized cost estimates are based on contract bids for the current year average and can be adjusted regionally, since the unit costs vary among bridges. These values are based on the element condition states, as described in Chapter 2. Continually upgraded BMS algorithms simply link current MR&R alternatives with NBI condition data to prepare an estimated repair cost. When producing a 10 year budget plan, future funding or maintenance repair costs are determined by using the deterioration model described in this Chapter. Table 5-11 is an example of a 10 year budget plan for an individual bridge with the recommended funding.



Bridge NBI Rating			Age	Maintenance Alternatives	Yearly Schedule Limits
Deck =>7	Super =>7	Sub =>6	Age <120	Maintenance RPM	10-Last Paved
Deck =>7	Super =>7	Sub =5	Age <120	Substructure CBPM	Min 20- Last Rehab
Deck =>7	Super =>7	Sub <=4	Age <120	Substructure CBPM	<5
Deck =>7	Super =6	Sub =>6	Age <120	Maintenance RPM	10-Last Paved
Deck =>7	Super =6	Sub =5	Age <120	Substructure CBPM	10-Last Paved
Deck =>7	Super =6	Sub<=4	Age <120	Substructure CBPM	10-Last Paved or <5
Deck =>7	Super =5	Sub =>6	Age <120	Maintenance RPM	10-Last Paved
Deck =>7	Super =5	Sub =5	Age =>50	CBPM	Min 20- Last Rehab or Deck<=6
Deck =>7	Super =5	Sub =5	Age <=50	CBPM	10-Last Paved
Deck =>7	Super =5	Sub <=4	Age <=50	Substructure CBPM	<5
Deck =>7	Super =5	Sub <=4	Age =>50	CBPM	Min 20- Last Rehab or Deck<=6
Deck =>7	Super =5	Sub <=4	Age =>75	CBPM or TBR	Maintain to Service
Deck =>7	Super <=4	Sub =>6	Age <=25	Superstructure CBPM	<2
Deck =>7	Super <=4	Sub =>6	=>25,<=75	Superstructure CBPM	Min 20- Last Rehab or Deck<=6
Deck =>7	Super <=4	Sub =>6	Age =>75	Superstructure CBPM	Maintain to Service
Deck =6	Super =>6	Sub =>6	Age <=60	Deck CBPM	Min 20- Last Rehab
Deck =6	Super =>6	Sub =>6	Age >60	Deck Replacement	Min 20- Last Rehab
Deck =6	Super =>6	Sub =5	Age <=60	Deck/Sub CBPM	Min 20- Last Rehab
Deck =6	Super =>6	Sub <5	Age >60	Deck/Sub CBPM	Maintain to Service or 20-Last Rh
Deck =6	Super <=5	Sub =>6	Age <=60	Deck/Super CBPM	Min 20- Last Rehab
Deck =6	Super <=5	Sub =>6	Age >60	Deck/Super Replacement	Maintain to Service or 20-Last Rh
Deck =6	Super <=5	Sub <=5	Age <=60	CBPM	Min 20- Last Rehab
Deck =6	Super <=5	Sub <=5	Age >60	CBPM or TBR	Maintain to Service or 20-Last Rh
Deck <=5	Super =>7	Sub =>7	Age <=60	Deck CBPM	Min 20- Last Rehab
Deck <=5	Super =>7	Sub =>7	Age >60	Deck Replacement	1st Deck Replacement if not, Maintain to Service or 20-Last Rh
Deck <=5	Super <=6	Sub =>6	Age <=60	Super and Deck Replacement	Min 20- Last Rehab
Deck <=5	Super <=6	Sub =>6	Age >60	Super and Deck Replacement	1st Super Deck Replacement if not, Maintain to Service or 20-Last Rh
Deck <=5	Super <=6	Sub <=5	Age <=25	CBPM	10-Last Paved
Deck <=5	Super <=6	Sub <=5	Age <=60	CBPM	Min 20- Last Rehab
Deck <=5	Super <=6	Sub <=5	Age >60	TBR	Maintain to Service or 20-Last Rh
Concrete Culvert =>7				No Action	
Concrete Culvert <=6				CBPM	10-Last Paved
CMP Culvert =>7				No Action	
CMP Culvert <=6				CBPM	Maintain Service Life to 60 Years

Figure 4-11 MR&R Improvement and Cost Model

Table 4-9 Deck Maintenance Estimated Cost Repair

Preservation. Maintenance, Rehabilitation and Replacement	Unit	Quantity	Unit Cost
Preventive Maintenance	SF		$ 5.50
Bridge washing	SF		$0.10
Cleaning, sealing, and repairing deck joint	FT		$10.00
Water Repellant	GAL		$80.00
Concrete Surface Coating	SYD		$20.00
Cleaning drainage system	EA		$250.00
Cleaning channel	EA		$800.00
Bearing Lubrication	EA		$50.00
Spot painting	SF		$50.00
Resealing Bridge Construction Joints	FT		$14.00
Minor concrete repair Grade D	CYD		$1,150.00
Embedded Galvanic Anode	EA		$18.00
Deck Maintenance			
Concrete patch, membrane and joint	SF		$50.00
Patching Concrete,	CYD		$1,150.00
Penetrating Healer/Sealer, Bridge Deck	SYD		$22.00
Crack Sealer	FT		$10.00
End Header Replacement	FT		$65.00
Deck Drain,	EA		$500.00
Downspout Replacement	EA		$2,000.00
Deck Rehabilitation			
Concrete Deck Patch	SYD		$400.00
Full Depth Patch	SYD		$550.00
Concrete Deck Patch (placement only add item 511.02 and 511.03 convert to CY)	CY		$1,150.00
HMA Cap	Ton		$85.00
Concrete bridge deck pavement removal	SYD		$15.00
Hot Bituminous Bridge Pavement, 1" Base Course	Ton		$225.00
Barrier membrane, heat welded, machine method	SYD		$25.00
Painting existing structural steel	SF		$15.00
Repair Asphaltic Plug Expansion Joint	LF		$120.00
Bridge Rail	LF		$125.00
Deck Replacement			
Includes remove existing deck & new railing	SF		$100.00

Table 4-10 Superstructure Estimated Cost Repair

Preservation. Maintenance, Rehabilitation and Replacement	**Unit**	**Quantity**	**Unit Cost**
Superstructure Maintenance / Impact Repair			
High Load Hit Repair	SF		$260.00
PCI Beam End Repair	EA		$4,200.00
Repair Structural Steel	SF		$6,000.00
Paint Structural Steel	EA		$20.00
Partial Painting	SF		$40.00
Pin & Hanger Replacement	EA		$9,000.00
Superstructure Repair	Unit		Unit Cost
Repair Structural Steel	EA		$1.50
Pin & Hanger Replacement	SF		$20.00

Table 4-11 Substructure Estimated Cost Repair

Preservation. Maintenance, Rehabilitation and Replacement	**Unit**	**Quantity**	**Unit Cost**
Substructure Maintenance/Hit Repair	Unit		Unit Cost
Pier Repair	CYD		$1,200.00
Pier Repair Over Water	CYD		$1,400.00
Abutment Repair	CYD		$1,000.00
Temporary Supports for Substructure Repair	EA		$1,800.00
Slope Protection Repair	SYD		$100.00
Patching Concrete	CYD		$700.00
Patch Forming	SF		$35.00
Concrete Surface Coating Vertical Surface	SYD		$20.00
Horizontal Surface Sealer	SYD		$32.00
Water Repellent	SYD		$20.00
Substructure Rehabilitation	Unit		Unit Cost
Sub Rehab			
Pier Rehab	CYD		$4,500.00
Pier repair over water	CYD		$5,200.00
Pier replacement	CYD		$1,500.00
Abutment Rehabilitation	CYD		$4,500.00
Temporary Supports for Substructure Rehabilitation	EA		$1,800.00
Slope Protection Rehabilitation	SYD		$100.00

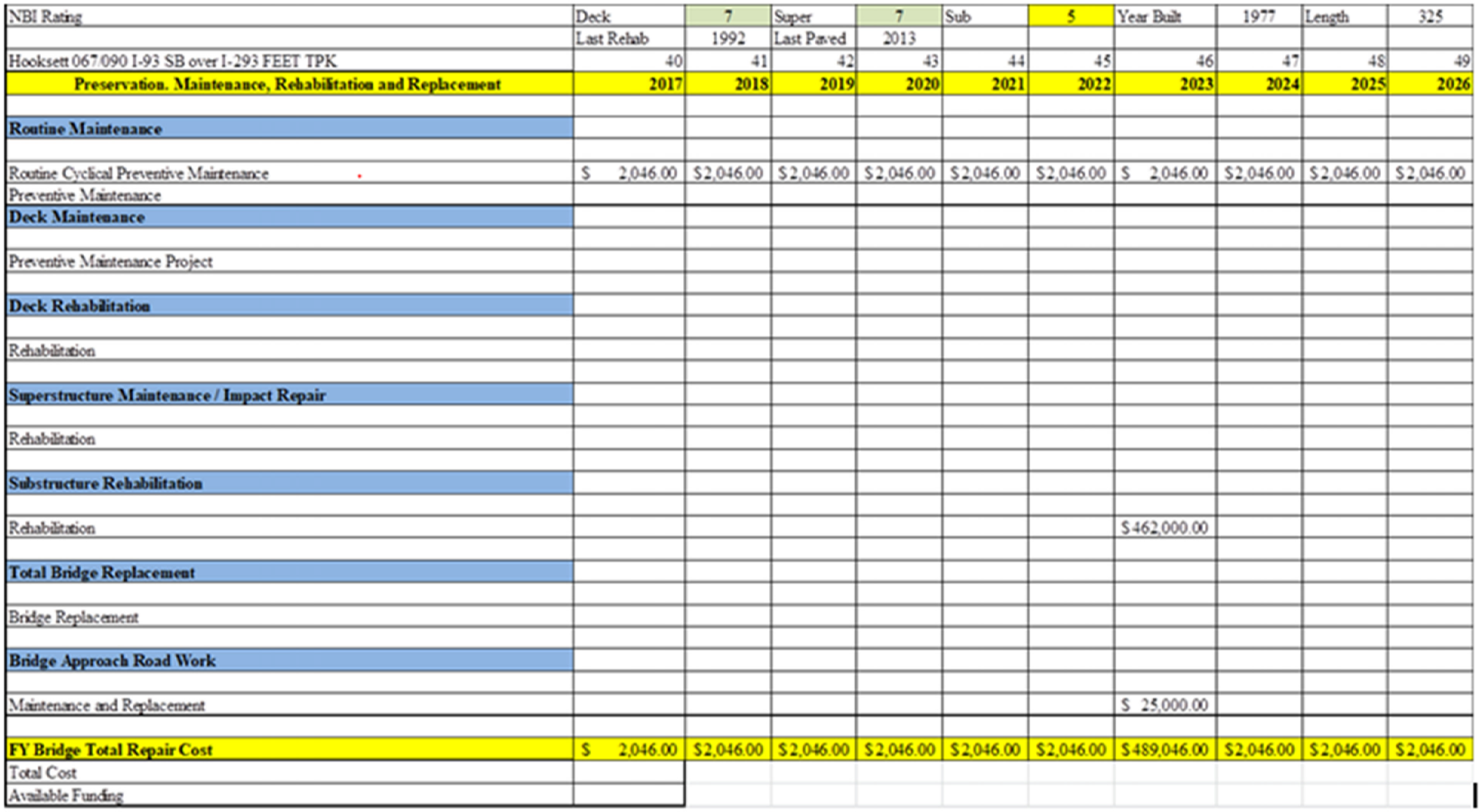
Table 4-12 Total Bridge Replacement Estimated Cost Repair

Preservation. Maintenance, Rehabilitation and Replacement	**Unit**	**Quantity**	**Unit Cost**
Total Bridge Replacement	Unit		Unit Cost
Bridge Replacement	SF		$650.00
Multiple Spans, Concrete	SF		$220.00
Over Water or Single Span	SF		$75.00
Precast Culvert	LF		$400.00
Temporary Bridge	U		$300,000.00
Bridge Shoes	EA		$3,000.00
Shear Connector	EA		$5.00
Reinforced Steel	LB		$1.15
Structural Steel	LB		$1.60
Pile Driving Equipment	U		$60,000.00
Expansion Joints	FT		$560.00
Concrete	SF		$140.00
New Deck	SF		$100.00

Table 4-13 Site Specific Special Project Estimated Cost Repair

Preservation. Maintenance, Rehabilitation and Replacement	**Unit**	**Quantity**	**Unit Cost**
Site Specific Special Project	Unit		Unit Cost
Removing Existing Bridge Structure	U		$120,000.00
Water Diversion Structure	U		$10,000.00
Cofferdams	U		$30,000.00
Stone Fill Class B (Bridge)	CYD		$35.00
Expansion Joints	FT		$560.00
Riprap	CYD		$50.00
Bridge Approach Rail Replacement	U		$4,500.00
Bridge Rail T3 With Snow Screening	FT		$175.00
Deck Drain Extensions	EA		$500.00
Slope Paving With Concrete	SYD		$55.00
Scour Countermeasures	LSUM		LSUM
Barrier membrane, heat welded, machine method	SYD		$25.00

Table 4-14 A Sample 10-Year Budget Plan



NBI Rating	Deck	7	Super	7	Sub	5	Year Built	1977	Length	325
	Last Rehab	1992	Last Paved	2013						
Hooksett 067/090 I-93 SB over I-293 FEET TPK	40	41	42	43	44	45	46	47	48	49
Preservation. Maintenance, Rehabilitation and Replacement	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Routine Maintenance										
Routine Cyclical Preventive Maintenance	$ 2,046.00	$2,046.00	$2,046.00	$2,046.00	$2,046.00	$2,046.00	$ 2,046.00	$2,046.00	$2,046.00	$2,046.00
Preventive Maintenance										
Deck Maintenance										
Preventive Maintenance Project										
Deck Rehabilitation										
Rehabilitation										
Superstructure Maintenance / Impact Repair										
Rehabilitation										
Substructure Rehabilitation										
Rehabilitation							$462,000.00			
Total Bridge Replacement										
Bridge Replacement										
Bridge Approach Road Work										
Maintenance and Replacement							$ 25,000.00			
FY Bridge Total Repair Cost	$ 2,046.00	$2,046.00	$2,046.00	$2,046.00	$2,046.00	$2,046.00	$489,046.00	$2,046.00	$2,046.00	$2,046.00
Total Cost										
Available Funding										

4.4 Preservation Strategy

Bridge maintenance activities encompass preventive and reactive maintenance. The preventive maintenance is applied to the bridge elements (bridge elements are described in Chapter 2) that are still in good condition and have a significant remaining useful life. The preservation work should restore bridge elements to a state of good repair (SGR). The state of good repair is defined by FHWA "*A condition in which the existing physical assets, both individually and as a system (a) are functioning as designed within their useful service life, (b) are sustained through regular maintenance and replacement programs. SGR represents just one element of a comprehensive capital investment program that also addresses system capacity and performance*" (Guide, B. P. 2011). FAST Act (Fixing America's Surface Transportation Act) signed into law l On December 4, 2015, by President Obama. It is the first law enacted in over ten years that provides long-term funding for surface transportation. This enables States and local governments to move forward with critical transportation projects.

