THE EFFECT OF VISUAL INSPECTION RELIABILITY ON RISK-BASED INSPECTION

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by

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The undersigned, appointed by the Associate Vice Chancellor of the Office of Research and Graduate Studies, have examined the dissertation entitled

THE EFFECT OF VISUAL INSPECTION RELIABILITY ON RISK-BASED INSPECTION

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Dr. Roger Fales

Dr. Erik Loehr

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For my parents,

Maryam and Mohammad Mustafa

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THE EFFECT OF VISUAL INSPECTION RELIABILITY ON RISK-BASED INSPECTION

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ABSTRACT

Bridge inspection has come a long way from its inception as a component level practice following the Silver Bridge collapse in 1967 to the most recent advancement enacted by the Moving Ahead for Progress in the 21st Century (MAP-21) legislation to determine the inspection interval using risk-based inspection (RBI) and mandated element-level data collection for all the states. RBI, a well-researched topic in other fields is new to the bridge inspection practice and element-level bridge inspection provides data for RBI condition attributes. The first objective of the research was to determine how inspection variability in condition state (CS) assignment and defect quantification affect the attributes in RBI practice. Based on the data collected from Indiana and Michigan, about 9% of the inspectors incorrectly assigned the bridges' elements to CS 4 (RBI screening attribute), and 18% of the inspectors incorrectly assigned the bridges' elements to CS 2 (low ranking score). The conclusion was made assuming that if most of the inspectors assign the same CS for a bridge's element, it is the correct CS assignment. The second objective was to determine how the inspection data variability affects the deterioration models (Markov chain, Kaplan-Meier, and Weibull). Based on the National Bridge Inventory (NBI) data from the seven states, it was shown that the NBI data do not fit the Weibull distribution and the variability in NBI data on Kaplan-Meier either extends or shortens the median time in condition rating (TICR) for a bridge component.

Build on the details of the second objective, the Markov chain was proposed to calculate the probability of failure (POF) for the RBI occurrence factor (OF).

1 Introduction

1.1 Background

Federally-mandated bridge inspections in the United States began in the aftermath of the disastrous collapse of the Silver Bridge between Point Pleasant, West Virginia and Gallipolis, Ohio. The collapse occurred at 5:15 PM on December 15, 1967 and resulted in the deaths of 46 people. Currently, bridge inspection in the U.S. is categorized into seven different types – initial inspection, routine inspection, in-depth inspection, fracture-critical inspection, underwater inspection, special inspection(s), and damage inspection [1]. Routine inspections are performed periodically during the service life of a bridge at intervals of 24 months for most bridges, and 48 months for bridges meeting certain requirements and approved by the Federal Highway Administration (FHWA) [1, 2]. For certain bridges with damage or deterioration, this interval may be reduced for specific components/sections/elements or the entire bridge.

Much of the data used for a bridge management system is collected by routine inspection [3, 4]. Routine inspection is commonly performed from the deck, shoulder, ground level, and/or water level to fulfill the National Bridge Inspection Standard (NBIS) requirements. The inspection relies primarily on visual inspection to assess bridge conditions. Routine inspection may result in recommendations for defect-specific and event-specific inspection techniques [1]. For example, damage requiring further exploration may initiate an in-depth or special inspection; a damage inspection may be completed in response to an event such as impact damage from an over-height vehicle colliding with a bridge.

Currently, condition data on bridges is reported based on two metrics, a bridge condition ratings (CR) for all bridges and Condition States (CS) for bridge elements in bridges on the National Highway System (NHS). The collection of element-level data for NHS bridges became a requirement for all agencies in 2014 to meet the requirements of the "Moving Ahead for Progress in the 21st Century Act (MAP-21)" legislation. Some bridge owners collected element-level data within their programs as part of their normal business practice before this requirement, although the specific characteristics of element-level data have evolved, as will be discussed. Required data to be collected and reported generally includes National Bridge Elements (NBEs) and certain Bridge Management Elements (BMEs) deemed to be necessary to analyze bridge conditions on a national scale [5]. The NBEs include elements describing the primary bridge load path components of deck, superstructure, and substructure, and -BMEs include secondary elements such as joint seals, wearing surfaces, and so on.

Bridge CR is comprised of a numeric rating for the deck, superstructure, and substructure components of a bridge (also known as National Bridge Inventory (NBI) rating) that characterizes the condition of the entire component in a single rating number. Element-level inspection is comprised of a four standard CSs with a qualitative descriptor (CS 1 – good to CS 4 – severe) that includes material and defect identification, defect severity, and defect quantity assigned to a bridge element (steel girder, reinforced concrete (RC) deck, etc.). An important difference between these two descriptors is that the NBI rating assesses the existing condition of the entire component as compared with the as-built condition, considering both the severity of deterioration and the extent to which it is widespread throughout the component. The CR is expressed as a single digit on a scale of 0 to 9 [6]. In contrast, the element-level inspection data records the quantity of damage in a bridge element in each of the four CSs (CS 1-CS 4) [7].

Element-level bridge inspection was introduced in 1998 through the Commonly Recognized (CoRe) Structural Elements manual [8]. The three NBI bridge components were subdivided into 98 elements defined based on the specific construction material of an element, such as element 12 – RC bare deck with uncoated rebar, element 26 – RC bare deck with coated rebar, and so on. Measurement units of each (EA), area (square meter), and length (meter) were used to quantify the elements. Condition state of an element was defined using five, four, or three qualitative CSs accompanied by appropriate generalized maintenance, repair, and rehabilitation (MR&R) actions [8]. Bridge elements were supplemented with "Smart Flags," a term "to identify additional problems that are not reflected in the CoRe element condition state language" such as steel fatigue, pack rust, deck cracking, settlement, scour, traffic impact, section loss, and soffit. An issue with the Smart Flags was the location and the element was not identified – so pack rust was not associated with any parent element such as a girder or a pile [8]. In addition to the CoRe element manual, there was additional review and incorporation of element definitions from NCHRP Project 12-28(2)A (BRIDGIT) and subsequent development by AASHTO that included element definitions, CSs and parent/child element relationships [9].

AASHTO Guide Manual for Bridge Element Inspection (GMBEI) was proposed to replace CoRe elements in 2011 as a pilot program to refine the requirements of the element, defect flags, and CS language. The manual incorporated findings from the international scan tour on "Bridge Evaluation Quality Assurance in Europe" and the European element-level bridge data collection processes, descriptions and categorizations [10]. In GMBEI, bridge elements were divided into two groups, NBEs and BMEs. NBEs define elements that are critical to the load path and safety and are a refinement of the deck, superstructure, substructure, and culvert element definitions and smart flags of the NBI elements. BMEs describe secondary elements "such as joints, wearing surface, and protective coating" which comprised the elements that bridge owners were collecting that were focused on safety, functional needs, and primary element protection [11]. In addition, bridge owners could add additional elements that would enhance the management processes or account for materials/elements that were unique to that owner. Multilevel CS descriptions (Five, four, or three) from CoRe elements were standardized to four CS for all elements in the GMBEI. Three of the four standardized CSs were defined for each applicable defect for an element using qualitative descriptors, and the fourth CS was defined generally as "beyond the limits established in CS 3 and/or warrants structural review to determine the strength or serviceability of the elements or bridge." [11]

Manual for Bridge Element Inspection (MBEI) first edition published in 2013 replaced GMBEI. MBEI content was different than GMBEI in several ways. Qualitative descriptors such as Good, Fair, Poor, and Severe were added to the standardized four CS definitions [12]. Defects were formalized as sub-elements to accommodate the analysis and project selection functions of bridge management systems. These defects used the quantitative descriptions from the 2011 GMBEI and the quantities to be rolled into the parent element condition assessment [12]. The MBEI first edition was revised in 2015. These revisions included removing the quantitative descriptions of cracking in RC and prestressed concrete (PSC) in the body of the MBEI and defining qualitative descriptions in their place. The quantitative descriptors moved to the element commentary as a recommended practice for standardization of data collection [12]. A major revision for the MBEI was approved in 2018 that reorganized the manual and added visual standards in the form of photographs for many of the defects identified in the manual along with grouping element description, defects, and units of measure by material type [7].

Since its inception, the bridge inspection has focused on an isolated structure in different levels of data granularity collected every 24 months as discussed before. But a bridge as defined by the Bridge Design Specifications is a built structure part of the highway with at least 20.0 ft length parallel to the driveway [13]. That is, a bridge is built in an environment to serve users at a specified service level and the users are in continuous interaction with the bridge. To avoid the isolation, and keep the bridge, the environment it is built in, and the users' interaction with the bridge integrated, the concept of risk-based inspection (RBI) is defined. RBI could be used to calculate the inspection interval and intervention scope before the bridge reaches a state to pose threats for the safety of the users and the environment or it becomes unserviceable. If a bridge functions at the intended level of service safely, redundant data collection will not provide extra information to any party involved in the bridge life cycle management. Therefore, RBI, the new criterion to improve the safety and serviceability of the bridges was enacted by the MAP-21 legislation to be used for determining the inspection interval and intervention scope.

The National Cooperative Research Program (NCHRP) Report 782 – "Proposed Guideline for Reliability-Based Bridge Inspection Practices" provides the guideline for this new dimension to the routine bridge inspection process. The NCHRP Report 782 and several papers by Washer et al., discuss and demonstrate RBI practice to determine bridge inspection interval. RBI combines the probability of failure and its consequences to direct resources to the bridges in need to avoid redundant data collection for bridges in good condition [14-16]. The suitability of the RBI for bridges was verified by Washer et al. using samples of prestressed bridges in Oregon and steel bridges in Texas using component level inspection data. The study found that the inspection interval of 48 – 72 months was appropriate for “certain bridges” [17]. The FHWA allowed the use of the RBI for bridges by issuing a memorandum on June 8, 2018. The memorandum approved using the risk-based approach in lieu to the NBIS Section 650.311(a)(3) to determine bridge inspection interval for bridges with extended inspection interval longer than 24 months that “historically been accomplished by following Technical Advisory 5140.21” and those bridges requiring less than 24 month inspection interval [18]. However, the element-level bridge inspection data was not used for the original RBI application and the effect of the visual inspection quality on RBI was not studied. One reason for the limited research on the quality of the element level data on RBI is that the element level inspection and RBI both were enacted by the MAP-21 legislation.

1.2 The Problems’ statements

This section provides three problem statements that form the body of this dissertation.

1- As stated in detail before, bridge inspection has come a long way from its inception as a component level practice following the Silver Bridge collapse in 1967 to the element level that was mandated for all the states by the act of the MAP-21 legislation. Since its inception, the bridge inspection has focused on an isolated structure in different levels of data granularity mostly collected every 24 months. As a result, the bridges are either overinspected or underinspected. To avoid the overinspection and underinspection of the bridges, the MAP-21 legislation enacted the RBI to determine bridge inspection interval as well.

The core content of the MBEI is the subdivision of a bridge to elements, the specification of the measurement units, and the applicable defects for the elements and defining the four CSs for the applicable defects to capture the condition of an element during its service life. Similarly, the RBI practice moves from the coarse levels of details (damage modes) to finer levels of details (attributes) to find all the factors affecting the reliability and durability of a bridge. For the RBI condition attributes (those captured by the routine inspection), bridges are already divided to finer details in the MBEI, i.e., bridge elements, applicable defects, and CSs. To determine how well the MBEI inspection data could provide information to the RBI practice, the MBEI elements, defects, and CSs will be mapped to the RBI attributes' criteria.

2- Another step in RBI practice is to prove that applying the RBI would not compromise the safety and severability of bridges. This step is completed using the rich component level or NBI bridge inspection data that is available online through the FHWA website which provides records from about 1992 to present. Previous research applied the Weibull distribution to extract information based on the Time in Condition Rating (TICR) – the number of years a bridge component stayed in each CR. As will be shown later, the component level data do not fit the Weibull distribution and therefore, the statistics calculated from this distribution do not provide reliable information about the performance of the bridges. Therefore, the Kaplan-Meier method is proposed as a substitute to the Weibull distribution, and the NBI data for bridges from seven states are analyzed using this method.

3- As will be shown later, the RBI practice combines the occurrence factor (OF) and consequence factor (CF) to calculate the risk matrix and consequently determine the inspection interval. As will be demonstrated in the coming chapters, the four levels of the OF have an underlying theoretical probability of failure (POF) ranging from less than 1/10,000 to greater than 1/100. For a bridge component in the RBI context, failure is defined as reaching to CR 3. The NBI data for a bridge population could be used to determine a mere condition based POF. The condition based POF would provide another piece of information about the performance of the bridges and reduce the notion of "one size fit all" theoretical POF that may not be the same for a bridge family with better condition bridges compared to an aged and lower condition family. The Markov chain is used to calculate the POF based on the NBI data for bridge components.

1.3 Approaches to Solve the Problems

As stated in section 1.2 above, element-level data collection was mandated for all the states by the MAP-21 legislation. The same legislation enacted using the RBI to determine bridge inspection interval as well. The RBI practice was developed independently to account for the design, loading, and condition attributes of bridges to determine the inspection interval. The RBI design and condition attributes for bridges address topics or issues that constitute the core content of the MBEI. That is, the element-level data collected using the MBEI would provide over 95% of the data for RBI practice. But, a thorough analysis of the RBI and MBEI to find the common ground and differences between these two contemporaries is not yet undertaken. The following approach was taken to map the MBEI content to RBI and it is presented in chapter 2.

1. The design and condition attributes addressed in the reliability assessment panel (RAP) meetings of the eight RBI participating states were analyzed to determine how these criteria match the MBEI elements and defects.
2. The RAP data were used to find the prominent MBEI elements and defects which appeared in the RBI as damage modes or attributes. These data were also used to find bridge components used as the RBI bridge deck, superstructure, and substructure. This step also analyzed the language used in different states for the same standard MBEI defects.
3. The MBEI elements, defects, and CSs were mapped to the RBI attributes' criteria to determine the extent to what the MBEI data could provide information to be used as an input for the RBI practice.
4. Using the above three steps, data collected for the NCHRP 12-104 "Guidelines to Improve the Quality of Element-Level Bridge Inspection Data" project were analyzed to assess how inspection variability in defect detection and CS assignment affects RBI.

To demonstrate that the RBI practice does not compromise the safety and serviceability of bridges, the Kaplan-Meier method was introduced as a substitute for the Weibull distribution. The literature is provided to show that the NBI data do not fit the Weibull distribution and the data collected every two years could best be analyzed using the Kaplan-Meier method. The component level or NBI data from seven states were analyzed using this method and is the results are reported in Chapter 3.

Finally, as stated in section 1.2 above, there is a theoretical foundation for the POF corresponding to each of the four OF levels. The Markov chain could be used to predict the POF – percentage of the bridges reaching CR 3 – based on the current condition of the bridge family. This is addressed in Chapter 4.

1.4 Goals and Objectives

The goal of the study is to increase the safety and serviceability of bridges by optimizing the use of inspection resources through a risk-based inspection (RBI) approach.

The objective of the study is to determine the effect of inspection quality on RBI. To achieve this objective, the study will seek:

1. To determine how inspection variability in CS assignment and defect quantification affect the attributes in RBI practice, and
2. How inspection variability in CR affects deterioration modeling (Markov, Weibull, and Kaplan-Meier).

Bridge elements and defect elements will be assessed to determine their effect on the attributes in the RBI process and the inspection interval. For these elements, inspection exercises in two states (Indiana and Michigan) have been completed to measure the element-level inspection variability. Similarly, risk models that identify key attributes and element CSs were developed through RAP meetings in six states participating in the Pooled Fund Project “Developing Implementation Strategies for Risk Based Inspection (RBI).” These data will be analyzed to determine:

1. How current practice of the state Departments of Transportations (DOT) affect the attributes in risk models used to identify inspection intervals, and

2. How these models (attributes) differ between states.

Deterioration modeling using the NBI data for the seven participating states will be compared to the common theoretical deterioration models to get a better sense of the number of years to reach certain decision thresholds that affect the RBI results. Similar deterioration models as well as the effect of inspection variability on element-level bridge deterioration will be assessed.

The results of the field testing, assessment of key attributes for RBI, and the effect of inspection variability on deterioration predictions was analyzed to determine how the quality of element-level inspection data will affect RBI and proposed quality levels for inspection (i.e., tolerances) were developed.

1.5 The Dissertation Outline

The dissertation contains five chapters and three appendices.

Chapter 1 provides a short general background of the problems addressed in this dissertation. The problems' statements, the approaches to solve the problems, the goals and objectives of the research, and the dissertation outline is provided in this chapter as well.

Chapter 2 answers the first objective of the dissertation - how inspection variability in defect quantification and CS assignment affects the RBI. This chapter provides the result of the detailed mapping of the MBEI defects and CSs to the RBI attributes' criteria, two different ways to account for the effect of the element-level bridge inspection data on RBI, analysis of the RAP data collected from the states participating in the RBI projects, and the results of the bridge inspection exercises conducted in Indiana and Michigan as part of the NCHRP 12-104 project. Detailed tables for this chapter are provided in Appendix A.

Chapter 3 introduces the Kaplan-Meier method, a substitute for the Weibull distribution to analyze the reliability of bridge components using the NBI data available through the FHWA website. This chapter provides a literature review on different types of deterioration techniques, explains why the component level data do not fit the Weibull distribution, and describes how the nature of the component level data collection makes Kaplan-Meier a substitute for the Weibull distribution. This chapter also presents the result of the component level data analyzed for seven participating states in the RBI Pooled Fund Project. This chapter has two appendices that provide the SAS code for component level data preparation and analysis in Appendix AAppendix B and the analysis results' tables and figures for bridge components for each of the seven states in Appendix C.

Chapter 4 draws on the background literature of Chapter 3 regarding the Markov chain and uses this method to determine POF for OF for bridge components.

Chapter 5 restates the research goals and objectives; combines the conclusions made in Chapter 2, 3, and 4 in one section; states the contributions made to reach the objectives; outlines the impact of the contributions; provides recommendations based on the research results; and finally suggests the future work to further the research presented in this dissertation.

2 The Effect of Element-Level Bridge Inspection Data Quality on Risk-Based Inspection

2.1 Introduction

Bridge inspection has come a long way from its inception as a component level practice following the Silver Bridge collapse in 1967 to the element level, now practiced across the country. The granularity of data to identify and quantify bridge defects using element level inspection is more refined compared to the component level bridge inspection practice. Element level data collection and submittal to Federal Highway Administration (FHWA) was mandated for all the states by the act of the Moving Ahead for Progress in the 21st Century (MAP-21) legislation, but several states collected element level data in the late 1990s using the Commonly Recognized (CoRe) Structural Elements manual.

Since its inception, the bridge inspection has focused on an isolated structure in different levels of data granularity collected every 24 months. But a bridge as defined by the Bridge Design Specifications is a built structure part of the highway with at least 20.0 ft length parallel to the driveway [13]. That is, a bridge is built in an environment to serve users at a specified service level and the users are in continuous interaction with the bridge. To avoid the isolation, and keep the bridge, the environment it is built in, and the users' interaction with the bridge integrated, the concept of risk-based inspection (RBI) is defined. RBI could be used to determine the inspection interval and intervention scope before the bridge reaches a state to pose threats for the safety of the users and the environment or it becomes unserviceable. If a bridge functions at the intended level of service safely, redundant data collection will not provide extra information to any party involved in the bridge life cycle management. Therefore, RBI, a new criterion to improve the safety and serviceability of the bridges, was enacted by the MAP-21 legislation to be used for determining the inspection interval and intervention scope.

The National Cooperative Research Program (NCHRP) Report 782 – "Proposed guideline for Reliability-Based Bridge Inspection Practices" provides the guideline for this new dimension to the routine bridge inspection practice. The NCHRP Report 782 and several papers by Washer et al., discuss and demonstrate RBI practice to determine bridge inspection interval. RBI combines the probability of failure (POF) and its consequences to direct resources to the bridges in need to avoid redundant data collection for bridges in good condition, and optimize costs [14-16]. The suitability of the RBI for bridges was verified by Washer et al., using samples of prestressed bridges in Oregon and steel bridges in Texas using component level inspection data. The study found that the inspection interval of 48 – 72 months was appropriate for "certain bridges" [17]. The FHWA allowed the use of the RBI for bridges by issuing a memorandum on June 8, 2018. The memorandum approved using the risk-based approach in lieu to the National Bridge Inspection Standards (NBIS) Section 650.311(a)(3) to determine bridge inspection interval for bridges with extended inspection interval longer than 24 months that "historically been accomplished by following Technical Advisory 5140.21," and for bridges requiring less than 24 months inspection interval based on Section 650.311(a)(2) [18]. However, the element-level bridge inspection data were not used for the RBI application and the effect of the visual inspection quality on RBI was not studied. One reason for the limited research on the quality of the element level data on RBI is that the element-level inspection was recently mandated for all the states by the MAP-21 legislation and RBI practice is new to the bridge inspection field.

The objective of the research in this chapter is to determine how inspection variability in condition state (CS) assignment and defect quantification affect the attributes in RBI practice. Bridge inspection data from Indiana and Michigan inspection exercises completed as part of the NCHRP 12-104 were used to study the effect of the element-level bridge inspection data quality on RBI. The purposes of this chapter are 1) to define two ways or methods for calculating the effect of the element-level inspection data quality on RBI 2) to map the content of the Manual for Bridge Element Inspection (MBEI) to the RBI design and condition attributes 3) to compile and analyze the data collected from the reliability assessment panel (RAP) meetings participated in RBI projects to date and 4) present the result of the element-level data quality effect on RBI for steel and prestressed bridges collected from Indiana and Michigan bridge inspection exercises.

2.2 Risk-based Inspection Background

A review of the literature provides the reasons why RBI has been preferred and employed in the oil and nuclear industry, offshore structures, and dam maintenance for a long time [19-21]. For example, RBI has been practiced for different deterioration mechanisms in offshore structures since the 1980s [19]. Probabilistic Risk Assessment (PRA) was recommended by the U.S. Nuclear Regulatory Commission in 2003 for inspection of in-service piping in plants [20]. Similarly, risk-based methods to analyze risk, assess downstream consequences, and account for structural model uncertainty is recommended as “a useful tool” by the International Commission on Large Dams (ICOLD) [21]. Risk-based maintenance (RBM) was quantitatively applied in 2003 to a heating, ventilation, and air conditioning (HVAC) system to lower the higher level of risk to an acceptable level, provide cost-effective maintenance, minimize the failure consequences, and better use funds and assets [22].

The applicability, appropriateness, improvements in safety, and financial benefits of RBI reported in the above-mentioned industries can potentially bring similar outcomes to the bridge inspection practice.

For the economic benefit, for instance, the aim of the U.S. Nuclear Regulatory Guide for RBI was to “reduce unnecessary conservatism” of pipe inspection in plants and not only to focus on justification of reduced inspection, but also on “enhancement of inspection, and validation of operability” [20]. Similarly, an RBI research on a pilot nuclear plant found that the safety of piping increased two-fold and the inspection was minimized by 80% compared to the ongoing practice [23]. RBI financial benefits for offshore structures were demonstrated by Straub et al. to range from one to several million US dollars compared to its prescriptive inspection practice counterpart [19]. The benefit of RBI for inspection of fatigue hot spots for offshore structures was investigated and it was found that RBI inspection was more economical than its calendar-based inspections of 4 and 20 year intervals, especially the 20 year interval, while satisfying the “risk acceptance criteria” [24]. Also, it was claimed that RBI brings transparency and accountability by funding the bridges prioritized based on performance [25]. Finally, RBI could prevent overinspection. The monetary consequence of overinspection is “unnecessary and costly repairs or replacement” compared to monetary consequence of overdesign which is a slight increase in construction cost [26].

For inspection personnel safety, the reduction in inspection means higher safety for the inspectors due to less exposure to “person-rem” (rem is the measurement unit for radiation amount) in nuclear plants [23]. Similarly, it is reported that RBI for offshore structures account for the safety and the acceptable risk level for the personnel and environment which the prescriptive inspection practices lack [19].

Risk-based approaches have been around and used for bridge applications long before to be proposed as a new dimension for determining the inspection interval in MAP-21. For example, risk-based prioritization for "repair, rehabilitation or replacement for structurally deficient or functionally obsolete bridges was approved by the House of Representatives in July 24th, 2008 as reported in H.R.3999, and the National Highway Bridge Reconstruction and Inspection Act of 2008 (S.3338) after the collapse of a bridge in Minnesota resulted in the death of 13 people. Similarly, RBI for bridge management was recommended by the ad hoc group of the American Society of Civil Engineers/Structures Engineering Institute (ASCE/SEI) and American Association of State Highway and Transportation Officials (AASHTO) as an improvement to the current bridge inspection practice in 2009 [27, 28]. The NCHRP Report 782 "Proposed Guideline for Reliability-Based Bridge Inspection Practices" was completed in 2014. The NCHRP Report 782 and several papers by Washer et al., discussed and demonstrated the RBI practice to determine bridge inspection interval [14-16]. A combined version of RBI with stochastic technique was applied by Ekpiwhre et al. in 2016 to prioritize bridge maintenance and repair interval [29]. Similarly, the NCHRP 20-07, task 378 "Guideline for Risk Assessment for Bridge Management Systems" published in 2016, documents risk assessment for bridges based on the likelihood of occurrence and its consequence based on the literature "for 16 hazards including earthquake, landslide, storm surge, high wind, flood, scour, wildfire, temperature extremes, permafrost instability, overload, over-high collision, vessel collision, sabotage, advanced deterioration, and fatigue" [30]. Risk-ranking was applied by Stewart et al. for MR&R prioritization and found that risk assessment should be only based on condition assessment because some bridges might have lower risk due to being "service proven or subject to lower traffic volume or load" [26]. It is also recommended to "perform an RBI inspection during the design of a new structure."[19]. That is, to use structural components that are identical in durability to function for a longer period. Otherwise, the less durable element would require a shorter inspection interval compared to the durable one.

Difficulties and problems that have hindered the RBI application for bridge inspection and other industries are reported in the literature as well. For example, RBI using the Bayesian method was computationally daunting, but Straub and Faber proposed an approach with statistical computations precomputed and stored in the background to provide time to focus on inspection and planning rather than to computations [31]. Similarly, the application of the RBI in offshore structures was slowed down initially due to the complicated computational aspect of the practice [19]. Difficulty in communicating risk management for extreme events for bridges with legislators to secure funds for robust programs is discussed by Thompson. Thompson argues that translating risk into understandable and shared scales such as safety (shared objective), and dollar (shared benefit) or another common term would ease communication and securing funds [32]. A case study done by the British Health and Safety Laboratory found a noncoherent approach towards risk-based inspection and dispersed output [33]. To address such discrepancy, Khan et al., proposed a structured method based on fuzzy logic for the likelihood of failure and its consequence and demonstrated its validity by several previously completed case studies. Khan et al. claim that the method applies to qualitative and quantitative data, dispersing the linguistic uncertainty into the overall hierarchy of the process, open to newly available information, and computer programable [33].

Alternative methods to improve the RBI practice that incorporates the probability of failure and its consequences has been proposed in the literature as well. For example, portfolio risk assessment (PRA), a method like RBI is applied for family of dams to prioritize actions to minimize risk [34]. PRA, unlike the RBI which only accounts for the public safety and serviceability, can account for "due diligence, business criticality, insurance, and the regulatory environment" besides the public safety through maximizing actions that reduce risk while "considering the cost effectiveness" of the actions [34]. To overcome the subjective factors of the RBI method using the probability and consequence of failure which "may increase the complexity of decision-making and its associated cost of error," a new RBI approach is proposed by Rashidi et al. [35]. In this new method an index showing the "overall efficiency of the structure in terms of safety and serviceability" is calculated using all the information gathered through inspection which "includes structural efficiency, functional efficiency, and client impact factor" for priority ranking of the bridges in the network [35].