For national highway system (NHS) bridges the limit is 10% of deck area in poor condition (NBI ≤ 4) per the National Bridge Inspection Standards (NBIS). The target for good (NBI ≥7) is a minimum of 55% for Principal Arterials (PA) and 50% Non-Principal Arterials (NPA). The target for good and satisfactory (NBI ≥ 6) is a minimum of 84% for PA and 80% NPA. The target for fair and poor (NBI ≤ 5) is a maximum of 16% for PA and 20% for NPA. The target for poor or structurally deficient (NBI ≤ 4) is a maximum of 2% for PA or 8% for NPA.

The 120 year preservation Model; Figure 5-9 indicates a preservation strategy designed to improve the condition rating based on a level of repair with minimum cost. Identifying the key repairs and preventive maintenance at the right time is critical for an effective bridge management system. Each bridge requires a series of investments throughout its life, a new bridge requires preventive maintenance at the middle or near the end of an NBI condition rating of 7, the time of X_i can be determined by the aforementioned deterioration model. As the bridge ages, additional reactive maintenance may be required. Rehabilitation or major preservation repairs such as joint replacement or a deck overlay to prolong its service life can be initiated at mid to end of the NBI 6 cycle. Eventually, a bridge will require a major rehabilitation or replacement due to functional improvement.

The goal of bridge preservation is to maximize the remaining useful life of bridges in a most cost effective way. The goals developed for this study are the following:

1. The goal for good bridges (NBI≥7) is a minimum of 55%.
2. The goal for good and satisfactory bridges (NBI≥6) is a minimum of 85%.
3. The goal for fair and poor bridges (NBI≤5) is a maximum of 15%.
4. The goal for poor bridges (NBI≤4) is a maximum of 2%.

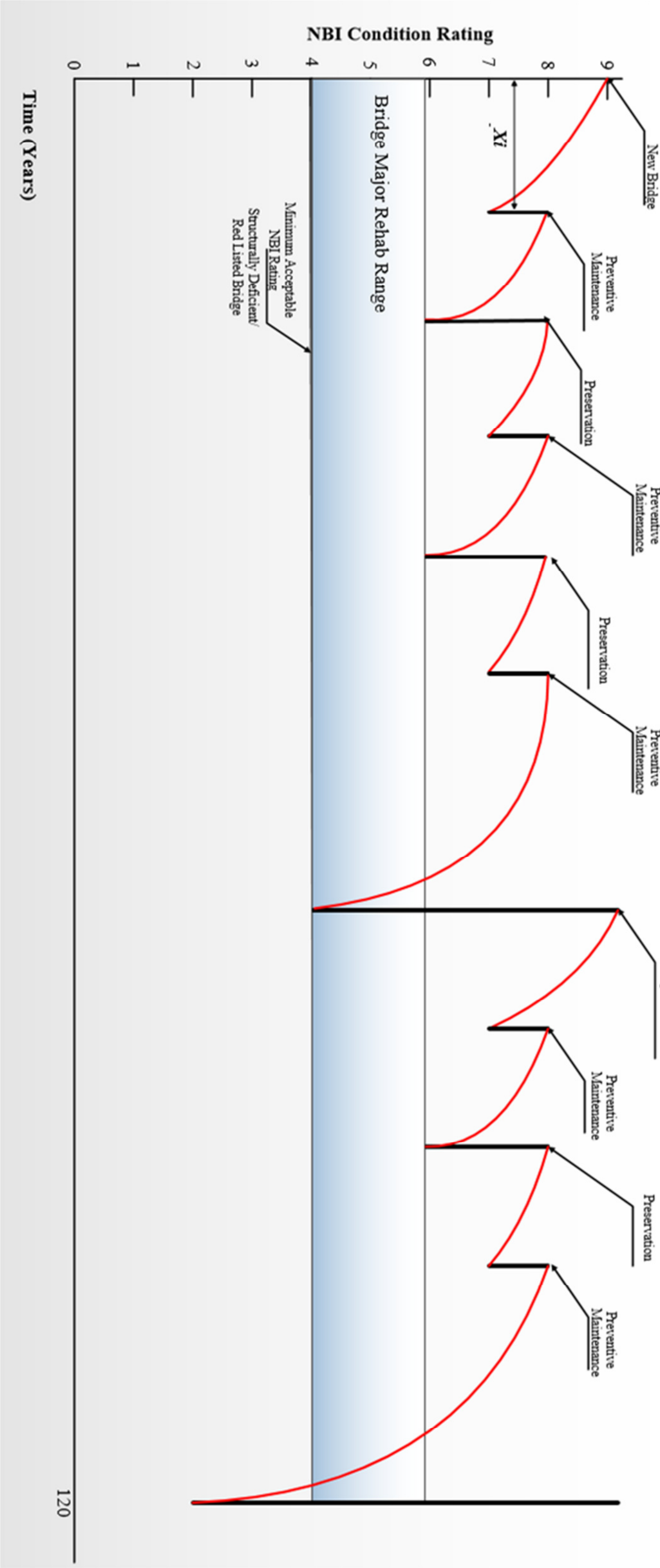


Figure 4-12 An Example of 120-Years Preservation Strategy

Cost Criteria; The cost criteria for MR&R activities is shown in Figure 5-6. A project to meet cost criteria for preservation the total cost of the preservation should be less than 25% of the cost of the new bridge a user can adjust based on their policy. If the cost is greater than the recommended 25% a consideration should be given to postponing the project for future rehabilitation to improve the bridge condition to the minimum criteria for rehabilitation noted in section 5.3.

4.5 Summary

A deterioration model was developed for this BMS based on the CBR method. The advantages of this method are: (1) At network level CBR provides the BMS with reasonably accurate predictions; (2) CBR compares the current problem bridge deterioration rate with the average deterioration rate of similar bridges with the same structure type, traffic volume, maintenance level, and similar environmental and operation conditions; (3) CBR works well with large networks by providing large database information that can be used to manage average case bridges; (4) The data from other large bridge networks can be used for smaller networks, for example, a city or town with a small network consisting of 5 to 100 bridges can use the state DOT's data or neighboring state data since all bridge inspection histories can be extracted from the NBI file. This method provides the bridge deterioration rates based on their NBI condition ratings or by their structural element condition ratings. The NBI condition rating has been in place for the past few decades; in the

United State NBI condition history for all publicly owned bridges has been available since the late 1980s.

The drawbacks of a CBR system is: (1) CBR requires a large network of bridges, but as noted above, a neighboring state or DOTs bridge data can be used; (2) In certain unique situations when a bridge structure is the first of its own type or made of new material, a matching type may not be available for use in determining the deterioration rate. In this case, the deterioration rate may be determined based on the expected lifespan recommended by the manufacture, and (3) The degree of similarity and weighting factors are based on engineering experience and judgment which can be biased.

Chapter 5: Conclusions

5.1 Summary and Conclusions

Most DOTs, cities, and towns in the United States are continually pursuing ways to improve bridge management in order to better direct limited funds for bridge rehabilitation, replacement, and preventive maintenance. The Bridge Management System (BMS) helps bridge owners to meet their goals by identifying and prioritizing preventive maintenance, rehabilitation, and replacement projects.

Bridge management cannot continue the old way of priority ranking in which the bridge deemed to be in worst condition is addressed first. A bridge in good condition should not be allowed to age and deteriorate without preventive maintenance. The cost of rehabilitation and replacement projects will continue to increase. Many local and state agencies are faced with increasing pressure to keep bridges in service and safe for the traveling public with little or no funding.

The BMS can generate datasets including inventory data, condition assessment, inspection reports, inspection history, construction as build plans, material certification, correspondence, photographs, maintenance history, Priority Ranking System for Rehabilitation and Replacement, Preservation Program, and forecasting model.

The proposed specification for a Bridge Management System application was presented and the underlying methods were explained. This BMS consists of five modules: 1) bridge overall information visualization and database system, 2) priority ranking system, 3) deterioration model, 4) cost model, and 5) preservation strategy. These modules interact together to enhance the BMS.

(1) These BMS components consist of inventory data, asset condition index, site specific user data, engineering documents, work reports, construction, and maintenance cost data being integrated into a web-based application. The publicly assessible web-based system will be available to bridge managers and engineers to assist in managing their bridge network inventory.

(2) The web-based application provides the insight needed for the decision-making process and justifies funding for priority projects that can be defended to the public by network managers. The priority ranking algorithms include multiple criteria, for example client preference, risk, condition, criticality, functionality, and other criteria to minimize costs over the long run while maintaining the bridge in good condition and providing the desired level of service.

(3) The quality of decision making depends on the ability to accurately predict the future condition of bridge components. The deterioration process due to normal aging under different environmental conditions is a very complex occurrence of

physical and chemical changes in bridge components. To address this deterioration model based on the artificial intelligence (AI) technique, the case-based reasoning (CBR) method is integrated into the web-based application. CBR methodology solves new problems based on the solutions of similar past problems. The proposed model is based on: 1) The development of a case library based on classifications outlined in Figure 4-3. This method uses the similarity in the performance among bridges under analogous environmental conditions, similar traffic volume, similar level of maintenance procedures within a district, analogous operating conditions, and matching bridge type and material; 2) The evaluation of the problem bridge to project its future deterioration rates, and the system retrieval searches the database for similar Average Case Bridges (ACB). If the ACB is found, then the system retrieval searches for higher similarities and if there are none then the system proceeds to a final solution as shown in Figure 5-6.

(4) A technique was developed to evaluate the different combinations of bridge component conditions (deck, superstructure, and substructure) that utilize a multi-criteria method for bridge rehabilitation (Figure 5-8). This cost model evaluates alternative maintenance and rehabilitation strategies using detailed costs for various types of MR&R activities and recommends a work program that maximizes benefits to the network. These various types of MR&R and estimated repair costs can be used to develop a 10-year budget plan. The system is also

capable of developing a preservation strategy to sustain a 120-year life span for each bridge in the network.

5.2 Contributions

The goal of this research was to develop comprehensive BMS components which would advance knowledge in the area of transportation infrastructure management. The proposed model has unique aspects: provides priority ranking system at the network level, a deterioration model that uses optimized case-based reasoning (CBR) method, and a cost model that considers different repair strategies along with 120-year preservation plan.

This is a tool for state DOTs and local bridge agencies to identify their needs and appropriately allocate available funds. The most salient contributions of this research are presented below:

- **A better understanding of bridge management system needs:**

  This research has reviewed a number of studies, practices, and drawbacks of the components of a bridge management system. The results indicated a need for a web-based BMS approach.

- **Development of priority ranking system for MR&R activities:**

  The priority ranking system was developed to prioritize MR&R projects. Bridge owners face the challenge of having many bridges in the same condition and with limited funding, thus they can only rehabilitate one or two bridges per fiscal year. The priority ranking justifies the bridge selection, improves communication, substantiates credibility, offers accountability for decision making, and has the potential to reduce infrastructure failures and their consequences.

- **Customization of the Case Based Reasoning (CBR) deterioration model:**

  A deterioration model was developed using the CBR technique. The developed deterioration model CBR is practical and uses the detailed knowledge of previously experienced, tangible problem circumstances stored in the BMS library database. Every time a new experience is stored, it will be available immediately for analyzing future problems. CBR has overcome the limitations of other deterioration models. The current condition state is utilized by CBR model searching through the case library database by matching the condition history, thus eliminating the uncertainty and randomness of other Markovian models. This CBR model works best with large-size networks; however, it can also be used on small networks by accessing neighboring larger network databases.

- **Integration of Cost Model and Preservation Strategy:**

  The cost model developed identifies the types of MR&R activities using NBI component condition ratings and provides bridge repair recommendations with estimated cost repairs on a yearly basis to prepare a 10-year budget plan within a 120-year service life preservation plan.

- **Consideration of the bridge agencies' needs:**

  The contribution of this research would be valuable to state DOTs and municipalities involved in the rehabilitation of their bridge network infrastructure. This research is intended to meet the needs of bridge engineers and decision makers to manage their bridges more cost effectively as outlined below:

  - ❖ The system is user adjustable, practical, interactive and easy to use.
  - ❖ The model can forecast beyond five-year planning.
  - ❖ The BMS can be accessed virtually from anywhere and anytime through the internet.
  - ❖ Bridge maintenance activities work report documentation.

5.3 Future Research

In order to improve the BMS the following recommendations need to be studied in future research:

1. Improvement of data security. Currently the system provides two levels of security. The first level allows privileged users to access the application. For example, the user can add work reports and other information to the

database. At the second level, the users have limited privileges using the application that accesses the bridge data.

2. The priority ranking system is based on multiple criteria; the recommended range of weighing factor is based on engineering experience and judgment which can be biased. Bridge replacement cost criteria continuously need to be updated and integrated into the priority ranking system and cost analysis.
3. The CBR case database library can be expanded by combining the neighboring state DOTs bridge data or creating a regional CBR case database library.
4. The CBR similarity weighing factor is based on engineering experience and judgment, which can be continuously updated.
5. Utilizing the CBR deterioration model, evaluate the after-repair deterioration and before-repair deterioration performance for each bridge component and elements.
6. Utilizing the existing BMS database, assessing CBR deterioration model against other leading deterioration models such as a regression model, simulation technique, and Markovian models.
7. The BMS cost model has a potential to generate a detailed itemized cost estimate based on a structural elements inspection report. This estimate can

be used by engineering consultants or transportation agencies to advertise bridge projects.

8. A web-based GIS software application for BMS will be developed as an extension to this research as outlined in Appendix D.

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Appendix A

NBI Condition Ratings		
Genral Condition Rating		
Code	**Condition**	**Description of Condition**
N	Use for all culverts	
9	**Excellent Condition**	
8	**Very Good Condition**	No problems noted
7	**Good Condition**	Some minor problems
6	**Satisfactory Condition**	Structural elements show some minor deterioration
5	**Fair Condition**	All primary structural elements are sound but may have minor section loss, cracking, spalling or scour
4	**Poor Condition**	Advanced section loss, deterioration, spalling or scour
3	**Serious Condition**	Loss of section, deterioration, spalling or scour have seriously affected primary structural components Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present
2	**Critical Condition**	Advanced deterioration of primary structural elements. Fatigue cracks in steel 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
1	**Immenent 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.
0	**Failed Condition**	out of service - beyond corrective action

NBI Condition Ratings		
Concrete Deck Condition Rating		
Code	**Condition of Deck Item**	**Description of Condition**
N	Use for all culverts	
9	**Excellent Condition**	Normaly new decks.Cracking none to hairline. No deficiencies which affect the condition of the deck. 100% of the deck surface area is in excellent condition .
8	**Very Good Condition**	Minor hairline cracks less than 1/32 inch wide and 1/8 inch deep with less than 1% of the deck surface deterioration.
7	**Good Condition**	Some cracks, light scaling less than 1/4 inch depth and 1/16 inch wide. Significant deterioration of curbs, sidewalks, parapets, railing or deck joints with less than 2% of the deck surface deterioration.
6	**Satisfactory Condition**	More cracks and scaling 1/4 inch to 1/2 inch in depth and more than 1/16 inch wide at 5 feet intervals or less. Extensive deterioration of the deck at the sidewalks and curb lines.The deck surface deterioration is less than 5%.
5	**Fair Condition**	Excessive cracking ½ inch to 1 inch deep. Substantial scaling some area of the deck has a exposed rebar. The deck distressed area is less than 10%. Deck joint in need of replacement.
4	**Poor Condition**	More than 25% of the deck area is showing distress. Exposed rebar. Substantial partial depth failures .Deck and the deck joint in need of replacement.Heavy build-up with rust staining.
3	**Serious Condition**	Excessive deteriorations. Exposed rebar, disintegrating deck at the sidewalk and the curb line. 25% to 50% of the deck area showing distress. Post load-carrying capacity. A full depth or partial depth failure. Structural review is required.
2	**Critical Condition**	Close bridge until the deck is serviceable. Emergency repair is required. Structural review has been completed and bridge is posted.Damage caused by the impact need emergencey repair.
1	**Immenent Failure Condition**	Close bridge until the deck is serviceable.
0	**Failed Condition**	Close bridge.

NBI Condition Ratings		
Steel Deck Condition Rating		
Code	**Condition of Deck Item**	**Description of Condition**
N	Use for all culverts	
9	**Excellent Condition**	Normaly new decks.No corrosion. No deficiencies which affect the condition of the deck. 100% of the deck surface area is in excellent condition .
8	**Very Good Condition**	No corrosion and no cracks. The connection are in place with no loose fasteners.No damage.
7	**Good Condition**	Slight corrosion has initiated. Significant deterioration of curbs, sidewalks, parapets, railing or deck joints. Minor cracks with some loose fasteners.
6	**Satisfactory Condition**	Loose connection, pack rust but the connection is functioning. Impact damage. Some rusting with no section loss. Extensive deterioration at the sidewalks ,curbs, parapets and bridge railing.
5	**Fair Condition**	Significant corrosion some pack rust is present with localized area of section loss. Excessive cracking. Loose connection with broken welds.
4	**Poor Condition**	Heavy corrosion with section loss. Loose connection with missing bolts and broken welds and pack rust with distortion. Impact damage.
3	**Serious Condition**	This rating will apply if severe or critical signs of structural distress are visible. Welds in grids and/or broken grids (replace deck soon).
2	**Critical Condition**	The condition requires a structural review. Post load capacity. Critical signs of structural distress are visible. Impact damage.
1	**Immenent Failure Condition**	Close bridge until the deck is serviceable.
0	**Failed Condition**	Close bridge.

NBI Condition Ratings		
Timber Deck Condition Rating		
Code	Condition of Deck Item	Description of Condition
N	Use for all culverts	
9	**Excellent Condition**	New deck no craks or splits and deficiencies which affect the condition of the deck
8	**Very Good Condition**	No decay or splits. No loose connection. No sign of wathering.Solid deck planks.
7	**Good Condition**	Minor cracking or splitting . Moderate decay at the curbs, sidewalks, parapets or railing . Loose deck planks with no loss of load capacity
6	**Satisfactory Condition**	Moderate cracks less than 50% of the depth and splits less than 25% of the length. Some impact damage with no loss of load capacity. Loose planks. Minor to moderate decay with less than 10% surface penetration.
5	**Fair Condition**	Less than 10% of the deck planks need replacement. Up to 40 % of the deck is deteriorated. Section loss less than 25%. Heavy cracking, weathering may require post load capacity. Imapact and or fire damage require some replacement.
4	**Poor Condition**	Less than 50% of the deck planks have decay in tension zone. Cracks and splits penetrating 50% of the thickness of the member. Extensive impact or fire damage may require post load capacity. More than 10% of the deck planks need replacement.
3	**Serious Condition**	More than 50% of the deck planks have decay in tension zone with decay greater than 10% of the thickness of the member. Extensive crushing with splits length greater than 25% of the length and some broken planks. Cracks deeper than 50% of the member thickness. Post load capacity.
2	**Critical Condition**	Close bridge until the deck is serviceable. Emergency repair is required. Structural review has been completed and bridge is posted.Damage caused by the impact need emergencey repair.
1	**Immenent Failure Condition**	Close bridge until the deck is serviceable.
0	**Failed Condition**	Close bridge.

N	Use for all culverts	
9	**Excellent Condition**	New superstructure. No spall, cracking or damage. Connection in place. No deficiencies which affect the condition of the superstructure.
8	**Very Good Condition**	Minor collision damage.Superficial cracks with some discoloring. No deficiencies which affect the condition of the superstructure
7	**Good Condition**	Hairline cracks without delamination or spall in the superstructure. No exposed rebar. Some efflorescence staining. No damage. Bearings have corrosion problems .
6	**Satisfactory Condition**	Minor spall and delamination 1 inch or less deep by 6 inch or less in diameter with exposed rebar with no section loss. Impact damage at condition state 2. Minor cracks with evidence of efflorescence.
5	**Fair Condition**	Substantial impact damage that has been captured in Condition State 2. Bearing need adjustment. Moderate water saturation efflorescence, and deterioration of the girder ends. Moderate spall and delamination 1 inch or less deep by 6 inch or less in diameter with exposed rebar with some section loss. Unsealed moderate cracking.
4	**Poor Condition**	Extensive impact damage that has been captured in Condition State 3 that may affect the Structural capacity of some structural members. Measurable structural cracks or large spalled areas greater than 1 in. deep or greater than 6 in. diameter with exposed rebar that has a measurable section loss. Bearing are frozen and not functioning. This condition does not require structural review. Large cracks visible.
3	**Serious Condition**	Critical collision damage to structural elements, the damage caused by the impact has been captured in Condition State 4.The condition require structural review may need to post load capacity. Extensive section loss. Large structural cracks and spalls with exposed rebar and loss of section in tension bars. May require a post load capacity.
2	**Critical Condition**	Extensive deterioration with section loss in many location and concrete disintegration around reinforcing steel effecting the structure ability to support design load. Impact damage will require emergency repair. Post load capacity or bridge may need to be closed.
1	**Immenent Failure Condition**	Close bridge extensive deterioration of superstructure
0	**Failed Condition**	Close bridge

NBI Condition Ratings		
Prestressed Concrete Superstructure Condition Rating		
Code	**Condition of Deck Item**	**Description of Condition**
N	Use for all culverts	
9	**Excellent Condition**	New superstructure. No spall, cracking or damage. No deficiencies which affect the condition of the superstructure.
8	**Very Good Condition**	Minor collision damage.Superficial cracks . No deficiencies which affect the condition of the superstructure.
7	**Good Condition**	Hairline cracks without delamination or spall in the superstructure. No exposed rebar. No exposed prestressing.Some efflorescence staining. No damage. Bearings have corrosion problems .
6	**Satisfactory Condition**	Minor spall and delamination 1 inch or less deep by 6 inch or less in diameter with exposed rebar with no section loss and no exposed prestressing . Impact damage at condition state 2. Minor cracks with evidence of efflorescence.
5	**Fair Condition**	Substantial impact damage that has been captured in Condition State 2. Bearing need adjustment. Exposed prestressing with no section loss. Moderate spall and delamination 1 inch or less deep by 6 inch or less in diameter with exposed rebar with some section loss. Unsealed moderate cracking.
4	**Poor Condition**	Extensive impact damage that has been captured in Condition State 3 that may affect the Structural capacity of some structural members. Measurable structural cracks or large spalled areas greater than 1 in. deep or greater than 6 in. diameter with exposed rebar that has a measurable section loss. Exposed prestressing with section loss but does not require structural review.
3	**Serious Condition**	Critical collision damage to structural elements, the damage caused by the impact has been captured in Condition State 4.The condition require structural review may need to post load capacity. Extensive section loss. Large structural cracks and spalls with exposed rebar and loss of section in tension bars. May require a post load capacity.
2	**Critical Condition**	Extensive deterioration with section loss in many location and concrete disintegration around reinforcing steel effecting the structure ability to support design load. Impact damage will require emergency repair. Post load capacity or bridge may need to be closed.
1	**Immenent Failure Condition**	Close bridge extensive deterioration of superstructure
0	**Failed Condition**	Close bridge

NBI Condition Ratings		
Steel Superstructure Condition Rating		
Code	**Condition of Deck Item**	**Description of Condition**
N	Use for all culverts	
9	**Excellent Condition**	New superstructure. No corrosion, distortion, cracking or damage. Connection in place. No deficiencies which affect the condition of the superstructure.
8	**Very Good Condition**	No corrosion, distortion, cracking or damage. Connection in place. No deficiencies which affect the condition of the superstructure.
7	**Good Condition**	Corrosion of the steel has initiated. No visible cracks. No loose fasteners. Minor collision damage. Bearing have corrosion need lubrication.
6	**Satisfactory Condition**	Extensive corrosion, some cracks, loose fasteners with no section loss. Damaged section.Bearing have a extensive corrosion.
5	**Fair Condition**	Moderate corrosion with small section loss. Cracks has self arrested. Pack rust without distortion, connection in place. Bearing out of adjustment frozen or not functioning. Impact damage with Condition state 2.
4	**Poor Condition**	Critical collision damage to structural elements The damage caused by the impact has been captured in Condition State 3.Pack rust with section loss. Visible cracks with some distortion, missing bolts or broken welds. Bearing frozen and not functioning. The condition does not warrant structural review.
3	**Serious Condition**	Critical collision damage to structural elements The damage caused by the impact has been captured in Condition State 4.The condition require structural review may need to post load capacity. Extensive section loss.
2	**Critical Condition**	Extensive corrosion with section loss in many location and distortion effecting the structure ability to support design load. Impact damage will require emergency repair. Post load capacity or bridge may need to be closed.
1	**Immenent Failure Condition**	Close bridge extensive deterioration of superstructure
0	**Failed Condition**	Widespread corrosion of superstructure resulting in significant distortion of a main member, Close bridge.