Research on the effect of the element-level data quality on risk-based inspection is limited. The suitability of the RBI for bridges was verified by Washer et al., using samples of prestressed bridges in Oregon and steel bridges in Texas using component level inspection data. This chapter provides the result of the effect of the element-level data quality on RBI using the data collected for steel bridges in Indiana and prestressed concrete bridges in Michigan.

2.3 Introduction to Risk-based Inspection

The RBI practice “considers the structure type, age, condition, importance, environment, loading, prior problems, and other characteristics that contribute to the reliability and durability of highway bridges” to determine the inspection interval [14]. This consideration is achieved in a three-step process outlined below.

“What can go wrong and how likely is it?” This step identifies “possible damage modes” for a given bridge type’s elements [14]. And considers “design, loading, and condition characteristics (attributes)” and categorizes “the likelihood of serious damage occurring into one of the four occurrence factors (OFs), ranging from remote (very unlikely) to high (very likely).” [14].

“What are the consequences?” The second step assesses “the consequences” of damage modes given they occur, and categorizes “the potential consequence into one of the four consequence factors (CFs) ranging from low (minor effect on serviceability) to severe (i.e., bridge collapse, loss of life).” [14]. “The OF and CF are combined to form a “risk model” for the bridge, which can be used to estimate the required inspection interval [14].

“Determine the inspection interval and scope.” In this step, the outcomes from the steps 1 and 2 organized in a “4 x 4 matrix” is used “to prioritize inspection needs and assign an inspection interval for the bridge” [14]. In this matrix, the damage modes with high occurrence likelihood and high consequences would require shorter inspection intervals compared to damage modes that are “unlikely to occur” or have low consequences [14].

Based on the inspection interval specified using the above procedure, a bridge or family of bridges is inspected, and the results are assessed to check if the applied RBI procedure is just right, requires modification to match the inspection findings, or an updated one is required.

To shed light more on OF, the *failure* should be defined. Failure in the RBI application to highway bridges is defined as reaching to CR 3 based on the Recording and Coding Guide for a bridge component and reaching to CS 4 for a bridge element based on the MBEI. The OF is the probability that a damage mode would fail (reach CR 3 or CS 4) in the next 6 years (72 months) – the longest inspection interval proposed in the NCHRP 782. Each damage mode is considered separately and OF and the deterioration mechanism causing the damage is evaluated and accounted for in the RBI process. To calculate the OF for a bridge element's damage mode, the element's attributes – "characteristics of a bridge element that contribute" positively or negatively "to the element's reliability, durability, or performance" are considered [14]. An element's positive attribute has upgrading effect (longer inspection interval) and an element's negative attribute has a downgrading effect (shorter inspection interval). For example, the presence of epoxy-coated reinforcing steel in a bridge deck would have an upgrading effect (better durability). If for the same bridge deck, deicing salt is heavily applied, then the salt application has downgrading effect (more corrosion risk and shorter inspection interval). Figure 2-1 shows the relation between damage mode, attributes, and criteria. The figure also illustrates how attributes are ranked and scored.

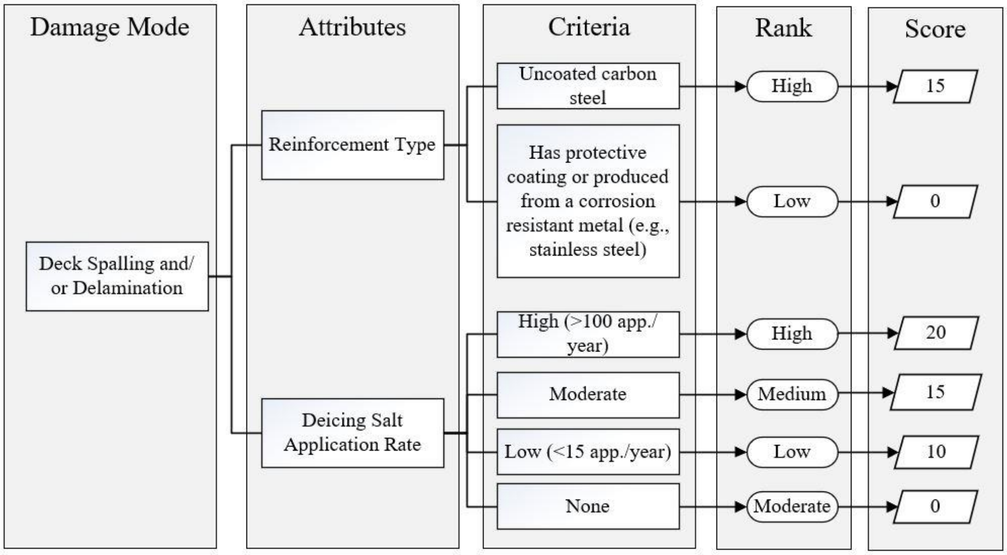


Figure 2-1. Flow chart showing the relation between damage mode, attribute, and criteria [14]

A bridge elements' attributes may stay fixed during the life of the bridge or may change, which consequently affect the likelihood of damage mode occurrence. These changing attributes are captured and accounted for in the subsequent application of RBI for the bridge.

Step 2 of the RBI process considers the CF given a damage mode reaches failure. The failure of an element in CF assessment "is not an anticipated event" but "merely a tool to rank the importance of a given element relative to other elements" to prioritize "inspection needs." [14] The shortest inspection interval calculated for any element of a bridge from the risk matrix (OF and CF matrix) would be selected as the inspection interval for the bridge [14].

The inspection scope as mentioned in step 3 consists of selecting an inspection technique capable of detecting the most important damage modes effectively and reliably. The scope may require nondestructive evaluation (NDE) techniques or visual inspection combined with sounding. The damage modes for a bridge element are prioritized using the Inspection Priority

Number (IPN), the multiplication result for the OF and CF calculated for each damage mode separately.

2.4 Risk-based Inspection and the Element-level Data Confluence

The RBI and the element-level data collection merged in the Moving Ahead for Progress in the 21st Century (MAP-21) legislation as an amendment to Title 23, United States Code, Section 144 (23 U.S.C. 144) as the new criteria for bridge inspection. Component level bridge inspection data (i.e., NBI data) is used in RBI application for the bridges selected for the original RBI project – NCHRP 782, and recently to the states' bridges participating in the pooled fund project "Developing Implementation Strategies for Risk Based Inspection" project. In the NCHRP 782 report, the element level data is not discussed in detail. Only failure is defined as CS 4 for element-level data, and element level data is used as an implication for absence or minimal presence of attributes "such as shear or flexural cracking, corrosion induced cracking, spalling, or efflorescence" for prestressed concrete (PSC) girder in Oregon [14]. To have these contemporaries (RBI and element-level data) shoulder to shoulder, RBI application using the element level data is discussed in this chapter.

The core content of the MBEI is the subdivision of a bridge to elements, the specification of the measurement units, and the applicable defects for the elements and defining the four CSs for the applicable defects to capture the condition of an element during its service life.

Similarly, the RBI practice moves from the coarse levels of details (damage modes) to finer levels of details (attributes) to find all the factors affecting the reliability and durability of a bridge. For example, to find the factors affecting/causing the damage mode of spall for a bridge deck, attributes of deicing application, reinforcing steel type, concrete cover, deck drainage, and so on are accounted for. Then criteria are identified to score the attributes based on the possible cases available for the last level of detail, i.e., reinforcing steel type could be epoxy coated or galvanized and black reinforcement. These three criteria (reinforcing steel types) are scored based on their durability, i.e., black reinforcement contribute to a shorter inspection interval compared to epoxy coated or galvanized reinforcing steel, given all other attributes are the same. For the RBI condition attributes (those captured by the routine inspection), bridges are already divided into finer details in the MBEI, i.e., bridge elements – applicable defects – CSs. Therefore, mapping the MBEI elements, defects, and CSs to the RBI attributes' criteria would show how well the MBEI fits to the RBI risk model to use the two practices' common language consistently.

The RBI practice and the element-level bridge inspection confluence require finding the commonalities and the differences between these two practices. The MBEI divides bridges to elements of two different types – National Bridges Elements (NBEs) and Bridge Management Elements (BMEs). Regardless of the element types, all elements have standard four CSs designated as good (CS 1), fair (CS 2), poor (CS 3), and severe (CS 4). And the elements are measured in the unit of square feet, linear feet, or each. The MBEI uses "multiple distress paths within the defined condition states" to capture the applicable defects for the elements [12]. "The NBEs are a refinement of the deck, superstructure, substructure, and culverts condition ratings as defined in the Federal Highway Administration's Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" with the addition of the bridge rail and bearings [12]. The BMEs include "joints, wearing surfaces, and protective coating systems and deck/slab protection systems that are typically managed by agencies utilizing Bridge

Management Systems." [12] As given in the introduction of the MBEI, the BMEs conditions assessments can be modified to fit the "agencies' needs" [12].

To determine the effect of the element-level bridge inspection data quality on risk-based inspection, the MBEI elements, defects, and CSs are mapped to the design and condition attributes defined in the NCHRP 782 seminal work for RBI. The NCHRP 782 attributes relevant to the MBEI content are listed in Table 2-1.

Table 2-1. List of the NCHRP 782 Attributes used for mapping MBEI elements and defects

Screening Attributes	
S.1 – Current Condition Rating	S.6 – Longitudinal Cracking
S.4 – Flexural Cracking	S.9 – Significant Level of Active Corrosion or Section Loss
S.5 – Shear Cracking	S.10 – Design Features
Design Attributes	
D.1 – Joint Types	D.10 – Deck Overlays
D.5 – Use of Open Decking	D.16 – Element Connection Type
D.7 – Application of Protective Systems	
Condition Attributes	
C.2 – Current Element Condition State	C.12 – Presence of Spalling
C.3 – Evidence of Rotation or Settlement	C.13 – Efflorescence/Staining
C.4 – Joint Condition	C.14 – Flexural Cracking
C.6 – Previously Impacted	C.15 – Shear Cracking
C.8 – Corrosion Induced Cracking	C.16 – Longitudinal Cracking
C.9 – General Cracking	C.17 – Coating Condition
C.10 – Delamination	C.21 – Presence of Active Corrosion
C.11 – Presence of Repaired Areas	C.22 – Presence of Debris

The mapping is done because the MBEI contains all the bridge elements and their applicable defects and the RBI uses design, loading, and condition attributes to prioritize bridge inspection based on damage modes' severity. The comparison is made to find the common ground between the MBEI and RBI. That is, the RBI design and condition attributes imply the same things as those constitute the core content of the MBEI – bridges elements (design) and defects (approximately damage modes). It is hoped that mapping the MBEI to RBI criteria for design and condition attributes would illuminate the boundaries for each practice and find the gray areas. In this analysis, the relative numerical scores suggested in NCHRP 782 are discussed. The values are commonly adjusted within an actual risk model but are used herein for comparison. Mapping the MBEI to RBI is provided below.

2.5 Screening Attributes

Attributes that cause the likelihood of a bridge failure “very high”, “uncertain”, or introduces different “deterioration patterns than other bridges in the group,” are called screening attributes [14]. This section discusses those screening attributes that are relevant and related to the MBEI contents. The list of the screening attributes analyzed in this section are shown in Table 2-2. S.1, S.2, … in Table 2-2 are the references to the NCHRP 782 attributes.

Table 2-2. List of the NCHRP 782 Screening Attributes analyzed

Screening Attributes	
S.1 – Current Condition Rating	S.6 – Longitudinal Cracking
S.4 – Flexural Cracking	S.9 – Significant Level of Active Corrosion or Section Loss
S.5 – Shear Cracking	S.10 – Design Features

2.5.1 S.1 – Current Condition Rating

The screening attribute “S.1 – Current Condition Rating” describes the two types of elements covered by the MBEI – National Bridge Elements (NBEs) and Bridge Management Elements (BMEs). It is stated that elements in CS 4 could be considered as screening attributes if it is established as a criterion for a bridge inventory. But, based on the MBEI, this criterion applies to the NBEs only but not the BMEs. In the MBEI, the current condition of an element is specified by the applicable defects, but “S.1 – Current Condition Rating” does not consider the defects. This may cause agencies to collect element-level data without collecting defects, but later it will be shown that the MBEI defects are used as damage modes and attributes for the RBI. Therefore, for agencies wishing to apply RBI, the RBI criteria for attributes should be collected besides the MBEI defects.

2.5.2 S.4 – S.6 Cracking Types

The screening attributes “S.4 – Flexural Cracking”, “S.5 – Shear Cracking”, and “S.6 – Longitudinal Cracking in Prestressed Elements” guides how to screen bridges with these types of cracks. The NCHRP 782 states that the screening attribute “S.6 – Longitudinal Cracking in Prestressed Elements” could be assessed based on the inspection reports, but neither the NBI CR nor the MBEI CS assignment records this specific type of cracking. These attributes are RBI criteria as the MBEI does not differentiate between different crack types and should be included in the RBI assessment file for the bridge to remind the inspectors to search for such attributes (defects).

2.5.3 S.9 – Significant Level of Active Corrosion or Section Loss

The screening attributes “S.9 – Significant Level of Active Corrosion or Section Loss” for steel elements guides how to screen steel elements with active corrosion or section loss. In MBEI, corrosion (defect 1000) is a defined defect for elements made of steel. Similarly, for elements made of RCC and PSC, “section loss” is captured by Exposed Reinforcing Steel (defect 1090) and Exposed Prestressing (defect 1100), respectively. But the MBEI collects all corrosion under the same name without differentiating between “active” and “inactive” corrosion. Therefore, this attribute is an RBI criterion and should be included in the RBI application file for the bridge to remind the inspectors to differentiate between the corrosion types. An example of "inactive" corrosion would be a member with section loss that has been recoated and corrosion arrested.

2.5.4 S.10 – Design Features

The screening attribute "S.10 – Design Features" discusses unique bridge designs like bridges with pin and hanger connection and jointless bridges to screen them from the rest of the bridge inventory. The MBEI element 161 – "Steel Pin & Hanger Assembly or both" matches to part of this attribute. A jointless bridge is an RBI application criterion.