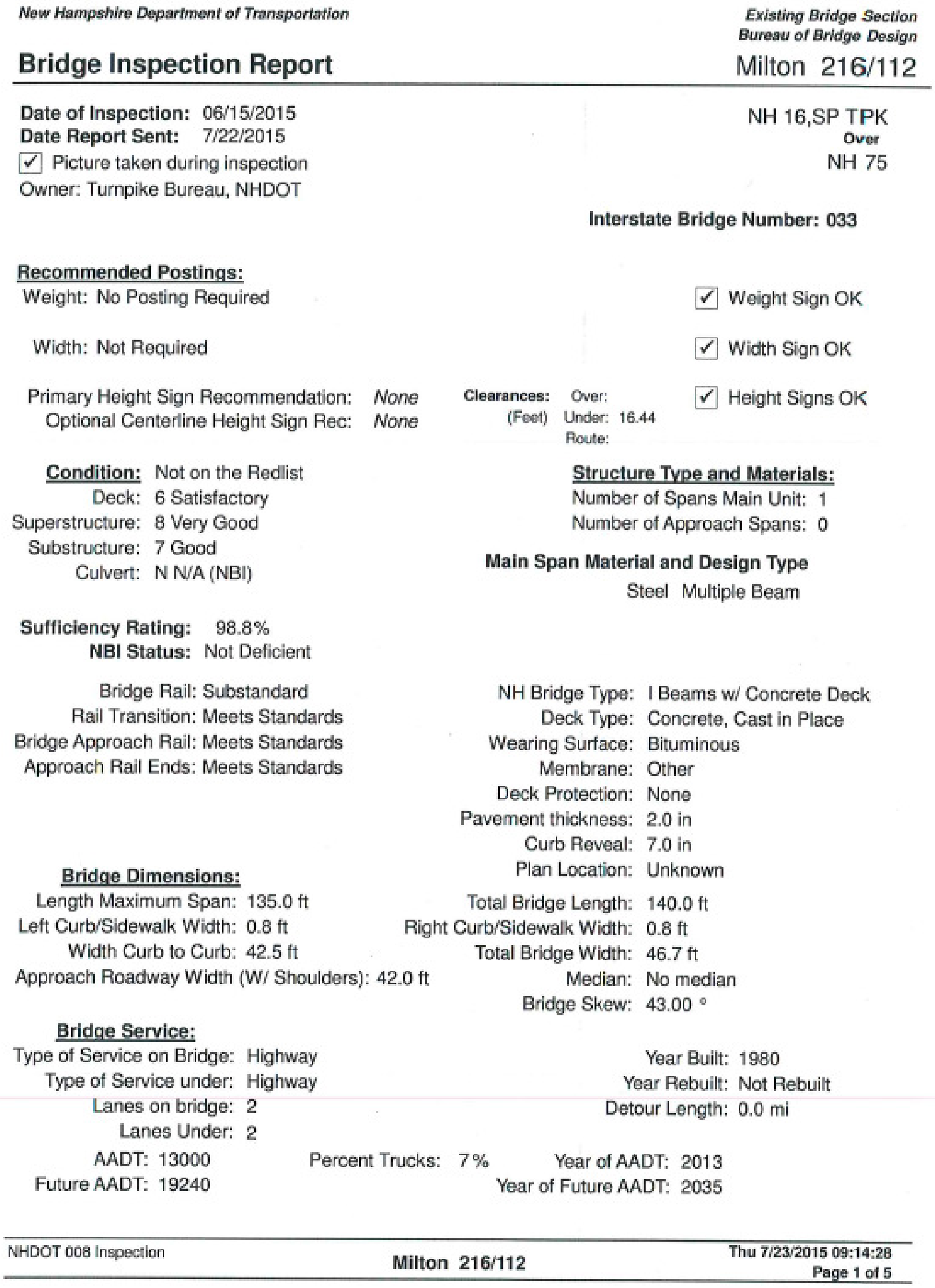
NBI Condition Ratings		
Timber Superstructure Condition Rating		
Code	**Condition of Deck Item**	**Description of Condition**
N	Use for all culverts	
9	**Excellent Condition**	New Superstructure no crakes or splits and deficiencies which affect the condition of the superstructure.
8	**Very Good Condition**	No decay or splits. No loose connection. No sign of wathering.Solid deck planks.Connection in place. No damage. Check surface penetration less than 5% of the thickness.
7	**Good Condition**	Minor cracking or splitting . The decay is less than 5% of the member. Loose connections with no distortion the connection is in place and functioning. Check penetration is less than 10% of thickness of the member. Minor damage.
6	**Satisfactory Condition**	Moderate cracks that has been arrested through effective treatment. Some impact damage with no loss of load capacity. Loose connection with no section loss. Check penetration is up to 40% of the thickness of the member. Minor split and abrasion less than 10% of the member thickness.
5	**Fair Condition**	Moderate decay, collision damage at Condition State 2, cracking, splitting or minor crushing of beams or stringers. Check penetration is up to 50% of thickness of the member. Loose connection with some section loss.
4	**Poor Condition**	Extensive decay, cracking, splitting that affect more than 10% of the member. Significant impact or fire damage or crushing of beams which may require post load capacity. Loos connection with missing bolts and section loss, this condition will require structural review.
3	**Serious Condition**	Extensive decay, deep cracks penetrating more than 50% of the thickness of the member. Major fire or impact require emergency repair. Local failure may be evident. Structural review is required.
2	**Critical Condition**	Extensive deterioration of superstructure with deformation of a main member and significant section loss. Bridge need to be closed until repaired..
1	**Immanent Failure Condition**	Close bridge extensive deterioration of superstructure
0	**Failed Condition**	Close bridge

NBI Condition Ratings		
Concrete Substructure Condition Rating		
Code	**Condition of Deck Item**	**Description of Condition**
N		Use for all culverts
9	**Excellent Condition**	New substructure. No spall, cracking or damage. No deficiencies which affect the condition of the superstructure.
8	**Very Good Condition**	Minor collision damage.Superficial cracks with some discoloring. No deficiencies which affect the condition of the superstructure
7	**Good Condition**	Hairline cracks without delamination or spall in the Substructure. No exposed rebar. Some efflorescence staining. Minor damage. Bearings have corrosion problems . Back wall has efflorescence. No settlement and no scour.
6	**Satisfactory Condition**	Minor cracking with spall 1 inch or less deep by 6 inch or less diameter with leaching on concrete . Some exposed rebar without section loss.Impact damage at Condition State 2. Settlement within tolerable limits. Corrosion of steel section in a steel substructure unit, but no measurable section loss. Some scouring have occurred at the foundation. Slope washout.
5	**Fair Condition**	Some cracking with spall 1 inch or less deep by 6 inch or less diameter with substantial leaching on the concrete . Some exposed rebar with some section loss.Impact damage at Condition State 2. Minor settlement within tolerable limits. Corrosion of steel section in a steel substructure unit, with measurable section loss. Some scouring has occurred at the foundation. Slope washout.
4	**Poor Condition**	Extensive impact damage that has been captured in Condition State 3 that may affect the Structural capacity of some structural members. Measurable structural cracks or large spalled areas greater than 1 in. deep or greater than 6 in. diameter with exposed rebar that has a measurable section loss.. This condition does not require structural review. Large cracks visible. Extensive scouring has occurred at the foundation exceeding the tolerable limits. Substantial deterioration at the back wall and the bridge sets.
3	**Serious Condition**	Critical collision damage to structural elements, the damage caused by the impact has been captured in Condition State 4.The condition require structural review may need to post load capacity. Extensive section loss. Large structural cracks and spalls with exposed rebar and loss of section. Severe scouring or undermining of footings exposing the piles affecting the stability of the structure. Settlement of the substructure has occurred.
2	**Critical Condition**	Extensive deterioration with section loss in many location and concrete disintegration around reinforcing steel effecting the structure ability to support design load. Impact damage will require emergency repair. Post load capacity or bridge may need to be closed.
1	**Immenent Failure Condition**	Close bridge extensive deterioration of substructure.
0	**Failed Condition**	Close bridge

NBI Condition Ratings		
Steel Culvert Condition Rating		
Code	**Condition of Culvert**	**Description of Condition**
N		Use if structure is not a culvert.
9	**Excellent Condition**	New culvert. No corrosion, distortion, cracking or damage. No deficiencies which affect the condition of the culvert.
8	**Very Good Condition**	No corrosion, distortion, cracking or damage. Connection in place.No settlement or scour and no damage. No deficiencies which affect the condition of the superstructure.
7	**Good Condition**	Shrinkage cracks, light scaling and insignificant spalling which does not expose reinforcing steel. Insignificant damage caused by drift with no misalignment and not requiring corrective action. Some minor scour has occurred near toe walls, wingwalls or pipes. Metal culverts have a smooth symmetrical curvature with superficial corrosion and pitting.
6	**Satisfactory Condition**	Deterioration or initial disintegration, minor chloride contamination, cracking with some leaching or spalls on concrete or masonry walls and slabs. Local minor scouring at toe walls, wingwalls or pipes. Metal culverts have a smooth curvature, nonsymmetrical shape, significant corrosion or deep pitting.
5	**Fair Condition**	Moderate to major deterioration or disintegration, extensive cracking and leaching or spalls on concrete or masonry walls and slabs. Minor settlement or misalignment. Considerable scour or erosion causing significant undermining at toe walls, wingwalls or pipes. Metal culverts have significant distortion and deflection in one section, significant corrosion or deep pitting.
4	**Poor Condition**	Large spalls, heavy scaling, wide cracks, considerable efflorescence or opened construction joint permitting loss of backfill. Considerable settlement or misalignment. Considerable scour or erosion causing significant undermining at toe walls, wingwalls or pipes. Metal culverts have significant distortion and deflection, or deep pitting with scattered perforations.
3	**Serious Condition**	Any condition described in code 4 but which is excessive in scope. Severe movement or differential settlement of the segments, or loss of fill. Holes may exist in walls or slabs. Integral wingwalls nearly severed from culvert. Severe scour or erosion at toe walls, wingwalls or pipes causing extensive undermining. Metal culverts have extreme distortion and deflection in one section, extensive corrosion or deep pitting with scattered perforations.
2	**Critical Condition**	Integral wingwalls collapsed, severe settlement of roadway due to loss of fill. Section of culvert may have failed and can no longer support embankment. Complete undermining at toe walls and pipes. Corrective action required to maintain traffic. Metal culverts have extreme distortion and deflection throughout with extensive perforations due to corrosion.
1	**Immenent Failure Condition**	Bridge closed. Corrective action may put back in light service.
0	**Failed Condition**	Bridge closed. Replacement necessary.

Appendix B

Bridge Inspection Report



New Hampshire Department of Transportation

Existing Bridge Section
Bureau of Bridge Design

Bridge Inspection Report

Milton 216/112

Date of Inspection: 06/15/2015
Date Report Sent: 7/22/2015
☑ Picture taken during inspection
Owner: Turnpike Bureau, NHDOT

NH 16,SP TPK
Over
NH 75

Interstate Bridge Number: 033

Recommended Postings:
Weight: No Posting Required
Width: Not Required
Primary Height Sign Recommendation: *None*
Optional Centerline Height Sign Rec: *None*

Clearances: (Feet) Over:
Under: 16.44
Route:

☑ Weight Sign OK
☑ Width Sign OK
☑ Height Signs OK

Condition: Not on the Redlist
Deck: 6 Satisfactory
Superstructure: 8 Very Good
Substructure: 7 Good
Culvert: N N/A (NBI)

Structure Type and Materials:
Number of Spans Main Unit: 1
Number of Approach Spans: 0

Main Span Material and Design Type
Steel Multiple Beam

Sufficiency Rating: 98.8%
NBI Status: Not Deficient

Bridge Rail: Substandard
Rail Transition: Meets Standards
Bridge Approach Rail: Meets Standards
Approach Rail Ends: Meets Standards

NH Bridge Type: I Beams w/ Concrete Deck
Deck Type: Concrete, Cast in Place
Wearing Surface: Bituminous
Membrane: Other
Deck Protection: None
Pavement thickness: 2.0 in
Curb Reveal: 7.0 in
Plan Location: Unknown

Bridge Dimensions:
Length Maximum Span: 135.0 ft
Left Curb/Sidewalk Width: 0.8 ft
Width Curb to Curb: 42.5 ft
Approach Roadway Width (W/ Shoulders): 42.0 ft

Total Bridge Length: 140.0 ft
Right Curb/Sidewalk Width: 0.8 ft
Total Bridge Width: 46.7 ft
Median: No median
Bridge Skew: 43.00 °

Bridge Service:
Type of Service on Bridge: Highway
Type of Service under: Highway
Lanes on bridge: 2
Lanes Under: 2

Year Built: 1980
Year Rebuilt: Not Rebuilt
Detour Length: 0.0 mi

AADT: 13000
Future AADT: 19240
Percent Trucks: 7%
Year of AADT: 2013
Year of Future AADT: 2035