2.6 Design Attributes

This section discusses the attributes related to the design of a bridge's elements. The design attributes relevant and related to the MBEI content is shown in Table 2-3.

Table 2-3. List of the NCHRP 782 Design Attributes relevant to the MBEI content

Design Attributes	
D.1 – Joint Types	D.10 – Deck Overlays
D.5 – Use of Open Decking	D.16 – Element Connection Type
D.7 – Application of Protective Systems	

2.6.1 D.1 – Joint Type

The design attribute "D.1 – Joint Type" divides the joints to closed and open systems and favors closed systems over the open ones. The open system joints are downgraded by 10-point score compared to the closed system joints. In the MBEI, joints are grouped under BMEs and divided into seven types. Six types of the MBEI joints mapped to the RBI criterion are shown in Table 2-4. Element 306 - Other Joint captures joints different from those six common types.

Table 2-4. RBI Attributes for joint type and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI Elements
Open Joint System	10	304 – Open Expansion Joint
		305 – Assembly Joint without Seal
Closed Joint System	0	300 – Strip Seal Expansion Joint
		301 – Pourable Joint Seal
		302 – Compression Joint Seal
		303 – Assembly Joint/ Seal (Modular)

2.6.2 D.5 – Use of Open Decking

The design attribute “D.5 – Use of Open Decking” describes the situation in which an open decking is used and downgrades its use over other types of decks with a 20-point score. The MBEI element 28 – Steel Deck with Open Grid corresponds to this RBI design attribute. The MBEI decks mapped to the RBI criterion are shown in Table 2-5.

Table 2-5. RBI Attributes for Open Decking and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI Elements
Bridge has an open deck	20	28 – Steel Deck with Open Grid
Bridge does not have an open deck	0	12 – Reinforced Concrete Deck
		13 – Prestressed Concrete Deck
		38 – Reinforced Concrete Slab
		15 – Prestressed Concrete Top Flange
		16 – Reinforced Concrete Top Flange
		30 – Steel Deck Corrugated/Orthotropic/Etc.
		31 – Timber Deck
		54 – Timber Slab

2.6.3 D.7 – Application of Protective Systems

The design attribute "D.7 – Application of Protective Systems" discusses the effect of protective systems applied over concrete elements and downgrades the elements that the protective system is "never applied, poor functioning, or non-functioning" by 10-point score, and the elements that protective system like penetrating sealer and crack sealer are applied with limited effectiveness by 5-point score compared to the elements that protective system is applied periodically and are effective [14]. The MBEI element 521 – Concrete Protective Coating covers this RBI attribute. The MBEI provides several defects for this element and four CSs that describe its effectiveness. The MBEI defects and CSs mapped to this RBI attribute are shown in Table 2-6.

Table 2-6. RBI Attributes for Concrete Protective Coating and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defects	MBEI Definition
Never applied, poor functioning, or non-functioning	10	CS 3	Wear (3510)	Underlying concrete is not exposed; thickness of the coating is reduced.
			Effectiveness (3540)	Limited effectiveness.
		CS 4	Wear (3510)	Underlying concrete exposed. Protective coating no longer effective.
			Effectiveness (3540)	The protective system has failed or is no longer effective.
Applied, penetrating sealer, crack sealer, limited effective	5	CS 2	Wear (3510)	Underlying concrete not exposed; coating showing wear from UV exposure; friction course missing.
			Effectiveness (3540)	Substantially effective.
Applied, periodically, effective	0	CS 1	Wear (3510)	None.
			Effectiveness (3540)	Fully Effective

2.6.4 D.10 – Deck Overlays

The design attribute “D.10 – Deck Overlays” discusses whether a deck has an overlay and downgrades decks with an overlay by 10-point score over bare decks, because the overlay makes it impossible to see the deterioration and corrosion damages that occur to the deck itself. The MBEI element 510 – Wearing Surfaces mapped to the RBI design attribute is shown in Table 2-7.

Table 2-7. RBI Attributes for Deck Overlays and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI Elements
Deck has an overlay	10	510 – Wearing Surfaces
Bare Deck	0	

2.6.5 D.16 – Element Connection Type

The design attribute “D.16 – Element Connection Type” discusses the connection type related to the susceptibility of a member in transferring fatigue crack from one part to the other in built-up members. This design attribute downgrades welded built-up members with 15-point score, and rivetted built up members with 7-point score compared to build-up members using high strength (HS) bolts. This attribute classifies rivetted connection as Fatigue category D and HS bolts as Category B. The attribute reappears with the same criteria in design attribute “D.17 – Worst Fatigue Detail Category” to score members built using all the connection types. This design attribute does not discuss the current or the next 72 months connection’s CSs. The defect 1020 – Connection in the MBEI captures the CSs a connection might undergo during its service life.

2.7 Condition Attributes

The condition attributes relevant and related to the MBEI are discussed in this section. A list of the condition attributes discussed are provided in Table 2-8. C.2, C.3, etc., provide references to the NCHRP 782 report discussing the condition attributes.

Table 2-8. List of NCHRP 782 Condition Attributes relevant to the MBEI content

Condition Attributes	
C.2 – Current Element Condition State	C.12 – Presence of Spalling
C.3 – Evidence of Rotation or Settlement	C.13 – Efflorescence/Staining
C.4 – Joint Condition	C.14 – Flexural Cracking
C.6 – Previously Impacted	C.15 – Shear Cracking
C.8 – Corrosion Induced Cracking	C.16 – Longitudinal Cracking
C.9 – General Cracking	C.17 – Coating Condition
C.10 – Delamination	C.21 – Presence of Active Corrosion
C.11 – Presence of Repaired Areas	C.22 – Presence of Debris

2.7.1 C.2 – Current Element Condition State

The condition attribute "C.2 – Current Element Condition State" discusses the current condition of an element according to the MBEI procedure. It downgrades elements in CS 3 with 20-point score compared to elements in CS 1, and within the text, it directs the users to graduate the score appropriately for elements in CS 2. But in a table for this condition attribute, a 10-point score is assigned for elements with "minor portion" in CS 2 [14]. The MBEI CSs could be mapped to the RBI criterion in two different ways – the CS method, and the CS and a quantity threshold method – discussed later in this chapter. The CS method mapped to the RBI criterion is shown in Table 2-9.

Table 2-9. RBI criteria for MBEI elements' CSs and it MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CSs
CS 2 is indicated for a significant portion of the element, or CS 3 is indicated for any portion of the element	20	CS 3
Condition State 2 is indicated for a minor portion of the element	10	CS 2
Condition State 1 is indicated for entire element	0	CS 1

2.7.2 C.3 – Evidence of Rotation or Settlement

The condition attribute “C.3 – Evidence of Rotation or Settlement” discusses the “rotation or settlement of abutments and piers” “for minor settlements or rotations that do not affect the structural capacity, but causes “accelerated deterioration patterns.” [14]. This attribute downgrades the situations where “rotation or settlement resulted in cracking of the concrete, misaligned joints, or misaligned members” by 15-point score and situations where “minor evidence of rotation or settlement with the potential to result in unexpected cracking or poor joint performance” by 5-point score compared to situations without “evidence of rotation” [14]. The MBEI defect 4000 – Settlement is defined for elements susceptible to this defect, and it has two CSs – CS 2 – fair, and CS 3 – poor. CS 1 – Good for this defect is defined as “None” and CS 4 requires structural review and therefore corresponds to the RBI screening attribute. The word “unexpected” used in NCHRP 782 for this attribute is not clear. The MBEI defect 4000 – settlement mapped to the RBI criterion is shown in Table 2-10.

Table 2-10. RBI Attributes for Evidence of Rotation or Settlement and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defect	MBEI Definition
Rotation or settlement resulted in cracking of concrete, misaligned joints, or misaligned members	15	CS 3	Settlement (4000)	Exceeds tolerable limits but does not warrant structural review.
Minor evidence of rotation or settlement with the potential to result in unexpected cracking or poor joint performance	5	CS 2	Settlement (4000)	Exists within tolerable limits or arrested with no observed structural distress.
No evidence of rotation	0	CS 1	Settlement (4000)	None

2.7.3 C.4 – Joint Condition

The condition attribute “C.4 – Joint Condition” discusses situations where “leaking joints” causes “corrosion related deterioration” for bridge elements under the bridge deck [14]. This attribute downgrades bridge joints with “significant amount of leakage” by 20-point score, joints with “moderate leakage” or “debris filled” by 15-point score and leaking-free joints by 5-point score compared to jointless bridges [14]. In this attribute, two MBEI defects for joints are discussed – defect 2310 – Leakage and 2350 – Debris Impaction. Based on the RBI, only “Joint Leakage” is discussed as an attribute affecting the reliability of the superstructure and substructure. But the MBEI defect 2320 – Seal Adhesion in CS 4 where the seal adhesion is lost completely, defect 2330 – Seal Damage in CS 3 and CS 4 where the seal is “punctured or ripped” partially or completely and defect 2340 – Seal Cracking in CS 4 where the crack “fully penetrates” the seal would allow water to reach the superstructure and substructure. Therefore, these defects imply the same problem as defect 2310 – Leakage and should be taken in to account accordingly [12]. The MBEI defects for joint conditions mapped to the RBI criterion are shown in Table 2-11.

Table 2-11. RBI Attributes for Joint Condition and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defect	MBEI Definition
Significant amount of leakage at joints	20	CS 4	Leakage (2310)	Free flow of water through the joint.
		CS 3	Leakage (2310)	Moderate. More than a drip and less than free flow of water.
		CS 4	Seal Adhesion (2320)	Complete loss of adhesion.
		CS 4	Seal Damage (2330)	Punctured completely through, pulled out, or missing.
		CS 4	Seal Cracking (2340)	Crack the fully penetrates the seal.
Joints have moderate leakage or are debris filled	15	CS 2	Leakage (2310)	Minimal. Minor dripping through the joint.
		CS 3	Seal Damage (2330)	Punctured or ripped or partially pulled out.
		CS 2	Debris Impaction (2350)	Partially filled with hard-packed material but still allowing free movement.
		CS 3		Completely filled and impacts joint movement.
		CS 4		Completely filled and prevents joint movement.
Joints are present but not leaking	5	CS 1	Leakage (2310)	None.
Bridge is jointless	0	No Equivalent is available in the MBEI.		

Another defect describing a joint’s condition is defect 2360 – Adjacent Deck or Header. This defect in CS 2, CS 3, and CS 4 captures delamination and spalling surrounding the joint like the deck’s defect 1080. Therefore, it should be counted toward the reliability of the deck and if it allows water to reach the superstructure and substructure, it should be considered in the reliability of the superstructure and substructure as well.

2.7.4 C.6 – Previously Impacted

The condition attribute “C.6 – Previously Impacted” discusses the probability of future impact for bridges previously “impacted by a vehicle.” [14] This attribute downgrades bridges previously impacted by 20-point score compared to bridges previously not impacted. In MBEI, defect 7000 – Damage captures the defect for elements that is applicable. Table 2-12 shows the MBEI defect mapped to the RBI criterion for the Previously Impacted condition attribute.

Table 2-12. RBI Attributes for Previously Impacted and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI Defects
Bridge has been previously impacted	20	Damage (7000)
Bridge has not been previously impacted	0	Not applicable.

2.7.5 C.8 – Corrosion-Induced Cracking

The condition attribute “C.8 – Corrosion-Induced Cracking” discusses “the presence of corrosion induced cracking in concrete bridge elements.” [14] In the description of this attribute, rust staining is described as the sign for corrosion-induced cracking, but it is mentioned that this attribute would be “scored based on the presence and the severity of corrosion-induced cracking in concrete bridge elements.” [14] Concrete members with “significant corrosion-induced cracking” are downgraded by 20-point score, members with “ moderate corrosion-induced cracking” are downgraded by 10-point score, and members with “minor corrosion-induced cracking” are downgraded by 5-point score compared to concrete members without “corrosion-induced cracking” [14]. In the MBEI, this attribute is collected using defect 1120 – Efflorescence/Rust Staining which is described as the sign for corrosion-induced cracking in the RBI. Also, based on the MBEI, if there is more than one defect on the same spot such as cracking and efflorescence/rust stationing. In that case, it is recommended to collect the most severe defect and ignore the less severe one. Based on this direction, if any of the defects (cracking or efflorescence/rust staining) are in the most severe condition, it would be collected. But the RBI recommends to score this attribute “based on the presence and the severity of corrosion-induced cracking in concrete bridge elements” which is not explicitly recorded in the MBEI [14]. Therefore, the unification of RBI and MBEI for this attribute (defect) would bring consistency in data collection and RBI application. Table 2-13 shows the MBEI defect mapped to the RBI criterion for corrosion-induced cracking.

Table 2-13. RBI Attributes for Corrosion-Induced Cracking and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defect	MBEI Definition
Significant corrosion-induced cracking	20	CS 3	Efflorescence/Rust Staining (1120)	Heavy build-up with rust staining.
Moderate corrosion-induced cracking	10	CS 2	Efflorescence/Rust Staining (1120)	Surface white without build-up or leaching without rust staining.
Minor corrosion-induced cracking	5	CS 2	Efflorescence/Rust Staining (1120)	Surface white without build-up or leaching without rust staining.
No corrosion-induced cracking	0	CS 1	Efflorescence/Rust Staining (1120)	None.

2.7.6 C.9 – General Cracking

The condition attribute “C.9 – General Cracking” addresses “the presence of non-structural cracks in concrete” elements [14]. This attribute downgrades concrete elements with “widespread or severe cracking” by 15-point score, and elements with “moderate cracking” by 10-point score compared to concrete elements with “minor or no cracking” [14]. In the NCHRP 782, it is stated that general cracking is “used for cracking other than corrosion-induced cracking”, but in the MBEI, corrosion-induced cracking is captured by defect 1120 – Efflorescence/Rust Staining which is described as the sign for corrosion-induced cracking in the RBI and other cracks are captured by defect 1130 – Cracking (RC and others). Table 2-14 shows the MBEI defect mapped to the RBI criterion for condition attribute of General Cracking.

Table 2-14. RBI Attributes for General Cracking and its MBEI equivalent

RBI Ranking Definition	**RBI Score**	**MBEI CS**	**MBEI Defects**	**MBEI Definitions**
Widespread or severe cracking	15	CS 3	Cracking (RC) (1130)	Wide cracks or heavy pattern (map) cracking.
Moderate cracking present	10	CS 2	Cracking (RC) (1130)	Unsealed moderate-width cracks, or unsealed moderate pattern (map cracking)
Minor or no cracking present	0	CS 1	Cracking (RC) (1130)	Insignificant cracks or moderate-width cracks that have been sealed.

2.7.7 C.10 – Delamination

The condition attribute “C.10 – Delamination” addresses this deterioration for concrete elements and deck overlays. The NCHRP 782 states that “concrete elements with delamination are more likely to experience deterioration and damage in the future”, but delamination is a by-product of reinforcing steel corrosion deterioration mechanism (volumetric expansion) and it is a damage mode but not the cause for “deterioration and damage” [14]. This attribute downgrades concrete elements with “significant amount of delamination (greater than 20% by area)” by 20-point score, “moderate amount of delamination (5% to 20% by area)” by 10-point score, and “minor, localized delamination (less than 5% by area)” by 5-point score compared to elements with no delamination [14]. In the MBEI, delamination is recorded with the spall and patched area together by defect 1080 – Delamination/Spall/ Patched Area. Also, the measurement unit for this defect in the MBEI is sq ft for decks and linear ft for girders and RC columns, but the RBI provides scoring criteria only for area elements. The amount’s percentage should be revised to include linear elements as well. Also, since MBEI is a standard, the three RBI attributes (C.10– Delamination, C.11– Presence of Repaired Areas, and C.12– Presence of spalling) could be coalesced into one attribute (MBEI defect) for data collection and RBI application purposes. The MBEI defect is favored over the individual RBI criteria because the MBEI defect 1080 captures the development process for this deterioration accurately. That is, cracks would cause delamination, delamination would ultimately become spalls, and spalls would be repaired or patched. Table 2-15 shows the MBEI defect mapped to the RBI criterion for the condition attribute of Delamination.

Table 2-15. RBI Attributes for Delamination and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defects	MBEI Definitions
Significant amount of delamination present (greater than 20% by area) or unknown	20	CS 3	Delamination/Spall/ Patched Area (1080)	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area that is unsound or showing distress. Does not warrant structural review.
Moderate amount of delamination present (5% to 20% by area)	10	CS 2	Delamination/Spall/ Patched Area (1080)	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.
Minor, localized delamination (less than 5% by area)	5	CS 2	Delamination/Spall/ Patched Area (1080)	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.
No delamination present	0	CS 1	Delamination/Spall/ Patched Area (1080)	None.

2.7.8 C.11 – Presence of Repaired Areas

The condition attribute “C.11 – Presence of Repaired Areas” addresses the “repaired spalls and patches” [14]. In this attribute, it is stated that the “repaired areas should be scored based on the total” repaired surface area [14]. This attribute recommends distinguishing between the repaired areas of the impact damage where the chloride level is lower than those of the corrosion-induced repaired areas. This attribute downgrades concrete elements with a “significant amount of repaired areas” by a 15-point score, elements with “moderate amount of repaired areas” by 10-point score, elements with “minor amount of repaired areas” by 5-point score compared to elements with no repaired areas [14]. In the MBEI, the patched area is collected using defect 1080 – Delamination/Spall/Patched Area which neither distinguishes from delamination and spall nor from impact damage and corrosion induced areas. Also, since MBEI is a standard, the three RBI attributes (C.10– Delamination, C.11– Presence of Repaired Areas, and C.12– Presence of spalling) could be coalesced into one attribute (MBEI defect) for data collection and RBI application purposes. The MBEI defect is favored over the individual RBI criteria- because the MBEI defect 1080 captures the development process of this deterioration accurately. That is, cracks would cause delamination, delamination would ultimately become spalls, and spalls would be repaired or patched. Table 2-16 shows the MBEI defect mapped to the RBI criterion for the condition attribute of the Presence of Repaired Areas.

Table 2-16. RBI Attributes for Presence of Repaired Areas and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defects	MBEI Definitions
Significant amount of repaired areas	15	CS 3	Delamination/Spall/ Patched Area (1080)	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area that is unsound or showing distress. Does not warrant structural review.
Moderate amount of repaired areas	10	CS 2	Delamination/Spall/ Patched Area (1080)	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.
Minor amount of repaired areas	5	CS 2	Delamination/Spall/ Patched Area (1080)	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.
No repaired areas	0	CS 1	Delamination/Spall/ Patched Area (1080)	None.

2.7.9 C.12 – Presence of spalling

The condition attribute “C.12 – Presence of spalling” addresses this deterioration for concrete elements and it is recommended in the NCHRP 782 that users may combine this attribute with condition attribute “C.11 – Presence of Repaired Areas” or use the two separately. This attribute downgrades concrete elements with “significant spalling (greater than 10% of area with spalling, reinforcing steel or strands exposed” by 20-point score, elements with “moderate spalling (greater than 1 inch deep or 6 in diameter or exposed reinforcement)” by 15-point score, elements with “minor spalling (less than 1 inch deep or 6 in diameter)” by 5-point score compared to those elements with no spalling [14]. This attribute combines the MBEI defect

1090 – Exposed Reinforcing steel and defect 1100 – Exposed Prestressing with defect 1080 – Delamination/Spall/Patched Area for the first scoring criterion and combines defect 1090 – Exposed Reinforcing steel with defect 1080 for the second criterion with a mixture of MBEI's CSs definition. It also uses the definitions for CSs of defect 1080 for the scoring of the third criterion (1 in deep and 6 in diameter). Also, since MBEI is a standard, the three RBI attributes (C.10– Delamination, C.11– Presence of Repaired Areas, and C.12– Presence of spalling) could be coalesced into one attribute (MBEI defect) for data collection and RBI application purposes. The MBEI is favored over the individual RBI criteria because the MBEI defect 1080 captures the development process of this deterioration accurately. That is, cracks would cause delamination, delamination would ultimately become spalls, and spalls would be repaired or patched. Table 2-17 shows the MBEI defect mapped to the RBI criterion for the condition attribute of the Presence of Spalling.

Table 2-17. RBI Attributes for Presence of Spalling and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defects	MBEI Definitions
Significant spalling (greater than 10% of area with spalling, reinforcing steel or strands exposed)	20	CS 3	Delamination/Spall/ Patched Area (1080)	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area that is unsound or showing distress. Does not warrant structural review.
Moderate spalling (greater than 1 inch deep or 6 inches in diameter or exposed reinforcement)	15	CS 2	Delamination/Spall/ Patched Area (1080)	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.
Minor spalling (less than 1 inch deep or 6 inches in diameter)	5	CS 2	Delamination/Spall/ Patched Area (1080)	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.
No spalling present	0	CS 1	Delamination/Spall/ Patched Area (1080)	None.

2.7.10 C.13 – Efflorescence/Staining

The condition attribute "C.13 – Efflorescence/Staining" addresses the "corrosion damage associated with the presence of efflorescence on the surface of concrete elements." [14] This attribute downgrades concrete elements with "moderate to severe efflorescence with rust staining and severe efflorescence without rust staining" by 20-point score, elements with "moderate efflorescence without rust staining" by 10-point score, and elements with "minor efflorescence" by 5-point score compared to elements without efflorescence [14]. Based on the MBEI, this attribute duplicates condition attribute C.8 which addresses the same deterioration. The MBEI addresses this attribute by defect 1120 – Efflorescence/Rust Staining. Table 2-18 shows the MBEI defect mapped to the RBI criterion for the condition attribute of Efflorescence/Staining.

Table 2-18. RBI Attributes for Efflorescence/Staining and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defects	MBEI Definitions
Moderate to severe efflorescence with rust staining; severe efflorescence without rust staining	20	CS 3	Efflorescence/Rust Staining (1120)	Heavy build-up with rust staining.
Moderate efflorescence without rust staining	10	CS 2	Efflorescence/Rust Staining (1120)	Surface white without build-up or leaching without rust staining.
Minor efflorescence	5	CS 2	Efflorescence/Rust Staining (1120)	Surface white without build-up or leaching without rust staining.
No efflorescence	0	CS 1	Efflorescence/Rust Staining (1120)	None.

2.7.11 C.14 – Flexural Cracking

The condition attribute “C.14 – Flexural Cracking” addresses the excess likelihood of corrosion caused by “moderate to severe amount of flexural cracking [14]. This attribute downgrades concrete elements with “crack widths equal to 0.006 inches to 0.012 inches, depending on environment for reinforced concrete” and PSC elements with “crack widths equal to or less than 0.006 inches” by 10-point score compared to RCC and PSC elements with “no flexural cracking” [14]. In the MBEI, crack types for RCC members are not differentiated from each other, and only one type of cracking is defined – defect 1130 –

Cracking (RC and Other). Similarly, for PSC members, cracks types are not differentiated from each other and all cracks are identified by a single defect – defect 1110 – Cracking (PSC). Therefore, this attribute is an RBI criterion and agencies wishing to apply RBI should collect finer data required by the RBI criteria.

2.7.12 C.15 – Shear Cracking

The condition attribute "C.15 – Shear Cracking" discusses this type of cracking for RCC and PSC members relating to the load carrying capacity of the member. This attribute downgrades members with "minor, hairline to less than 0.0625 inch shear cracking" by 10-point score compared to members with no shear cracking [14]. In MBEI, crack types for RCC members are not differentiated from each other, and only one type of cracking is defined – defect 1130 – Cracking (RC and Other). Similarly, for PSC members, crack types are not differentiated from each other and all cracks are identified by a single defect – defect 1110 – Cracking (PSC). Therefore, this attribute is an RBI criterion, and agencies wishing to apply RBI should collect finer data required by the RBI criteria.

2.7.13 C.16 – Longitudinal Cracking in Prestressed Elements

The condition attribute "C.16 – Longitudinal Cracking in Prestressed Elements" addresses the deterioration where it indicates "corrosion or the fracture of the embedded prestressing strands." [14] This attribute downgrades PSC beam soffits with "minor longitudinal cracking" by 15-point score compared to beam soffits without longitudinal cracks [14]. In the description of this attribute, it is stated that it "is scored based on the inspection results." [14] But neither the MBEI nor the

NBI collect this defect explicitly and for PSC member cracking is identified by defect 1110 – Cracking (PSC). Therefore, this attribute is an RBI criterion, and agencies wishing to apply RBI should collect finer data required by the RBI criteria.

2.7.14 C.17 – Coating Condition

The condition attribute “C.17 – Coating Condition” addresses the quality of coating on how it affects the corrosion likelihood for steel members. This attribute downgrades “coating system in very poor condition, limited or no effectiveness for corrosion protection, greater than 3 % rusting” by 10-point score, and “coating system in poor condition, 1% to 3 % rusting, substantially effective for corrosion protection” by 5-point score compared to “coating in fair to good condition, effective for corrosion protection” [14]. This attribute uses the MBEI terminology “poor”, “good”, and “fair”, but in the first criterion, it uses “very poor” which is ambiguous. Also, the use of 1 % and 3 % is not clear if it refers to the percentage of the total element length or the percentage of the total coating systems measurement unit. Table 2-19 shows the MBEI defects mapped to the RBI criterion for the condition attribute of Coating Condition.

Table 2-19. RBI Attributes for Coating Condition and its MBEI equivalent

RBI Ranking Definition	RBI Score	MBEI CS	MBEI Defects	MBEI Definitions
Coating system in very poor condition, limited or no effectiveness for corrosion protection, greater than 3% rusting	10	CS 4	Peeling/Bubbling/Cracking (3420)	Exposure of bare metal.
			Oxide Film Degradation Color/Texture Adherence (3430)	Dark black color. Large flakes, 1/2-in. diameter or greater, or laminar sheets or nodules.
			Effectiveness (3440)	Failed; no protection of the underlying metal.
Coating system is in poor condition, 1% to 3% rusting, substantially effective for corrosion protection	5	CS 3	Chalking (3410)	Loss of pigment.
			Peeling/Bubbling/Cracking (3420)	Finish and primer coats.
			Oxide Film Degradation Color/Texture Adherence (3430)	Small flakes, less than 1/2-in. diameter.
			Effectiveness (3440)	Limited effectiveness.
Coating is in fair to good condition, effective for corrosion protection	0	CS 1, CS 2	Chalking (3410)	None or Surface dulling.
			Peeling/Bubbling/Cracking (3420)	None or Finishes coats only.
			Oxide Film Degradation Color/Texture Adherence (3430)	Yellow-orange or light brown for early development. Chocolate-brown to purple brown for fully developed. Tightly adhered, capable of withstanding hammering or vigorous wire brushing. Granular texture.
			Effectiveness (3440)	Fully effective or substantially effective.

2.7.15 C.21 – Presence of Active Corrosion

The condition attribute "C.21 – Presence of Active Corrosion" addresses this deterioration for steel elements and distinguishes this type of corrosion from inactive corrosion. This attribute downgrades steel elements with a "significant amount of active corrosion" by 20-point score, elements with "moderate amount of active corrosion" by 15-point score, and elements with "minor amount of active corrosion" by 7-point score compared to elements without active corrosion [14]. In the MBEI, this type of corrosion is not recorded explicitly, but defect 1000 for steel members capture the same phenomenon. Therefore, this attribute is an RBI criterion, and agencies wishing to apply RBI should collect finer data required by the RBI criteria. Table 2-20 shows the MBEI defect mapped to the RBI criterion for the condition attribute of Active Corrosion.

Table 2-20. RBI Attributes for Active Corrosion and its MBEI equivalent

RBI Ranking Definition	**RBI Score**	**MBEI CS**	**MBEI Defect**	**MBEI Definition**
Significant amount of active corrosion present	20	CS 3	Corrosion (1000)	Section loss is evident, or pack rust is present but does not warrant structural review.
Moderate amount of active corrosion present	15	CS 2	Corrosion (1000)	Freckled rust. Corrosion of the steel has initiated.
Minor amount of active corrosion present	7	CS 1	Corrosion (1000)	None.
No active corrosion present	0	CS 1	Corrosion (1000)	None.