NHDOT 008 Inspection
Milton 216/112
Thu 7/23/2015 09:14:28
Page 1 of 5

No.	Description	Env.	Quantity	Units	State 1	State 2	State 3	State 4	State 5
14	Concrete Deck - Protected w/ Membran	Severe	6,534	(SF)	0 %	100 %	0 %	0 %	0 %
106	Weathering Steel Beam/Girder (Open W	Severe	981	(LF)	100 %	0 %	0 %	0 %	
215	Reinforced Concrete Abutment	Severe	167	(LF)	99 %	1 %	0 %	0 %	
300	Strip Seal Expansion Joint	Severe	66	(LF)	0 %	100 %	0 %		
311	Moveable Bearing (roller, sliding, etc.)	Moderate	14	(EA)	100 %	0 %	0 %		
330	Uncoated Metal Bridge Railing	Benign	525	(LF)	0 %	100 %	0 %	0 %	
359	Soffit of Conc Deck or Slab Condition W	Severe	1	(EA)	0 %	100 %	0 %	0 %	0 %

Bridge Notes:

Approach and Roadway Notes: *ASPHALT- CRACKED AT DECK END.. W- BEAM DAMAGED.*

Unusual or experimental features: *November 6, 1998 installed M&R Experimental Feature 1993-03, Silicoflex SF400 Expansion Joint In Report dated 10-1-2001 product was considered unsatisfactory due to separation and leaking.*

Inspection History:

Inspection Date: 06/15/2015 **Inspector:** KJT

Deck: 6 Satisfactory
Super: 8 Very Good
Substr: 7 Good
Culvert: N N/A (NBI)

Notes:

KJT inspection comments -
DECK:ASPHALT-GOOD CONDITION. RAIL SCRAPES AND GOUGES RAIL AND CHAIN LINK POST BENT AT WEST. JOINT HOLED AND LEAKING. DECK HAUNCH AREA SPALLED AT NORTH. MINOR DELAMINATION IN THIRD BAY SOUTH END. CRACKS WITH EFFLORESCENCE. GRANITE CURBS AT SOUTH EAST AND WEST CRACKED PUSHED OUT.
SUPERSTRUCTURE: BACKWALLS HAVE FINE CRACKS.
SUBSTRUCTURE: ABUTMENTS FINE CRACKS.

PICTURE: C535.
04. RAIL BENT AT WEST.

Inspection Date: 07/11/2013 **Inspector:** KJT

Deck: 6 Satisfactory
Super: 8 Very Good
Substr: 7 Good
Culvert: N N/A (NBI)

Notes:

KJT inspection comments -
DECK:ASPHALT-NEW. DECK HAUNCH AREA SPALLED AT NORTH. MINOR DELAMINATION IN THIRD BAY SOUTH END. CRACKS WITH EFFLORESENCE. GRANITE CURBS AT SOUTH EAST AND WEST CRACKED PUSHED OUT.
SUPERSTRUCTURE: BACKWALLS HAVE FINE CRACKS.
SUBSTRUCTURE: ABUTMENTS FINE CRACKS.

PICTURE: C484-
33. CURB SPALLED, GRANITE FACE PUSHED OUT AT SOUTHEAST.

Inspection Date: 02/15/2013 **Inspector:** KJT

Deck: 6 Satisfactory
Super: 8 Very Good
Substr: 7 Good
Culvert: N N/A (NBI)

Notes:

inspection comments -
DECK:ASPHALT-NEW. DECK HAUNCH AREA SPALLED AT NORTH. MINOR DELAMINATION IN THIRD BAY SOUTH END. CRACKS WITH EFFLORESENCE.
SUPERSTRUCTURE: BACKWALLS HAVE FINE CRACKS.
SUBSTRUCTURE: ABUTMENTS FINE CRACKS.

Inspection History:

Inspection Date: 07/01/1997 **Inspector:** Not Available
Deck: 8 Very Good
Super: 8 Very Good
Substr: 7 Good
Culvert: N N/A (NBI)
Notes:
Sufficiency Rating Calculation Accepted by DEP at 12-23-98 08:08:21

Inspection Date: 06/01/1995 **Inspector:** Not Available
Deck: 8 Very Good
Super: 8 Very Good
Substr: 8 Very Good
Culvert: N N/A (NBI)
Notes:

Inspection Date: 10/01/1993 **Inspector:** Not Available
Deck: 8 Very Good
Super: 8 Very Good
Substr: 8 Very Good
Culvert: N N/A (NBI)
Notes:

Inspection Date: 04/01/1991 **Inspector:** Not Available
Deck: 7 Good
Super: 8 Very Good
Substr: 8 Very Good
Culvert: N N/A (NBI)
Notes:

Traffic Sign Notes: *PLANK- OK.*
Traffic Sign Mounts: *BOLTED- OK.*

Copy Distribution:

☐ (2) Bureau of Municipal Hghways
☐ (3) Bureau of Municipal Hghways
☑ Bureau of Turnpikes
☐ Border State
☐ Bureau of Rail and Transit
☐ Army Corps Of Engineers
☐ Railroad
☐ Dept. of Res. and Econ. Dev.
☐ Dept. of Environmental Services
☐ USDA Forest Service
☐ Bureau of Traffic

Appendix C

Core element

Core Element		
SE #	**Description**	**Unit**
585	Alert	EA
520	Asphaltic Plug Expansion Device	LF
303	Asiembly]oint/Seat (Modular)	LF
583	Beam End Deterioration	EA
582	Bridge Railing Traffic Impact	EA
334	Coated MetafBridge Railing	LF
147	Coated Steel Cable	EA
302	CompressionJointSeal	LF
241	Concrete Culvert	LF
12	Concrete Deck - Bare	EA
13	Concrete Deck with Bituminous Overlay	EA
400	Concrete Deck with Bituminous Overlay and Coated Bars	EA
27	Concrete Deck with Cathodic System	EA
26	Concrete Deck with Coated Bars	EA
14	Concrete Deck with Membrane and Bituminous Overlay	EA
401	Concrete Deck with Membrane, Bituminous Overlay, and Coat	EA
403	Concrete Deck with Reinforced Rigid Overlay	EA
22	Concrete Deck with Rigid Overlay	EA
402	Concrete Deck with Rigicl Overlay and Coated Bars	EA
18	Concrete Deck w'ith Thin Overlay	EA
38	Concrete Slab - Bare	EA
39	Concrete Slab with Bituminous Clverlay	EA
410	Concrete Slab with Bituminous Overlay ancl Coated Bars	EA
53	Concrete Slab with Cathodic System	EA
52	Concrete Slab with Coated Bars	EA
40	Concrete Slab with Membrane and Bituminous Overlay	EA
411	Colcrete Slab with Membrane, Bituminous Overlay, and Coate	EA

413	Concrete Slab with Reinforced Rigid Overlay	EA
48	Concrete Slab with Rigid Overlay	EA
412	Concrete Slab with Rigicl Overlay and Coated Bars	EA
44	Concrete Slab with Thin Overlay	EA
500	Concrete Structural Deck	SF
589	Critical Cracking	EA
504	Deck - Other	EA
358	Deck Cracking	EA
580	Deck Joint	EA
586	Deterioration of Pin or Pin and Hanp;er Assembly	EA
315	Disk Bearing	EA
310	Elastomeric Bearing	EA
312	Encloseci/Conceale Bearing	EA
584	Fascia Beam Deterioration	EA
503	Fiber Reinforced Polymer (FRP) Deck with Overlay	EA
313	Fixed Bearing	EA
530	Galvanizecl Steel Open Circler/Beam	LF
579	Headwall	LF
519	Indepencient Sidewalk	LF
529	Joint Trough	LF
551	Masonry Abutrnent	LF
569	Masonry Culvert	LF
550	Masonry Pier Wall	LF
311	Movable Bearing (roller/sliding/etc.)	EA
552	MSE Abutrnent	LF
553	MSE Retaining Wall/Wingwall	LF
304	Open Expansion Joint	LF
421	Open]oint - Steel Sliding I']late	LF
422	Open Joint - Steel Tooth Dam (not Sealed)	LF

217	Other Abutment	LF
145	Other Arch	LF
333	Other Bridge Railing	LF
243	Other Culvert	LF
521	Other Expansion]oint	LF
211	Other Pier Wall	LF
560	Other WingwaillRetaining Wall	LF
357	Pack Rust	EA
161	Painted Pin and Hanger Assembly	EA
141	Painted Steel Arch	LF
102	Painted Steel Closed Web/Box Girder	LF
432	Painted Steel Closed Web/Box Transvetse Girder	LF
202	Painted Steel Column or Pile Exteruion	EA
131	Painted Steel Deck Truss	LF
152	Painted Steel Floorbeam	LF
107	Painted Steel Open GirderlBeam	LF
437	Painted Steel Open Transverse Girder	LF
231	Painted Steel Pier Cap	LF
113	Painted Steel Stringer (stringer-floorbeam system)	LF
121	Painted Steel Through Truss (bottom chorcl)	LF
126	Painted Steel Through Truss (excluding bottom chord)	LF
587	Pin and Hanger Retrofit	EA
314	Pot Bearing	EA
301	Pourable]oint Seal	LF
561	Prefabricated Concrete Wall	LF
320	Prestressed Concrete Approach Slab with or without Bitumino	EA
143	Prestressed Concrete Arch	LF
104	Prestressed Concrete Closed Web/Box Girder	LF
204	Prestressed Concrete Column or Pile Extension	EA

154	Prestressed Concrete Floorbeam	LF
109	Prestresseel Concrete Open Girderf Beam	LF
233	Prestressed Concrete Pier Cap	LF
115	Prestressed Concrete Stringer (stringer-floorbeam system)	LF
226	Prestressed Concrete Submerged Pile	EA
439	Prestressed Concrete Transverse Girder	LF
215	Reinforced Concrete Abutment	LF
321	Reinforced Concrete Approach Slab with or without Bitumino	EA
144	Reinforced Concrete Arch	LF
105	Reinforced Concrete Closed Web/Box Girder	LF
205	Reinforced Concrete Column or Pile Extermion	EA
155	Reinforced Concrete Floorbeam	LF
110	Reinforced Concrete Open Cirder/Bearn	LF
234	Reinforced Concrete Pier Cap	LF
210	Reinforced Concrete Pier Wall	LF
565	Reinforced Concrete Pile Cap/Footing	EA
116	Reinforced Concrete Stringer (stringer-floorbeam system)	LF
227	Reinforced Concrete Submerged Pile	EA
220	Reinforced Concrete Submerged Pile Cap/Footing	EA
440	Reinforced Concrete Transverse Girder	LF
557	Reinforced Concrete Wingwall/Retaining Wall	LF
361	Scour	EA
363	Section Loss	EA
360	Settlement	EA
420	Silicone Joint Seal	LF
359	Soffit (or undersurface) of Concrete Deck or Slab	EA
581	Soffit (or undersurface) of Concrete Deck or Slab with Stay-I	EA
590	Spandrel Wall (Closed Spandrel Concrete Arch Bridge)	EA
240	Steel Culvert	LF
29	Steel Deck - Concrete Filled Grid	EA

30	Steel Deck - Corrugated/Orthotropic/Etc.	EA
502	Steel Deck - Exodermic	EA
501	Steel Deck - Filled Grid with Bituminous Overlay	EA
28	Steel Deck - Open Grid	EA
356	Steel Fatigue	EA
531	Steel open Girder/Beam- Concrete Enclosed	LF
300	Strip Seal Expansion Joint	LF
588	Temporary Support	EA
216	Timber Abutment	LF
332	Timber Bridge Railing	LF
206	Timber Column or Pile Extension	EA
242	Timber Culvert	LF
31	Timber Deck (Bare)	EA
32	Timber Deck with Bituminous Overlay	EA
156	Timber Floorbeam	LF
111	Timber Open Girder/Beam	LF
235	Timber Pier Cap	LF
54	Timber Slab	EA
55	Timber Slab with Bituminous Overlay	EA
117	Timber Stringer (stringer-floorbeam system)	LF
228	Timber Submerged Pile	EA
135	Timber Truss/Arch	LF
362	Traffic Impact	EA
330	Uncoated Metal Bridge Railing	LF
146	Uncoated Steel Cable	EA
140	Unpainted Steel Arch	LF
101	Unpainted Steel Closed Web/Box Girder	LF
431	Unpainted Steel Closed Web/Box Transverse Girder	LF
201	Unpainted Steel Column or Pile Extension	EA
130	Unpainted Steel Deck Truss	LF

151	Unpainted Steel Floorbeam	LF
106	Unpainted Steel Open Girder/Beam	LF
436	Unpainted Steel Open Transverse Girder	LF
230	Unpainted Steel Pier Cap	LF
160	Unpainted Steel Pin ancl/or Pin and l{anger Assembly	EA
112	Unpainted Steel Stringer (siringer-floorbeam system)	LF
225	Unpainted Steel Submerged Pile	EA
120	Unpainted Steel Through Truss (bottom chord)	LF
125	Unpainted Steel Through Truss (excluding bottom chord)	LF

Structural Core Elements (PUB 590, 2006)

Appendix D

Defects #	Defects
1000	Corrosion
1010	Cracking
1020	Connection
1080	Delamination/Spall/Patched Area
1090	Exposed Rebar
1100	Exposed Prestressing
1110	Cracking in Prestressed Concrete
1120	Efflorescence/rust staining
1130	Cracking in reinforced concrete and other materials.
1140	Decay/Section Loss
1150	Check/Shake
1160	Crack (Timber)
1170	Splits/delaminations in timber
1180	Abrasion/Wear (Timber)
1190	Abrasion/Wear (Concrete)
1220	Deterioration (Other)
1610	Mortar Breakdown(Masonry)
1620	Split/Spall (Masonry)

1630	Patched Area (Masonry)
1640	Masonry Displacement
1900	Distortion
2210	Movement
2220	Alignment
2230	Bulging, Splitting or Tearing
2240	Loss of Bearing Area
2310	Leakage
2320	Seal Adhesion
2330	Seal Damage
2350	Debris Impaction
2360	Adjacent Deck or Header
2370	Metal Deterioration or Damage
3210	Delamination/Spall/Patched Area Area/Pothole (Wearing Surfaces)
3220	Crack (Wearing Surface)
3230	Effectiveness (Wearing Surface)
3410	Chalking (Steel Protective Coatings)
3420	Peeling/Bubbling/Cracking (Steel Protective Coatings)
3430	Oxide Film Degradation Color/Texture Adherence (Steel Protective Coatings)
3440	Effectiveness (Steel Protective Coatings)
3510	Wear (Concrete Protective Coatings)
3540	Effectiveness (Concrete Protective Coatings)
3600	Effectiveness-Protective System (e.g. Cathodic)
4000	Settlement
7000	Damage

Appendix D: Model Implementation

Currently, (2018) NHDOT and University of New Hampshire Technology Transfer Center SADES (Statewide Asset Data Exchange System) are in the process of developing Web-based Geographic Information Systems software based on this proposed model and the following framework outlined below:

D.1 General

Web-based Geographic Information Systems are being widely used as the key index variable to facilitate immediate access to the volume of transportation infrastructure data pertaining to a government managed highway network. A fully functional network system per transportation assets, for example bridges data that includes: (a) inventory data, (b) asset condition index, (c) site-specific user data, (d) engineering documents, (e) work reports, (f) construction and maintenance cost data, and (g) maintenance budget forecasting are key components of this BMS model.