2.7.16 C.22 – Presence of Debris

The condition attribute “C.22 – Presence of Debris” addresses the detrimental effect of debris accumulation and stays for a long time on “flanges, bearings, connections, or other details” that causes accelerated deterioration [14]. This attribute downgrades the accumulation and presence of debris on the above-mentioned elements by 15-point score compared to elements without debris. In the MBEI, defect 2350 – Debris Impaction is defined for joints only, but not for other elements. Table 2-21 shows the MBEI defect mapped to the RBI criterion for the condition attribute for the Presence of Debris.

Table 2-21. RBI Attributes for Presence of Debris and its MBEI equivalent

RBI Ranking Definition	**RBI Score**	**MBEI CS**	**MBEI Defect**	**MBEI Definition**
Debris is or is likely to be present	15	CS 2, CS 3, and CS 4	Debris Impaction (2350)	See the MBEI definitions.
Debris not likely to be present	0	CS 1	Debris Impaction (2350)	See the MBEI definition.

2.8 Reliability Assessment Panel Data

The Reliability Assessment Panel (RAP) data from the states participating in the original RBI project and those participating in the “Developing Implementation Strategies for Risk Based Inspection” project is compiled and analyzed in this section. The name of the states is shown in Table 2-22. The compilation and analysis of the data collected from these meetings would allow us to know the number of MBEI elements and defects explicitly or implicitly discussed within the RBI.

Table 2-22. List of participating states in RBI projects

NCHRP 782 participating states	**RBI pooled Fund Participating states**
Oregon	Idaho
Texas	Illinois
	Missouri
	New York (RAP meeting not held.)
	Pennsylvania
	Washington
	Wisconsin

The discussion of the deck, superstructure, and substructure in the RBI application like the component level bridge inspection practice is not a mere coincidence. But these three components are “the primary load carrying members” that provide the chance to define the abstract concept of risk (the probability of failure and its consequences) for a bridge concretely [12]. For example, the failure of a substructure or superstructure and its consequences is more pronounced and easily understood than the failure of a bridge joint, handrail, or a bearing pad. Similarly, the unserviceability of a bridge deck due to spalls on its surface is more easily understood than the leaking joints on the bridge deck. Therefore, all NBEs (except for the culvert which RBI is not yet applied to this element, handrail, and bearings) are equivalent to the NBI components used for defining the concept of RBI. And BMEs and Agency-Developed Elements (ADEs) could be used as attributes to NBEs, i.e., Steel Protective Coating (element 515) could be an attribute for coated Steel Open Girder/Beam (Element 107), or joints could be an attribute for superstructure and substructure. Therefore, the bridge elements that are used in the RBI applications to date are shown in Table 2-23. In the RAP meetings, the elements 205, 215, and 234 were discussed together as a single unit for the substructure.

Table 2-23. The MBEI Elements used as the **Deck, Superstructure**, and **Substructure** in RBI

MBEI Element's Number and Name	Name Recorded in the RAP
12 Reinforced Concrete Deck	RCC Deck
107 Steel Open Girder/Beam	Steel, PSC, and RCC Superstructure
109 Prestressed Concrete Open Girder/Beam	
110 Reinforced Concrete Open Girder/Beam	
205 Reinforced Concrete Column	RCC Substructure
215 Reinforced Concrete Abutment	
234 Reinforced Concrete Pier Cap	

Similarly, Table 2-24 shows the MBEI elements used as attributes for RBI damage modes. The RBI attributes were not recorded exactly as the elements presented in Table 2-24, but general names like joint types, steel protective coating, railing, pin and hanger, or coated reinforcing steel were used in the RBI.

Table 2-24. The MBEI Elements used as **Attributes** in RBI Damage Modes

Element Number and Name	Element Number and Name
161—Steel Pin and Pin & Hanger Assembly or both	331 Reinforced Concrete Bridge Railing
300 Strip Seal Expansion Joint	332 Timber Bridge Railing
301 Pourable Joint Seal	333 Other Bridge Railing
302 Compression Joint Seal	334 Masonry Bridge Railing
303 Assembly Joint with Seal	510 Wearing Surfaces
304 Open Expansion Joint	515 Steel Protective Coating
305 Assembly Joint without Seal	520 Concrete Reinforcing Steel Protective System
306 Other Joint	521 Concrete Coating
330 Metal Bridge Railing	

The MBEI defects used both as damage modes and as attributes in the RBI are shown in Table 2-25 and Table 2-26, respectively.

Table 2-25. The MBEI Defects used as **Damage Modes** in RBI

Defect Number and Name	Defect Number and Name
RCC Deck	
1080 Delamination/Spall/Patched Area	1120 Efflorescence/ Rust Staining
1090 Exposed Reinforcing steel	1130 Cracking (RC and Other)
1190 Abrasion/ Wear (PSC, RCC)	7000 Damage
PSC Superstructure	
1080 Delamination/Spall/Patched Area	1110 Cracking (PSC)
1090 Exposed Reinforcing steel	2240 Loss of Bearing Area
1100 Exposed Prestressing	7000 Damage
Steel Superstructure	
1000 Corrosion	2210 Movement
1020 Connections	7000 - Damage
Substructure	
1000 Corrosion	1140 Decay/Section Loss
1080 Delamination/Spall/Patched Area	4000 Settlement
1090 Exposed Reinforcing steel	7000 Damage
1130 Cracking	

The defects for damage modes and attributes are listed under the bridge elements they are related to. The separate list of the MBEI defects for damage modes and attributes is important because the attributes require ranking which will be discussed later in this chapter. But the damage modes just show how the RBI terminology could be mapped directly to the MBEI defects.

Table 2-26. The MBEI Defects used as **Attributes** in RBI

Defects Number and Name	Defects Number and Name
RCC Deck	
1080 Delamination/Spall/Patched Area	1120 Efflorescence/ Rust Staining
1090 Exposed Reinforcing steel	1130 Cracking (RC and Other)
7000 damage	
PSC Superstructure	
1080 Delamination/Spall/Patched Area	1090 Exposed Reinforcing steel
2350 Debris Impaction	1100 Exposed Prestressing
7000 Damage	
Steel Superstructure	
1000 Corrosion	2310 Leakage
1010 Cracking	2350 Debris Impaction
1020 Connection	7000 Damage
2210 Movement	
Substructure	
1080 Delamination/Spall/Patched Area	4000 Settlement
1130 Cracking	7000 Damage
2310 Leakage	

Table 2-23 - Table 2-26 shown above were summarized from the detailed data collected from each of the eight states’ RAP meetings. The detailed tables are shown in Appendix A. These data provide insight on how and which MBEI elements and defects were discussed in the RBI. In another step, the inspection data for these elements and defects collected by the inspectors in the NCHRP 12-104 project bridge inspection task were analyzed to determine the effect of visual inspection data quality on RBI.

The damage modes for RCC deck, steel and prestressed superstructures, and substructures are listed individually. Each table lists the damage modes exactly as discussed and their severity. The damage mode severity is captured by recording the number of participants indicated a percentage point to cause the failure. For example, in Table A-1, for the damage mode of Spalling/Delamination, two people indicated 30% likelihood, one person 40% likelihood, and two other people 60% likelihood that this damage mode would be the cause of reaching a bridge deck to failure (CR 3 or CS 4). The MBEI equivalent element's number and name is provided for each damage mode in the first column as well.

Similarly, the condition attributes are recorded and shown in tables for RCC deck, steel and prestressed superstructures, and substructures. For each attribute, the number of people indicated each of the four severity ranks (High, Moderate, Low, and Screening) is recorded. For example, in Table A-2, one person indicated that the severity of Efflorescence/Rust Staining to be moderate and four people indicated to be low. The grayed cells in the attribute's tables of Appendix A indicate the severity assigned for assessing the attributes to determine the OF for a damage mode. Cells with a dash in the attribute's tables show that the number of voters was not recorded during the RAP meetings.

2.9 Methods to Calculate the Effect of the Element-level Data Quality on RBI

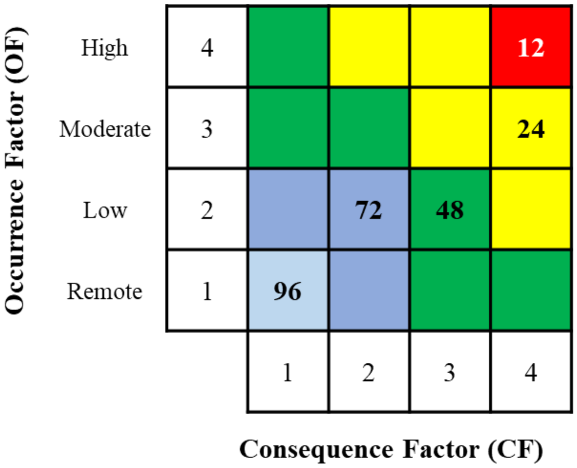
The effect of the quality of element-level data on RBI practice can be accounted for in two different ways: the CS method, and the CS and a quantity threshold method.

In the CS method, for NBEs used as the RBI deck, superstructure, and substructure any amount assigned to the most severe CS would control the attribute rank. For example, if any amount of an element is assigned to CS 4, the element's CS corresponds to the "screening attribute" and the RBI is not applicable for that bridge. Similarly, any amount of an element assigned to CS 3 would control the attribute rank irrespective of its quantity, and so on.

The effect of the inspection quality on RBI can be calculated using the following RBI equation for calculating the OF.

$$X_i = \frac{\sum S_{assigned}}{\sum S_{Possible}} \times 4 \tag{2-1}$$

In the above equation, X_i is the distinct damage mode for deck, superstructure, or substructure that the RAP participants consider to be the most likely one to develop and reach "failure" in the next 72 months. $S_{assigned}$ is the score assigned for an attribute affecting the damage mode X_i positively or negatively, and $S_{Possible}$ is the highest score possible for an attribute. The NCHRP 782 report provides the scores (assigned and possible) for the attributes discussed in the report and for attributes not covered by the NCHRP 782, information about scoring the attributes' criteria is provided. The calculated OF for each damage mode is assigned to one of the OF levels on the risk matrix shown in Figure 2-2 as follows. A number between 0 and equal to 1 corresponds to the “Remote” OF, values greater than 1 and less than and equal to 2 corresponds to the “Low”, values greater than 2 and less than and equal to 3 corresponds to the “Moderate” OF, and OF greater than 3 and equal to 4 corresponds to “High”. Based on the NCHRP 782 Appendix A, an OF equal to 1 corresponds to a failure rate of $\leq 1/10,000$, an OF equal to 2 corresponds to a failure rate 1/10,000 – 1/1000, an OF equal to 3 corresponds to the failure rate of 1/1000 – 1/100, and an OF equal to 4 is categorized as “High” where the failure occurrence is greater than 1/100. The numbers in the colored cells show the inspection interval for a bridge based on the OF and CF.



High	4	🟩	🟨	🟨	12
Moderate	3	🟩	🟩	🟨	24
Low	2	🟦	72	48	🟨
Remote	1	96	🟦	🟩	🟩
		1	2	3	4

Figure 2-2. Risk matrix showing the OF and CF [2]

Based on the above equation and the CS method, the effect of the inspection quality on RBI could be accounted for simply by mapping the MBEI CSs to the RBI condition attributes’ criteria rankings. Table 2-27 maps the MBEI elements' CSs to the RBI criteria given in Table 2-9. In this table, elements assigned to CS 3 are downgraded by 20-point score, and elements in CS 2 are downgraded by 10-point score compared to elements all assigned in CS 1.

Table 2-27. Mapping the CSs to the NCHRP 782 recommendation on scoring the CSs' attributes

RBI Ranking Definition	RBI Score	MBEI CSs
The element is assigned to CS 3 regardless of the amount	20	CS 3
The element is assigned to CS 2 regardless of the amount	10	CS 2
All the element is assigned to CS 1	0	CS 1

In the CS and a quantity threshold method, a threshold quantity is attached to the CS and if both criteria are met, then that would control the attribute rank. For example, if 5% of an element's area or length is assigned to CS 3, then the element would require a higher attribute rank. If the inspection result fulfills both criteria (at least 5% and CS 3) the element would require higher attribute rank, otherwise the CS 3 criterion would not control the attribute. A similar criterion could be established for CS 2. For example, if greater than 15% of an element quantity is assigned to CS 2 then the attribute's rank score is 15 and if less than and equal to 15% of an element's area or length is assigned to CS 2, then the attribute's rank score is 10, otherwise the element is accounted to be in CS 1 and the attribute's criteria rank score is zero. The CS and a quantity threshold method is shown in Table 2-28.

Table 2-28. Mapping the CSs and a threshold quantity to the NCHRP 782 recommendation on scoring the CSs' attributes

RBI Ranking Definition	RBI Score	MBEI CSs
The element is assigned to CS 3	20	At least 5% of the element area or length in CS 3
The element is assigned to CS 2	15	Greater than 15% of the element area or length in CS 2
The element is assigned to CS 2	10	At least 15% of the element area or length in CS 2
All the element is assigned to CS 1	0	CS 1

The threshold quantity with a CS could be decreased or increased for a bridge or family of bridges according to the serviceability level (the higher the serviceability level, the smaller the threshold, and vice versa). Or the threshold quantity might be defined differently for different elements based on the element's importance. Or even, the threshold quantity with a CS could be increased or decreased based on the RBI attributes' importance, e.g., smaller quantity threshold for shear cracking and flexural cracking; and larger quantity threshold for general cracking. Or a smaller quantity threshold for a bridge deck's spalling and delamination and larger quantity for cracking because spalling affects the deck's serviceability more than the cracking.

As an upper bound estimation, when all the attributes' criteria for a bridge are in the highest rank (the OF equation numerator and denominator are equal) each drop in CS assignment for NBEs would shorten the inspection interval by 2 years. Similarly in this case, the IPN would increase two-fold for each drop in CS which requires "enhanced inspection" to detect and correct those defects precisely [14].