In recent years significant advances have been made to manage the municipal infrastructure of sewer and water networks as well as for roadway assets. Several roadway utility management systems have already been integrated into GIS applications (Hu, 2009). Numerous other infrastructure asset management software tools such as Bridge Management System (BMS) have been developed to address the growing complexity of transportation infrastructure networks. However, the majority of these available tools were developed for stand-alone use, so they do not provide the full spectrum of the infrastructure management needs nor the ability to integrate the use or use other available analysis tools (Halfawy et al, 2002).

Batty and Xie (1994) describes GIS software as a tool for storing, analyzing, managing and displaying geo-referenced data including location as well as site attributes and general information describing the geographic entities (asset names, social, -economic, environmental, etc.). No analytical functions that include asset management capabilities are mentioned. It is being recognized that both infrastructure management system models and GIS deal with both; GIS providing the key index variable for linking spatial data and infrastructure management models to provide analytical analysis using inventory data. Linking an infrastructure management system with GIS will lead to improved tools for managing municipal and state assets. The Web GIS-based BMS, consisting of spatial and non-spatial data, supports a wide range of functionality, such as inventory and condition data, performance evaluation, forecasting model, planning and prioritizing MR&R operations, and evaluating alternative preservation strategies (NCR, 2004).

D.2 WebGIS Framework

ArcGIS Server (developed by ESRI) supports centralized management of geodata, imagery, interoperability and data sharing. WebGIS application can create maps and to access analytics applications. Figure D-1 shows the three tiers of the ArcGIS Server (ESRI 2008) service-oriented architecture (SOA) framework; (1) Desktop - an authoring tier of professional ArcGIS for Desktop users, (2) Server - a publishing tier of services, and (3) Client - a presentation tier of viewers with access to available published services (Peters, 2014). The geo-processing is developed from the bottom up to support interoperability and data sharing.

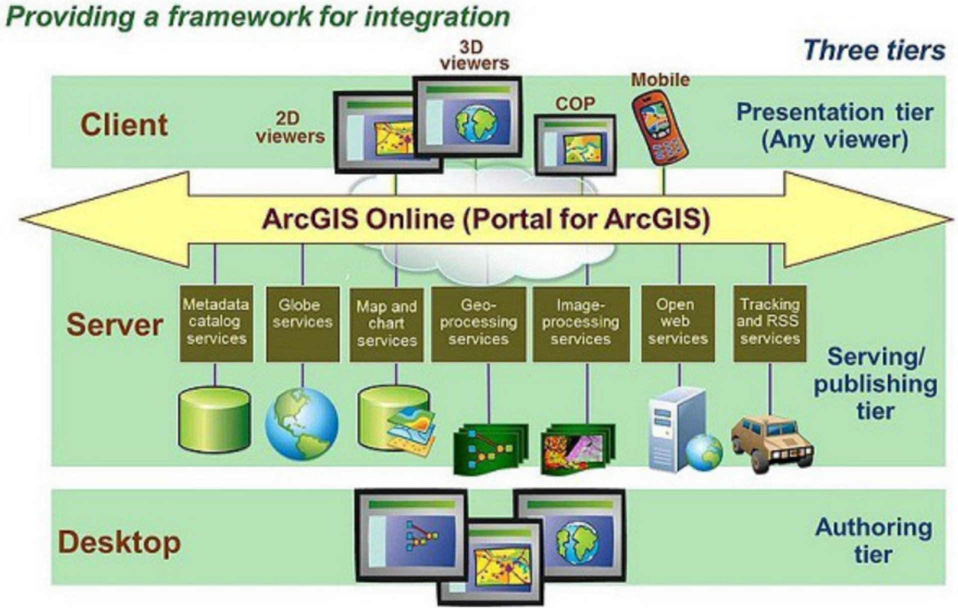


Figure D-1 Web Services GIS Framework (ESRI 2014)

D.3 GIS BMS Framework

A framework linking Bridge Management System (BMS) to GIS is essential to integrate and centralize BMS data (inventory items, inspection data, performance data, maintenance history, work order and work reports/cost data) to the GIS data model. The complete, "integrated model" would provide many benefits to bridge managers: (1) improved communication among clients (municipals and state DOTs) by making various features of bridge information accessible from one database model and (2) a single access point to a wide range of information about a single bridge. Bridge engineers and decision makers could access all information on demand. Figure D-2 represents the components of an integrated BMS data model that supports interoperability of analysis tools and data sharing. This is similar to Web Service ArcGIS Framework which is based on three tiers: (1) Client tier (2) GIS interface tier and (3) Integrated BMS Model.

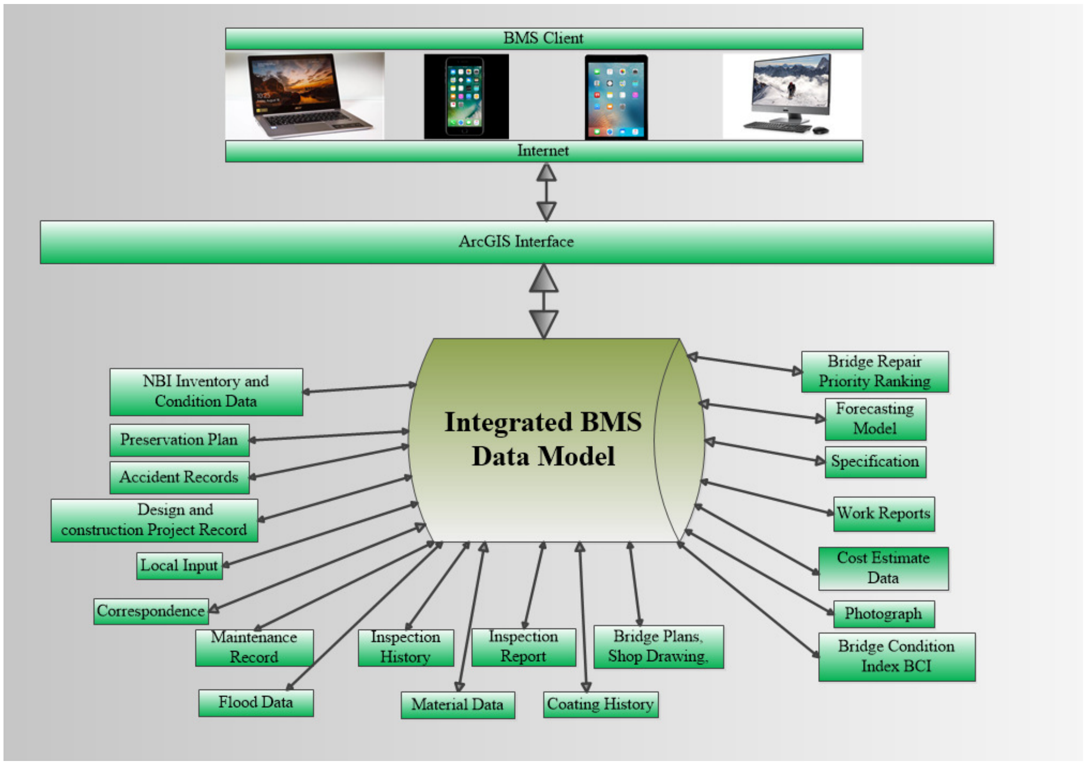


Figure D-2 The Integrated BMS Framework

D.3.1 Client tier

A system administrator responsible for maintaining the entire system, supporting and maintaining servers, and database administration will provide training to the client/user in this case municipalities and state DOTs. Clients from different disciplines completing training will have access and can use the integrated BMS model to prepare management schedules, budget, and query the selected bridge data.

D.3.2 GIS interface tier

The GIS interface tier consists of a set of menu’s facilitating communications between the client and the GIS software (integrated BMS model). The interface links the spatial characteristics of the BMS to a single map access point, to acquire the bridge physical component information, and navigate the system or input/retrieve data related to the selected bridge.

D.3.3 Integrated BMS Data Model Tier

The integrated BMS data model tier integrates the BMS inventory data with analytical application tools. The BMS model consists of the following components:

- NBI Inventory and Condition Data
- Preservation Plan
- Accident Record
- Design and construction Project Record
- Local Input
- Correspondence
- Maintenance Record
- Inspection Report
- Inspection History
- Bridge Plans and Shop Drawing
- Material Data
- Coating History
- Bridge Condition Index BCI
- Photograph
- Cost Estimate Data

- Flood Data
- Work Reports
- Specification
- Forecasting Model and
- Bridge Repair Priority Ranking

These components can improve the efficiency of the decision-making process by providing analytical information such as deterioration rate, maintenance cost, the optimization model for sustaining the bridge in the desired level of service at lowest maintenance cost and provide priority ranking.

The NBI Inventory and Condition Data can be extracted from FHWA NBI file or from NHDOT's BrM software and uploaded to BMS database.

Inventory data is the key aspect for a Bridge Management System, The National Bridge Inventory (NBI) database, compiled by the FHWA is the most comprehensive source of information on publicly owned bridges over 20 feet (6.1 meters) long throughout the United States. The NBI inventory items and condition data are described in more detail in chapter 2.

Preservation Plan is one of the major components of this BMS that is derived from a forecasting model which is described in Chapter 4. The preservation strategy is proposed to delay and prevent costly rehabilitation or replacement actions by applying preventive maintenance alternatives on bridges while they are still in good or fair condition. This can extend the life of the bridge most cost effectively.

Accident Record, is the component that contains any accident/impact damage to the bridge, the record should include date, description of the accident, picture, damaged section, level of repairs, and investigative reports.

Design and Construction Project Record, is one of the informational components which contain construction records. Most bridge owners do not keep these records beyond three years. On new bridges or reconstruction projects, the proposed BMS is capable of storing this document for future use.

Local Input, consists of additional inventory items and condition data that are not inventoried by the NBI system. The local input items are vital to a forecasting model priority ranking. This includes important local information such as the types of utility supported by the bridge or the impact of bridge closure on the local population. The local inputs are defined in more detail in later in this Chapter.

Correspondence, is the folder that contains all relevant letters, memoranda, notices and other related information during planning, design, construction, and maintenance related to the bridge.

Maintenance Record, is a very important component, most state DOTs and local bridge agencies lack having maintenance records, such as important modifications following subsequent maintenance and strengthening projects. There are no records of any kind for older bridges. A maintenance history can provide useful information about a bridge that can be used for future repair and budget preparation. The proposed BMS can document maintenance and repairs that have occurred on existing bridges. This will include details such as date, description of project, contractor, cost, project number, type of maintenance and related data.

Inspection Report and History components are vital to any BMS program; the National Bridge Inspection Standards (NBIS) requires periodic inspections of the nation's bridges and the reporting of bridge conditions based on NBIS. Condition ratings are given for each bridge components: deck, superstructure, and substructure. This component should include complete current and prior if available bridge inspection report and any available report/study related to scour, seismic, fracture-critical and corrosion.

Bridge Plans and Shop Drawings, are component includes that include all bridge construction as-built drawings and set of all approved shops drawing for the construction or repair of the bridge.

Material Data, contains all material certification, quality of materials incorporated in the construction of the bridge, manufacturers' certifications and any nondestructive and laboratory tests of materials incorporated during construction and maintenance should be included.

Coating History, is a coating history for structural steel, timber member, and concrete surfaces.

Bridge Condition Index BCI, describes the overall condition of the bridge, combining the deck, superstructure and substructure condition rating. The BCI rating is from 0 to 100, with a BCI of 100 being excellent.