In the upper bound case, using the CS method, an attribute could only be assigned to the “High” and “Low” OFs but using the CS and a quantity threshold method an attribute could be assigned to the “High”, “Moderate”, and “Low” OFs. The OF calculation for the above scenario for the CS method is shown below where only the OF equal to 0, 2, and 4 which correspond to the “Remote”, “Low” and “High” OFs is obtained.

$$X_{iCS1} = \frac{0}{20} \times 4 = 0$$
$$X_{iCS2} = \frac{10}{20} \times 4 = 2$$
$$X_{iCS3} = \frac{20}{20} \times 4 = 4$$

The OF calculation for the CS and a quantity threshold method is shown below. By using this method for the upper bound OF calculation, the OF equal to 3 corresponds to the “Moderate” OF.

$$X_{iCS1} = \frac{0}{20} \times 4 = 0$$
$$X_{iCS2,\le 15\%} = \frac{10}{20} \times 4 = 2$$
$$X_{iCS2,>15\%} = \frac{15}{20} \times 4 = 3$$
$$X_{iCS3,5\%} = \frac{20}{20} \times 4 = 4$$

But when the numerator and denominator for the OF equation are not equal, the effect of the condition attributes would not fluctuate as much as illustrated above. That is, the OF for different CS assignments may only differ slightly based on the OF assignment rules and the overall risk model.

Adding another criterion such as the quantity threshold with the CS would only reduce the effect of the inspection quality on RBI as long as the reported quantity is less than the threshold value for a CS, otherwise, the quality would affect the OF similar to the CS method as will be shown below.

In the following section, the effect of the element-level data quality on RBI is reported based on the data collected from Indiana and Michigan, respectively.

2.10 The Effect of the Element-level Data Quality on RBI Practice

The effect of the element-level data quality on RBI practice is analyzed and discussed in this section. The element level data were collected by inspectors from Indiana and Michigan as part of the NCHRP 12-104 “Guidelines to Improve the Quality of Element-level Bridge Inspection Data” project. In Indiana, 14 inspectors inspected two steel bridges and in Michigan 10 inspectors inspected two prestressed concrete bridges for superstructure and substructure and two other bridges’ decks due to the higher traffic volume on the PSC bridges.

As discussed in the preceding section, the RAP data collected from the eight states (two states from the NCHRP 782 project and six states from the RBI pooled fund project) were analyzed to find the MBEI elements and defects discussed in those meetings. Based on the RAP data analysis, the MBEI elements were divided into those discussed as superstructure, deck, and substructure; and those used as attributes. Similarly, the MBEI defects were divided into those used as damage modes, and those used as attributes for the damage modes in RBI. In this section, the data collected from the Indiana and Michigan field trials are analyzed to study the effect of the element-level data quality on RBI. That is, given a bridge is selected for RBI inspection, how the quality of the inspection (condition attributes) for the same bridge completed by different inspectors would affect the inspection interval and scope.

The RBI practice integrates the design, loading, and condition attributes for a bridge and based on this integration, calculates the inspection interval and scope. From those three attributes' categories, the condition attributes should be distinguished in terms of time, inspection type, and inspection detail. In terms of time, the condition attributes consist of the current condition of the element and the condition that would develop in the next 72-months. In terms of inspection type, the condition attributes consist of the conditions that could be captured by routine inspection and those that require special inspection such as; fracture critical inspection, scour inspection, and so on. In terms of inspection detail, the MBEI provides the applicable defects for an element explicitly and some that are not covered by the MBEI may be addressed within the scope of the RBI. For example, based on the MBEI for element 12 – RCC Deck, the defects are Delamination/Spall/Patched Area, Exposed Reinforcing steel, Efflorescence/Rust Staining, Cracking (RCC and Other), Abrasion/Wear (PSC/RC), and Damage. But based on the RBI for RCC Deck, the attributes of delamination, spall, and patched area should be captured separately to fulfill the RBI criteria set for these attributes. Similarly, based on the RBI the crack should be divided into shear cracking, flexural cracking, and general cracking to fulfill the RBI requirements. Therefore, for a bridge or a family of bridges selected for RBI application, defining the condition attributes' details from the beginning would save time and resources by directing the inspection to collect the details in the first place or to avoid collecting the unnecessary data that may not be useful at all. In the next section, the effect of the quality of the element-level data is discussed and reported.

2.11 Indiana Inspection Exercise Result

The effect of the quality of element-level data on RBI is reported below based on the data collected from the two steel bridges in Indiana by 14 inspectors. The data are used to study the effect of the condition attributes collected from the RAP meetings where bridges with steel superstructures were discussed. The data are presented for the two steel bridges separately. The bridges are identified by the Indiana abbreviation and a number: IN1 and IN2.

The MBEI elements inspected for the deck, superstructure, and substructure are shown in Table 2-29. Based on the RAP meeting data, the elements 205, 215, and 234 in Table 2-29 are combined and discussed as a single unit for the bridge substructure.

Table 2-29. The MBEI Elements inspected in Indiana

MBEI Element Number and Name	Name Generally Recorded in a RAP Meeting
12 Reinforced Concrete Deck	RCC Deck
107 Steel Open Girder/Beam	Steel Girder superstructure
205 Reinforced Concrete Column	RCC Substructure
215 Reinforced Concrete Abutment	
234 Reinforced Concrete Pier Cap	

2.11.1 RCC Deck

The attributes for bridge IN1 and IN2 are provided in the upper and lower part of Table 2-30, respectively.

Table 2-30. Condition Attributes for RC Deck with Steel Superstructure

Condition Attributes	Attribute's Criteria Ranking - Number of Inspectors			
	CS 1	CS 2	CS 3	CS 4
Bridge IN1				
12 – RCC Deck				
1080 – Delamination/Spall/Patched Area	-	2/14	5/14	1/14
1120 – Efflorescence/Rust Staining	-	4/14	2/14	-
1130 – Cracking (RC and Other)	-	2/14	5/14	1/14
331 – RCC Bridge Railing				
1120 – Efflorescence/Rust Staining	-	2/14	-	-
1130 – Cracking (RC and Other)	3/14	6/14	2/14	-
7000 – Damage	-	-	2/14	-
Bridge IN2				
12 – RCC Deck				
1080 – Delamination/Spall/Patched Area	1/14	5/14	5/14	-
1120 – Efflorescence/Rust Staining	-	5/14	-	-
1130 – Cracking (RC and Other)	-	4/14	2/14	-
331 – RCC Bridge Railing				
1080 – Delamination/Spall/Patched Area	-	2/14	-	-
1120 – Efflorescence/Rust Staining	-	2/14	-	-
1130 – Cracking (RC and Other)	-	7/14	2/14	-
7000 – Damage	-	1/14	1/14	-

Table 2-30 shows the number of inspectors assigned a condition attribute (MBEI defect) to any one of the four criteria (MBEI CSs). The table is built based on the CS method. That is, if an inspector assigned any quantity of a defect to the worst CS, that assignment would control the OF. For example, for the MBEI defect 1080 (although discussed separately in RBI) one inspector assigned an area of the RC deck to CS 4 which corresponds to the RBI screening criterion. If the remaining quantity of the RC deck is assigned to CS 3, CS 2, or CS 1 by the same inspector, that would not be counted among the number of inspectors who assigned the element to other attribute criteria. Because based on this inspector and the CS method, the RCC deck has already reached the failure (CS 4) and is not qualified for RBI assessment. Similarly, 5/14 inspectors assigned some quantity of the RCC deck to CS 3, and 2/14 inspectors assigned some quantity of the RCC deck to CS 2. Other attributes listed in Table 2-30 could be interpreted similarly.

Sometimes, the sum across each row in Table 2-30 would not equal to the total number of inspectors, because all the inspectors did not report the same defect for an element. The defect detection rate analysis for Indiana inspection exercise will be provided at the end of this section. The defect rate analysis provides insight on how much inspectors can capture the defects defined for an element in the MBEI that corresponds to the RBI damage modes and attributes. The cells with a dash in Table 2-30 indicate that no inspector assigned an attribute to that condition attribute criteria.

The MBEI defects listed for bridge IN1 and IN2 decks in Table 2-30 could be seen in two different ways. First, for the damage modes affected by these defects, these defects act as the condition attributes. Second, according to the MBEI these defects define the “current condition” or “existing condition” of the decks as recorded as an attribute in the RAP meetings. Therefore, the analysis is presented for both cases separately.

The RAP participants in each of the eight states indicated that delamination/spalling damage mode for RCC deck have a higher likelihood to reach failure (CS 4) in the next 72 months as shown in Table A-1 Damage Mode Severity column. Also, the RAP participants listed attributes such as “quantity of spalls/patches”, “delamination patches”, “prior patching”, “delamination/spall to reinforcing steel”, “spalling”, and “delamination” for the delamination/spalling damage mode in Idaho, Oregon, Washington, and Texas. Therefore, for bridge IN1 delamination/spalling damage mode, 1/14 inspector assigned the deck for defect 1080 to CS 4 – the deck has already reached the screening criterion, 5/14 inspectors assigned to CS 3 (higher score), and 2/14 inspectors assigned the deck to CS 2 (lower score). The remaining number of inspectors (6/14) did not detect this defect for the RCC deck.

From the second point of view toward delamination/spalling mentioned before, this defect along with all other defects for RCC deck defines the “current condition” or “existing condition” of the deck which is recorded as an attribute for delamination/spalling damage mode. In this case, according to the CS method, 1/14 inspector assigned defects 1080 and 1130 to “failed” screening attribute, 5/14 inspectors assigned defect 1080 and defect 1130, and 2/14 inspectors assigned defect 1120 to CS 3 (higher score). And 2/14 inspector assigned defect 1080 and defect 1130, and 4/14 inspector assigned defect 1120 to CS 2 (lower score).

The MBEI defect 1130 cracking (RC and Other) in Table 2-30 was listed as an attribute for the delamination/Spalling damage mode in WA, and WI. As seen in this table, for bridge IN1 1/14 inspector assigned this attribute to CS 4 – Screening Attribute, 5/14 inspectors to CS 3, and 2/14 inspectors to CS 2.

The MBEI defect 1120 – Efflorescence/Rust Staining in Table 2-30 captures the same deterioration as described in the NCHRP 782 condition attribute for Corrosion-Induced Cracking, but since the two practices use different wording for the same phenomenon it is reported as it is. This defect is an attribute for RCC members for the Corrosion Damage Mode and in Idaho RAP meeting it was listed as an attribute for delamination/spalling damage mode. Based on this for bridge IN1, 2/14 inspectors assigned this attribute to CS 3, 4/14 inspectors assigned to CS 2, and 8/14 inspectors did not capture this defect.

The inspection data reported for bridge IN2 in Table 2-30 could be interpreted similarly.

2.11.2 Steel Superstructure

The condition attributes affecting the steel superstructure reliability are shown in Table 2-31.

Table 2-31. Condition Attributes for Steel Superstructures

Condition Attributes	**Attributes' Criteria Ranking - Number of Inspectors**			
	CS 1	**CS 2**	**CS 3**	**CS 4**
Bridge IN1				
107 – Steel Open Girder/Beam				
1000 – Corrosion	1/14	2/14	8/14	1/14
515 – Steel Protective Coating				
3410 – Chalking	-	-	1/14	-
3440 – Effectiveness	3/14	2/14	3/14	3/14
302 – Compression Joint Seal				
2310 – Leakage	-	-	1/14	-
2330 – Seal Damage	-	3/14	1/14	1/14
2350 – Debris Impaction	-	2/14	3/14	-
2360 – Adjacent Deck or Header	-	1/14	2/14	1/14
Bridge IN2				
107 – Steel Open Girder/Beam				
1000 – Corrosion	1/14	3/14	7/14	1/14
515 – Steel Protective Coating				
3410 – Chalking	-	1/14	1/14	-
3440 – Effectiveness	-	-	6/14	5/14
302 – Compression Joint Seal				
2310 – Leakage	-	-	1/14	-
2330 – Seal Damage	-	-	4/14	1/14
2350 – Debris Impaction	-	3/14	2/14	1/14
2360 – Adjacent Deck or Header	-	2/14	2/14	-

The upper part of Table 2-31 contains the attributes for bridge IN1 and the lower part contains the attributes for bridge IN2. During the RAP meetings, it was documented that the reliability of the steel superstructure is affected not only by the condition of the superstructure itself, but also by the condition of the steel protective coating (if coated) and the condition of the joints. Therefore, Table 2-31 lists the condition for the steel protective coating and joints as well.

Bridges with steel superstructure were discussed in IL, MO, PA, TX, and WI RAP meetings. In these meetings the damage mode of section loss/corrosion was identified by the RAP participants to have a higher likelihood to reach failure (CS 4) in the next 72 months. For the section loss/corrosion damage mode, the current condition of the steel girder is listed as one of the attributes. Based on the MBEI, the current condition of the steel girder is captured by the defects defined for this element. The inspectors in IN assigned defect 1000 – Corrosion for the steel girder. As shown in Table 2-31, for bridge IN1, 1/14 inspector assigned this attribute to CS 4 – Screening attribute, 8/14 inspectors assigned this element to CS 3, 2/14 inspectors assigned to CS 2, 1/14 inspector assigned this attribute to CS 1, and 2/14 inspector did not assign the corrosion defect for this element.

For coated steel girders, the coating condition is listed as an attribute for the section loss/ corrosion damage in four of the five states. Based on this, for bridge IN1 and IN2 two defects are reported for the Steel Protective Coating (SPC) – Chalking and Effectiveness. For bridge IN1, 3/14 inspectors assigned the SPC to CS 4 which corresponds to the attribute score of “High” with 10-point based on the result of the MBEI elements mapped to the RBI criteria as shown in Table 2-19. 3/14 inspectors assigned the SPC to CS 3 where “limited effectiveness” is available that corresponds to the attribute score of “Moderate” with 5-point; and 2/14 inspectors assigned SPC to CS 2 and 3/14 inspectors to CS 1 which both correspond to the attribute score of “Low” with zero point.