Photographs should be available for each bridge showing the important features, such as top view, side view, under the deck, any major defects and utilities on the bridge.

Cost Estimate Data is used in the forecasting model. The cost estimate is based on contract bids of the current year average and can be adjusted regionally, since the unit cost can vary among bridges.

Flood Data, is collected for bridges over waterways. It is very important to have a record of major flooding events, level of high water at the bridge and any scour activity. The most common cause of bridge failures is from floods causing scouring around the bridge foundations.

Work Report, relates to documentation prepared by a bridge engineer or bridge foremen during construction or maintenance repair. The work report will be used to record maintenance and repair history. The report is designed with drop down menus for this BMS. The bridge owners have the flexibility to modify or replace with their own work report.

Specification, this section includes a complete copy of the special technical specifications, which are not covered by the state DOT's general specification.

Forecasting Model, is the major component of any BMS program. Knowledge of bridge deterioration rates is crucial for cost-effective bridge management and long term MR&R planning. This component model uses cost models, deterioration models, optimization models, and alternative MR&R operations to support the decision-making process. The forecasting model is covered in Chapter 4.

Bridge Repair Priority Ranking, the ranking component evaluates all bridges in a network or in a subset of the network based on multiple criteria such as condition, criticality, risk, functionally, type, age, and size. The ranking on network level can be used to schedule rehabilitation or preservation projects. Figure D-3 illustrates the BMS work flow process, this is the default view and it can be customized by the bridge owner based on their interests. The program provides a single point of access by simply pointing to map features (Figure D-4) and selecting a bridge on the map which is linked to relevant information in the BMS database.

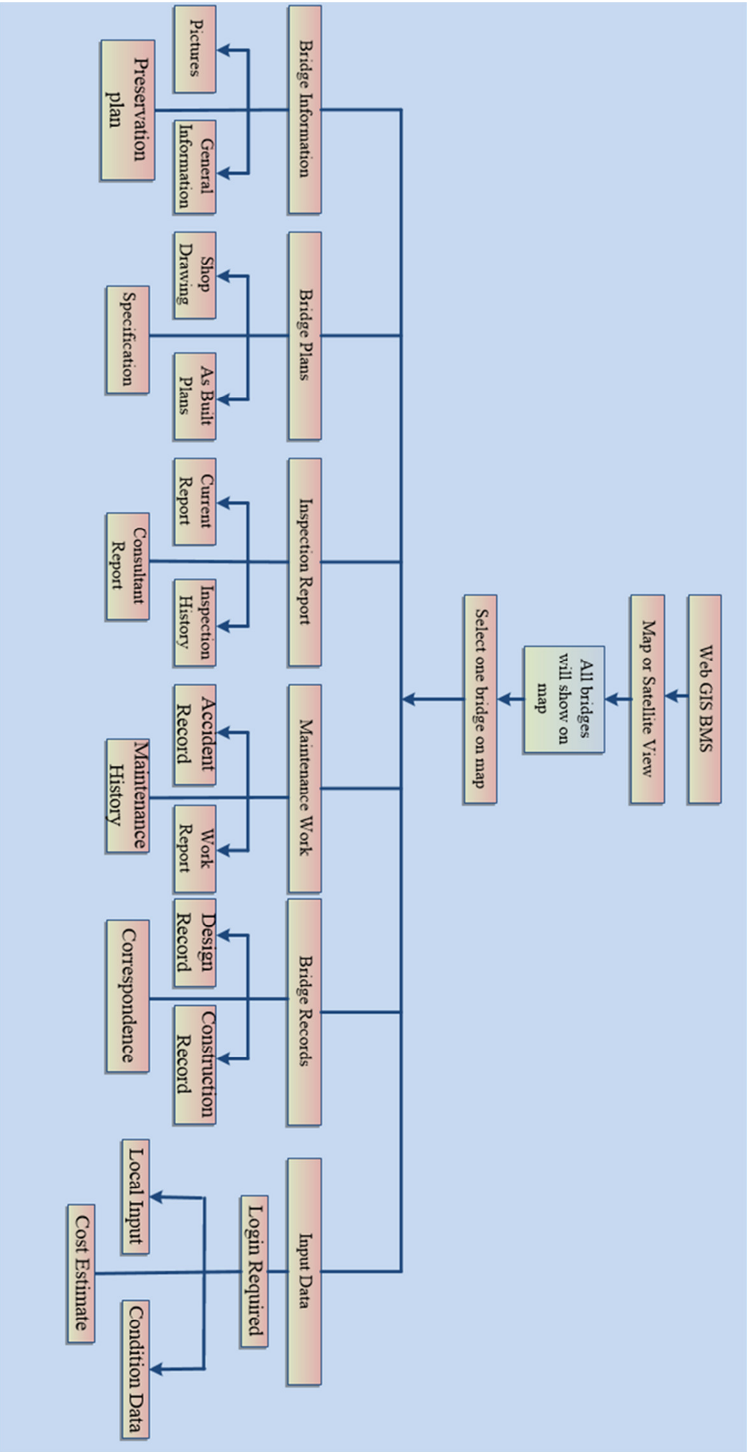


Figure D-3 BMS workflow overview

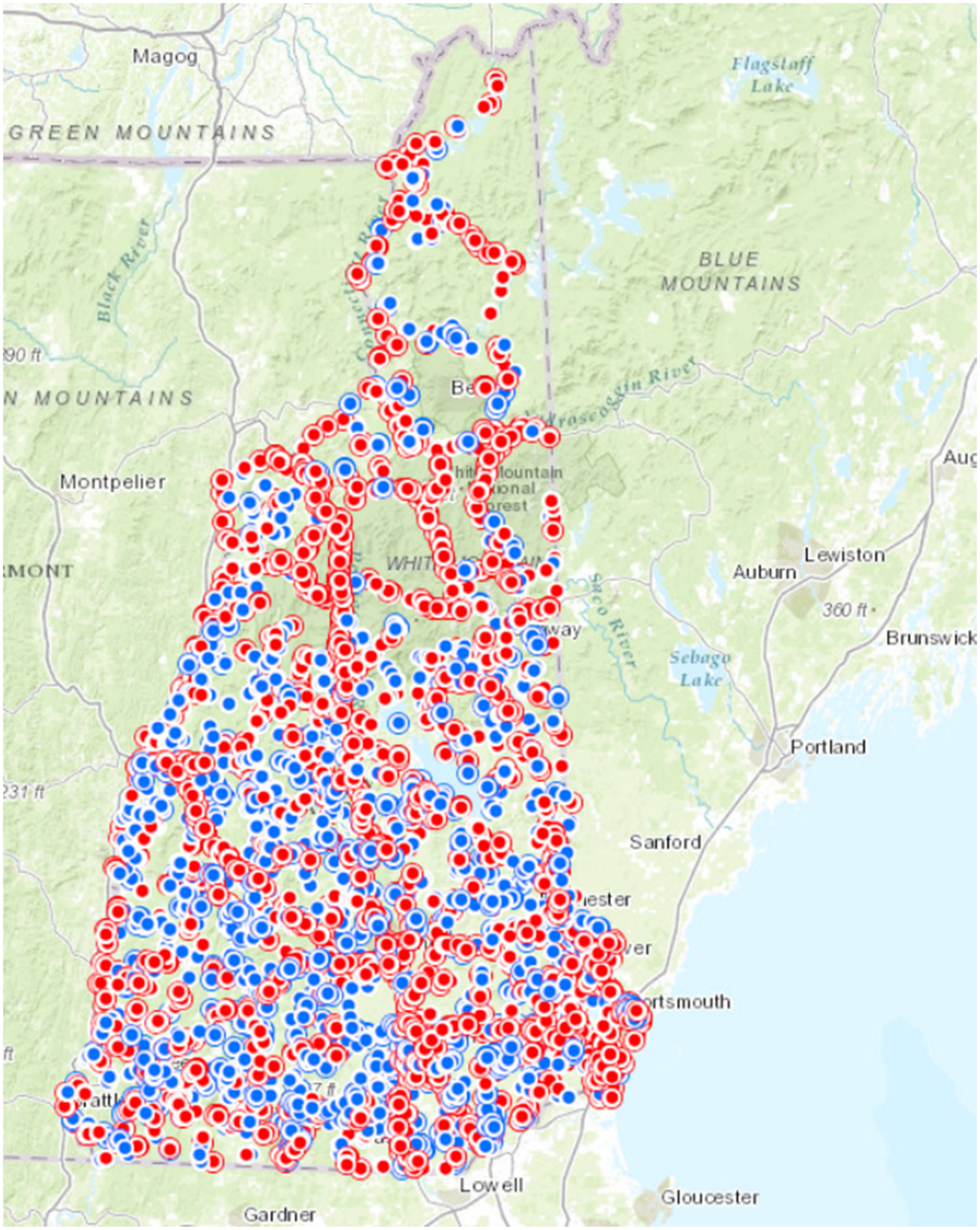
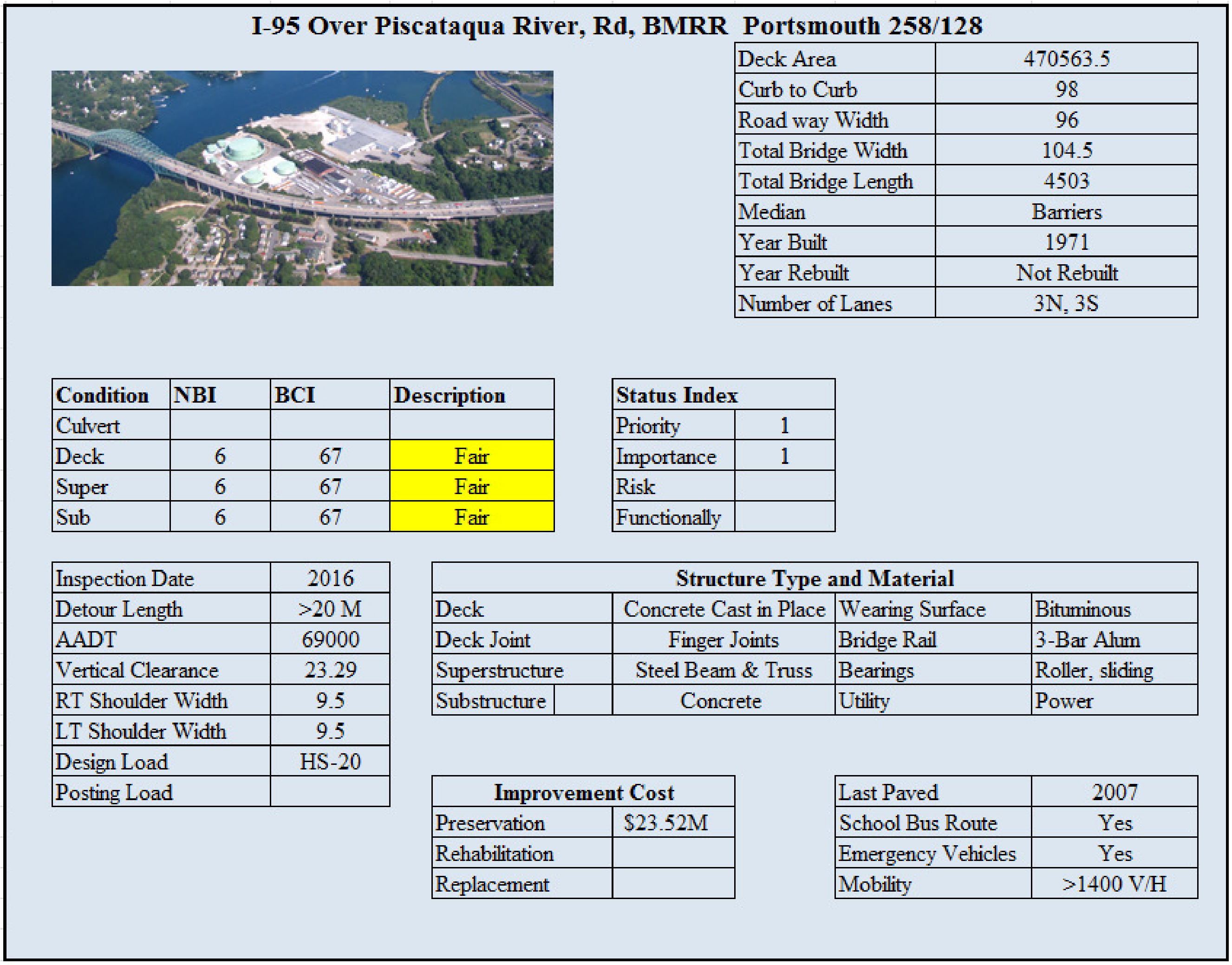

Magog
GREEN MOUNTAINS
Flagstaff Lake
BLUE MOUNTAINS
Black River
Connecticut River
90 ft
N MOUNTAINS
Androscoggin River
Montpelier
White Mountain National Forest
WHITE MOUNTAINS
RMONT
Saco River
Aug
Lewiston
Auburn
360 ft
Brunswick
Sebago Lake
231 ft
Portland
Sanford
ortsmouth
Lowell
Gloucester
Gardner

Figure D-4 State and Municipals Bridges Map Feature

For example, each bridge is linked to all the pertinent information such as inspection report, bridge plan, the photograph of the bridge, and the bridge information which includes general information as shown in Figure D-5.



I-95 Over Piscataqua River, Rd, BMRR Portsmouth 258/128

Deck Area	470563.5
Curb to Curb	98
Road way Width	96
Total Bridge Width	104.5
Total Bridge Length	4503
Median	Barriers
Year Built	1971
Year Rebuilt	Not Rebuilt
Number of Lanes	3N, 3S

Condition	NBI	BCI	Description
Culvert			
Deck	6	67	Fair
Super	6	67	Fair
Sub	6	67	Fair

Status Index	
Priority	1
Importance	1
Risk	
Functionally	

Inspection Date	2016
Detour Length	>20 M
AADT	69000
Vertical Clearance	23.29
RT Shoulder Width	9.5
LT Shoulder Width	9.5
Design Load	HS-20
Posting Load	

Structure Type and Material			
Deck	Concrete Cast in Place	Wearing Surface	Bituminous
Deck Joint	Finger Joints	Bridge Rail	3-Bar Alum
Superstructure	Steel Beam & Truss	Bearings	Roller, sliding
Substructure	Concrete	Utility	Power

Improvement Cost	
Preservation	$23.52M
Rehabilitation	
Replacement	

Last Paved	2007
School Bus Route	Yes
Emergency Vehicles	Yes
Mobility	>1400 V/H

Figure D-5 General Bridge Information

D.4 Inventory Items

Bridge data collection is the key aspect of a Bridge Management System; it provides essential information to assess safety, accountability for decision making, extend the service life, and reduce bridge failure. Most infrastructure inventory systems require the collection and organization of large quantities of data. The method of collecting and storing data has evolved over years with advancing computer technology. Some of the bridge inventory data is not subject to change such as structure number, name, location, year built etc. Other data such as condition assessment needs to be updated periodically. Most agencies have large databases that are not being used for bridge management decision making. Data sustainability is vital to decision makers managing bridge design, construction, preventive maintenance, preservation, rehabilitation, and replacement projects. Bridge inventory generally consists of physical attributes which include the following (FHWA,1995):

1. Bridge Identification, Location, and Description
2. Functional Class (Structure Classification and Roadway Classification)

3. Geometrical Data(Structure Dimension, Vertical Clearance, and Horizontal Clearance, Lateral Under Clearance on Right and Left and Length of Maximum Span)
4. Material Type (Deck, Superstructure, Substructure, and Wearing Surface)
5. Age (Year Build and Year Rebuild)
6. Average Daily Traffic
7. Inspection History
8. Service (Detour Length, Facility Carried by Structure, Lanes On and Under the Structure and Approach Roadway Width)
9. The Design Load Capacity and Current Load Capacity.
10. Maintenance History
11. Navigation Control, Vertical and Horizontal Clearance and Pier Protection
12. Environmental Data
13. Proposed Improvement

The National Bridge Inventory (NBI) is the most comprehensive source of information on publicly owned bridges over 20 feet (6.1 meters) long throughout the United States (Ryan et al, 2006).

The Recording and Coding Guide for the Structure Inventory and Appraisal of The Nation's Bridges provided by Federal Highway Administration (FHWA) requires all the bridge owners (federal, states, cities, towns and other agencies) to collect and maintain an inventory of all the publicly owned bridges according to the National Bridge Inspection Standards (NBIS) which must be submitted to the FHWA annually (FHWA, 1995). This will provide a complete and thorough inventory and an accurate report that can be provided to Congress on the number and state of the nation's bridges. This data is used by bridge owners as needed and for homeland security, FHWA, and military defense purposes to identify and classify the Strategic Highway Corridor Network (STRAHNET) and its connectors. The resulting information is stored in the National Bridge Inventory (NBI) database. The Guide was initially developed in 1972 following the collapse of the Silver Bridge in 1967. The 1460 foot suspended section of the Silver Bridge in West Virginia collapsed into the Ohio River which claimed the lives of 46 people. Guided by NBI standards, all bridges located on public roads receive periodic safety inspections. Through a series of changes, the guide was completed in 1995 (GAO, 2008).

As shown in Figure 3-7, which is reproduced based on information disseminated through *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* the coding guides are divided into Identification Items, Type and Material, Age and Service, Geometric Information, Functional Classification, Navigational Data, Inspection, Condition Rating, Appraisal Items, and Load Rating (FHWA, 1995) The coding guide items for each bridge are recorded, field measured, prepared, and submitted to the FWHA for NBI files by trained DOT professional bridge engineers. These items can be extracted from the NBI files or DOT's database into BMS. All bridge data in BMS are current and translated from NBI files to a useable friendly form. For example, a certain bridge on I-95 for NBI item 5E is coded in NBI files as 111000950, but in BMS database, it is shown as Interstate 95 over Woodbury Ave.

D.5 Local Inputs

The local factors are additional inventory items and condition data that are not inventoried by NBI system which includes the following:

1. Year Last Paved
2. Utility
3. Bridge Rail
4. Economic Impact
5. Environmental Impact
6. Societal Impact
7. School Bus Route
8. Emergency Vehicles Route
9. Mobility
10. Year of NBI 6 Deck Rating
11. Toll Plaza Impact

The aforementioned plays an important role in supporting the decision making process. The following is a brief description of each factor:

Year Last Paved is the date when the bridge deck was resurfaced; this information is used in the forecasting model to produce a 120-year preservation plan.

Utility this is to identify what type of utilities are on the bridge and are used in calculating the priority ranking outlined described in Chapter 4.

Bridge Rail is a safety feature of bridge decks; the majority of older bridges have a substandard railing/barrier to protect the traffic, this data is not in NBI files. The bridge rail criteria are used to calculate the priority ranking.

Economic Impact, Environmental Impact, and the Societal Impact are factors used in priority ranking. This is in event of bridge closure and the consequence of the above impact on the local community.

School Bus Route and the Emergency Vehicles Route are factors also used in priority ranking.

Mobility is a traffic based measurement based on the number of vehicles per lane traveling over the bridge at peak hour. These measurements are used to determine the ranking system.

Toll Plaza Impact is also used for a ranking system; this is to identify the impact of bridge closure on the toll plaza revenue.

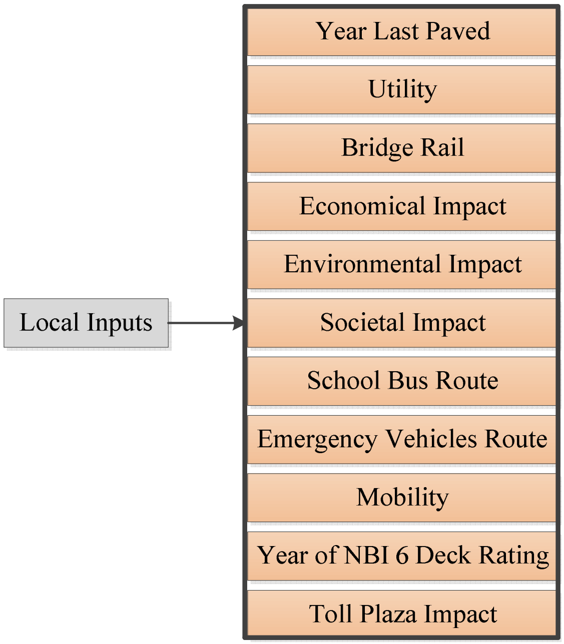


Figure D-6 Local Inputs

A complete list of all coding items is shown in Appendix A.

D.6 Summary

The need for integrated Bridge Management Systems (BMS) is for collecting, processing and updating data, identifying alternative Maintenance, Rehabilitation, and Replacement (MR&R) activities including their estimated repair costs, forecasting deterioration, recommend funding programs, and identifying optimal preservation policies. This is becoming more of a necessity in the face of challenges bridge owners have to maintain aging bridges.

This study creates an understanding of the applicability of integrated Web-based GIS BMS. This program will provide a quantity of information across various disciplines within municipalities and state DOTs, which in turn, will improve the communication, reliability, and consistency of bridge information to support decision making.

Appendix E: BRPRS Example

Example:

Condition Factor:

The NBI condition rating for NHDOT Bridge #216/112

Deck:	6	Satisfactory
Superstructure:	8	Very Good
Substructure:	7	Good

$$\boldsymbol{S = \{(NBI\ Condition\ Rating - 9)(-1)(\tfrac{40}{9})\}}$$

S*(deck)*=(6-9)(-1)(40/9)=13.33

S(superstructure)= (8-9)(-1)(40/9)=4.44

S(substructure)= (7-9)(-1)(40/9)= 8.88

Condition [C] = [0.2S (deck) +0.4S (superstructure) + 0.4S (substructure)]

C= [0.2(13.33)+0.4(4.44)+0.4(8.88)]=8.00

Total point condition = α*C = 0.4*8 = 3.2

The condition of this bridge is worth 3.2 out of 40.The maximum points in this category (bridge condition) will not exceed 40 points (i.e. the worst condition)

Example: Using Same bridge with the following information from BMS database:

Criticality Factor:

Bridge #216/112 Spaulding Turnpike over NH 75		
Criticality		
Traffic Volume ADT	35000	
Road Class	Tier 1	
Detour Length	9 miles	
Borde Bridge	No	
Utility	No	
Impact	Economic	Yes
	Environmental	No
	Societal	Yes
	School Bus Route	Yes

β= 18% see table 4-2 (criticality is 18% of PRPR). The traffic volume is 30% of criticality see figure 4-1, the ADT is 35,000 the total score will be 75%% of the 30% of the recommended percentage for criticality which is 75%*β*30%*100

CR (traffic) = (0.75)*(0.3)*(0.18)(100) = 4.05

In this case, traffic volume will contribute 4.05 points toward PRPR.

The maximum percentage the Detour Length can contribute is 15% of criticality (Figure 4-1). In this example, the detour length is 9 miles and from table 4-4 the distribution rate is 50% of the 30% of the recommended percentage for criticality

CR (Detour Length) = (0.5)*(0.15)*(0.18)(100) = 1.35

This bridge is not a border bridge so

CR (Border Bridge) = 0

Road classification is 20% of criticality (Table 4-4). The bridge is on tier 1 road, where from table 4-4 the distribution rate is 100% of the 30% of the recommended percentage for criticality.

CR (Road Class) = (1)*(0.2)*(0.18)(100) = 3.6

There is no utility on this bridge where

CR (Utility) = 0

The bridge closure impact is 20% of criticality (table 3-4). The distribution rate will apply to economics at 25%, no environmental impact, societal at 25% and this bridge is a school bus route.

CR (Impact) = (0.25+0.25+0.25)*(0.2)*(0.18)*(100) = 2.7

Total Criticality = 4.05+1.35+0+3.6+0+2.7 = 11.7

The criticality for this bridge is worth 11.7 points. The maximum point possible in this category is 18 point.

Risk Factor:

Using the same bridge to calculate the Risk distribution factor δ= 15% see table 3-2. In the Risk category as shown in table 4-5, this bridge is not over water so

Total point for Scour Critical = 0

Total point for Flood = 0

Total point for Ice = 0

The bridge rail does not meet the current standard, where the bridge rail is 10% of 15% Risk distribution factor

Total Point for Bridge Rail = (1)*(0.)*(0.15)*(100) = 1.5

There is no fracture critical member on this bridge and no impact damage.

Total point for Fracture Critical Member = 0

Total point for impact damage = 0

Total Risk = 0+0+0+0+1.5 = 1.5

Functionally Factor:

From BMS database following information is extracted for NHDOT Bridge #216/112

Load Limit = HS-20

Vertical Clearance = 16.8 ft
Lane Width = 12 Ft
Mobility = 1400
Shoulder Width = 10 Ft
Waterway Adequacy = NA

The functionally distribution factor γ= 15% see table 4-2.

The load limit is HS-20, from table 4-6 the value is 0% where $[(\gamma*0.2)*100]$.

Total point for Load Limit = 0

The vertical clearance is >16 the value is 0% of $[(\gamma*0.2)*100]$.

Total point for Vertical Clearance = 0

The lane width is 12 feet, from table 4-6 the value is 0% where $[(\gamma*0.1)*100]$.

Total point for Lane Width = 0

The shoulder width is 10 feet, from table 4-6 the value is 0% where $[(\gamma*0.1)*100]$.

Total point for Shoulder Width = 0

The mobility is >1400 vehicles per hour from table 4-6 the value is 100% where $[(\gamma*0.2)*100]$.

Total point for Mobility = (1)*(0.1)*(0.12)*(100) = 1.2

The bridge is over a road so the value for waterway adequacy is 0

Total point for Waterway Adequacy = 0

Total point Functionally = 0+0+0+0+0+1.2 = 1.2

Bridge Type Factor:

The bridge type distribution factor ε= 5% see table 4-2. From SADES database the Milton bridge is a girder type and the value is 80% of 5% where

Total point for Type = (0.8) * (0.05) * (100) = 4

Bridge Size Factor:

From NHDOT database the Milton bridge deck area is 6580 Sf from table 4-8 the value is 40% of 5% where

Total point for Size = (0.4) * (0.05) * (100) = 2

Bridge Age Factor:

The Milton Bridge was built in 1980 and is 37 years old. The bridge size distribution factor θ= 5% see table 3-2. From table 3-9 the value is 60% of 5% where,

Total point for Age = (0.6) * (0.05) * (100) = 3

The total PRPR is a summation of all categories.

Milton, NH Spaulding Turnpike PRPR = 3.2+11.7+1.2+4+2+3 = 25.1