Another attribute affecting the section loss/corrosion damage mode is the joints’ type and condition which the RAP participants indicated by having a “High” to

“Moderate” effect. Based on the design attribute for joint type, the Compression Joint Seal (CJS) present on this bridge is a Closed Joint System as shown in Table 2-4 with a 0-point score – positive attribute with upgrading effect. For the condition attribute of the CJS for bridge IN1, only 1/14 inspector assigned defect 2310 – Leakage in CS 3 for this element where leakage is “Moderate. More than a drip and less than free flow of water” could happen [12]. But the MBEI defect 2330 – Seal Damage in CS 3 and CS 4 where the seal is “punctured or ripped” partially or completely allows the water to reach the superstructure [12]. Therefore, it should be accounted as defect “Leakage”. For defect 2330, 1/14 inspectors assigned the CJS to CS 4 and 1/14 inspector assigned to CS 3 which correspond to the attribute ranking of “High” with 20-point score, and 3/14 inspectors assigned to CS 2 where there is seal abrasion without puncture which corresponds to the attribute ranking of “Low” with 5-point score.

Another MBEI defect captured by the inspectors for CJS is the defect 2350 – Debris Impaction. Based on the RBI criterion for joint condition, CS 2, CS 3, and CS 4 for this defect corresponds to the “Moderate” ranking of the attribute with 15-point score. Based on this, 2/14 inspectors assigned CJS to CS 2, and 3/14 inspectors assigned to CS 3 which both are scored equally with 15-point score.

Another defect captured for CJS is the defect 2360 – Adjacent Deck or Header. This defect in CS 2, CS 3, and CS 4 captures delamination and spall surrounding the joint like the deck’s defect 1080. Therefore, it should be counted toward the reliability of the deck and if it allows water to reach the superstructure, it should also be considered to the reliability of the superstructure. Based on this for bridge IN1, 1/14 inspectors assigned this defect to CS 4 which corresponds to the screening attribute for the deck, 2/14 inspectors assigned to CS 3, and 1/14 inspector assigned to CS 2. The inspection data for bridge IN2 could be interpreted similarly.

2.11.3 Substructure

The condition attributes affecting the substructure reliability are reported in Table 2-32. The upper part of Table 2-32 lists the attributes for the MBEI elements comprising the substructure for bridge IN1 and the lower part lists the MBEI elements comprising the substructure for bridge IN2. Based on the RAP meetings' data analysis, the substructure reliability is not only affected by the substructure condition itself, but also the condition of the joints and bearings. Therefore, the joints' attributes are listed in Table 2-31 and the attributes for the bearings are listed in Table 2-32.

The damage modes of spalling/delamination, cracking, impact, and settlement were indicated to be the most likely damage modes for substructure to develop and reach failure in the next 72 months. Sometimes, the damage modes of spalling/delamination and cracking were combined under a common heading of Corrosion Damages that will be used similarly here as well.

Based on the RAP data for the Corrosion Damage, the attributes are the current condition of the substructure, joint type and condition (leakage), and impact damage. The current condition of the substructure is captured by all the defects defined for a substructure. Based on this, for bridge IN1 RCC Pier Wall, 5/14 inspectors assigned defect 1080 to CS 3 and 1/14 inspector assigned defect 1130 to CS 3. Similarly, for RCC Pier Wall, 4/14 inspectors assigned defect 1080 to CS 2, 2/14 inspectors assigned defect 1090 to CS 2, 2/14 inspectors assigned defect 1130 to CS 2, and for RCC abutment 2/14 inspectors assigned defect 1080 to CS 2, and 7/14 inspectors assigned defect 1130 to CS 2.

In Table 2-32, the CSs for Movable and Fixed Bearings are provided too. The inspectors assigned defect 1000 – Corrosion to these elements. Based on the inspection results, 2/14 inspectors assigned element 311 to CS 4 where based on the MBEI "warrants structural review" [12]. Therefore, this CS corresponds to the RBI screening attribute. 11/14 inspectors assigned element 311 to CS 3 and 1/14 inspectors assigned element 313 to CS 3. Similarly, 1/14 inspectors assigned element 311 to CS 2 and 3/14 inspectors assigned element 313 to CS 2. Finally, 10/14 inspectors assigned element 313 to CS 1.

The inspection data provided for bridge IN2 in Table 2-32 could be interpreted similarly.

Table 2-32. Condition Attributes for Substructures

Condition Attributes	**Attributes' Criteria Ranking - Number of Inspectors**			
	CS 1	**CS 2**	**CS 3**	**CS 4**
Bridge IN1				
210 – RCC Pier Wall				
1080 – Delamination/Spall/Patched Area	3/14	4/14	5/14	-
1090 – Exposed Reinforcing steel	-	2/14	-	-
1130 – Cracking (RC and Other)	-	2/14	1/14	-
215 – RCC Abutment				
1080 – Delamination/Spall/Patched Area	-	2/14	-	-
1130 – Cracking (RC and Other)	2/14	7/14	-	-
311 – Movable Bearing				
1000 - Corrosion	-	1/14	11/14	2/14
313 – Fixed Bearing				
1000 - Corrosion	10/14	3/14	1/14	-
Bridge IN2				
210 – RCC Pier Wall				
1080 – Delamination/Spall/Patched Area	1/14	-	2/14	-
1090 – Exposed Reinforcing steel	1/14	3/14	-	-
1130 – Cracking (RC and Other)	-	5/14	1/14	-
215 – RCC Abutment				
1080 – Delamination/Spall/Patched Area	-	1/14	-	-
1120 – Efflorescence/Rust Staining	-	1/14	-	-
1130 – Cracking (RC and Other)	4/14	6/14	-	-
311 – Movable Bearing				
1000 – Corrosion	-	1/14	11/14	1/14
2220 – Alignment	-	1/14	1/14	2/14
7000 – Damage	-	-	-	1/14
313 – Fixed Bearing				
1000 – Corrosion	-	3/14	-	-

The joint condition attribute discussed before for the steel superstructure applies equally to the substructure Corrosion Damage.

2.11.4 Defect Detection Rate for Indiana Inspection Exercise

In the following paragraph, the defect detection rate is reported for the Indiana bridge inspection exercise. The defect detection rate analysis provides insight on how much inspectors can capture the defects defined for an element in the MBEI that corresponds to the RBI damage modes and attributes. For the attributes, Table 2-30-Table 2-32 provide the detection rate for each attribute (MBEI defect) and each criterion (CS). For each defect, the sum of the numerators in CS 1 – CS 4 should equal to 14 (total number of the inspectors participated in the field trial. The higher the sum of the numerators for each defect across CS 1 – CS 4, the higher the detection rate, and vice versa. The defect detection rate for RCC elements inspected in Indiana is shown in Table 2-33 for bridge IN1 and IN2 separately.

The detection rate for steel superstructure, steel protective coating, joints, and bearings could be calculated by summing along the rows for each attribute presented for deck, superstructure, and substructure tables before.

Table 2-33. Defect Detection Rate for RCC Elements in Indiana

Element No./Name	1080	1090	1120	1130	7000
Bridge IN1					
12 – RCC Deck	8/14	-	5/14	8/14	-
210 – RCC Pier Wall	10/14	2/14	-	3/14	-
215 – RCC Abutment	2/14	-	-	9/14	-
331 – RCC Railing	-	-	3/14	11/14	2/14
Bridge IN2					
12 – RCC Deck	11/14	-	5/14	7/14	-
210 – RCC Pier Wall	2/14	4/14	-	6/14	-
215 – RCC Abutment	1/14	-	1/14	8/14	-
331 – RCC Railing	2/14	-	2/14	9/14	2/14
Note: 1080 – Delamination/Spall/Patched Area; 1090 – Exposed Reinforcing steel; 1120 – Efflorescence/Rust Staining; 1130 – Cracking (RC and Other); 7000 - Damage Cells with a dash emerged when several elements were consolidated to fit in one table and in some cases none of the inspectors assigned the defect to the element.					

2.11.5 Indiana Inspection Exercise Conclusion

This section provides a general conclusion for the RBI deck, steel superstructure, and substructure based on the data collected by 14 inspectors in Indiana.

As mentioned before, individually the MBEI defects could be an attribute for the damage modes affected by, and collectively the defects define the “current condition” or “existing condition” for an element. And current condition is always an attribute for the damage modes that are likely to develop and reach failure in the next 72 months. Defects as attributes are affected by the inspectors’ detection rate (inspectors’ capability to identify and record a defect for an element) and the defect assignment dispersion between CS 1 – CS 4. For example, for the RCC bridge deck none of the three defects were identified by more than 57% of the inspectors. Similarly, for the steel girder 86% of the inspectors identified steel corrosion (defect 1000). As shown in Table 2-30 - Table 2-32, the CS assignment by inspectors is dispersed for each defect and element. The field test showed that there was inconsistency in defects identified by the inspectors. In terms of RBI, these inconsistencies may affect the quality of the risk models that include the presence of specific defects in defining attributes of a family of bridges. Hence, additional training to improve the consistency of defect identification may be needed. Additional analysis of this data can be found in NCHRP 12-104 [36]. The conclusion for the "current condition" attribute of the deck, superstructure, and substructure is provided as follows.

For bridge IN1 RCC deck, 2/14 (14.3%) inspectors assigned the deck to CS 4 which corresponds to the RBI screening attribute – the bridge deck is already failed. 10/14 (71.4%) inspectors assigned the deck to CS 3 (higher criterion score), and 1/14 (7.1%) inspector assigned the deck to CS 2 (lower criterion score).

For bridge IN1 RCC railing, 4/14 (28.6%) inspectors assigned the railing to CS 3, 8/14 (57.1%) assigned the railing to CS 2, and 2/14 (14.3%) inspectors assigned the railing to CS 1.

For bridge IN1 steel girder, 1/14 (7.1%) inspector assigned the girder to CS 4 which corresponds to the RBI screening attribute, 9/14 (64.3%) inspectors assigned the girder to CS 3, 3/14 (21.4%) assigned the girder to CS 2, and 1/14 (7.1%) inspector assigned the girder to CS 1.

For bridge IN1 steel protective coating (SPC), 4/14 (28.6%) inspectors assigned the SPC to CS 4, 4/14 (28.6%) inspectors assigned the SPC to CS 3, and 2/14 (14.3%) assigned the SPC to CS 2 and CS 1.

For bridge IN1 compression joint seal (CJS), 10/14 (71.4%) inspector assigned CJS to CS 3 and CS 4, and 3/14 (21.4%) inspectors assigned CJS to CS 2.

For bridge IN1 substructure, 6/14 (42.9%) inspectors assigned the substructure to CS 3, 6/14 (42.9%) inspectors assigned the substructure to CS 2, and 2/14 (14.2%) inspectors assigned the substructure to CS 1.

For bridge IN1 bearings, 2/14 (14.3%) inspectors assigned bearings to CS 4 which corresponds to the RBI screening attribute, 11/14 (78.6%) inspectors to CS 3, and 1/14 (7.1%) inspector to CS 2.

Table 2-34 summarizes the preceding discussions for the RBI deck, superstructure, and substructure. Assuming a CS assignment for a bridge component to be correct if it is assigned by most of the inspectors to that CS. Based on this assumption, most of the inspectors (72% - 10/14, 9/14, and 11/14) assigned bridge IN1 deck, superstructure, and substructure to CS 3. Relative to the assumed correct answer, about 14% (2/14, 1/14, and 2/14) of the inspectors assigned the components to CS 4 (screening attribute), and another 14% (1/14, 3/14, and 1/14) to CS 2. The total error relative to the assumed correct answer is about 28% based on the Indiana inspectors. The single percentage point (72% and 28%) is reported for the conclusion based on the median of the inspectors' rating for the three components, but the ratios for each component rating is different as seen in Table 2-34.

Table 2-34. Number of inspectors assigned the condition attribute criteria for bridge IN1

Attribute Criteria Ranking	**Deck**	**Superstructure**	**Substructure**
CS 4 (Screening)	2/14	1/14	2/14
CS 3	10/14	9/14	11/14
CS 2	1/14	3/14	1/14
CS 1	-	-	-

2.12 Michigan Inspection Exercise Result

In this section, the inspection results for prestressed concrete (PSC) bridges collected by 10 inspectors in Michigan are provided. These data are used to determine the effect of the condition attributes collected from the RAP meetings where PSC superstructure bridges were discussed. The data are presented for the two PSC bridges separately. Instead of the PSC bridges' decks due to the higher traffic volume, the decks of two other bridges were selected for the deck inspection task. And those decks are reported as the substitute for the deck of the PSC bridges to demonstrate the RBI application for a complete bridge. The bridges are identified by Michigan abbreviation and a number: MI1 and MI2 for the PSC superstructure and substructure and MI3 and MI4 for the two decks, respectively. The MI3 deck is reported as the substitute for the MI1 bridge deck and the MI4 deck is reported as the substitute for the MI2 bridge deck.

The MBEI elements from the Michigan inspection exercise that form the RBI deck, superstructure, and substructure are shown in Table 2-35.

Table 2-35. The MBEI Elements inspected in Michigan

MBEI Element Number and Name	Name Generally Recorded in a RAP Meeting
12 Reinforced Concrete Deck	RCC Deck
109 PSC Girder/Beam	PSC Girder superstructure
205 Reinforced Concrete Column	RCC Substructure
215 Reinforced Concrete Abutment	
234 Reinforced Concrete Pier Cap	

2.12.1 RCC Deck

The condition attributes for bridge MI1 and MI2 substituted decks are shown in the upper and lower part of Table 2-36, respectively. For bridge MI3 and MI4, only the decks and joints were inspected.

Table 2-36. Condition Attributes for RC Deck with PSC Superstructure

Condition Attributes	**Attributes' Criteria Ranking - Number of Inspectors**			
	CS 1	**CS 2**	**CS 3**	**CS 4**
Bridge MI3/ Assumed Deck for MI1				
12 – RCC Deck				
1080 – Delamination/Spall/Patched Area	-	2/10	8/10	-
1120 – Efflorescence/Rust Staining	-	2/10	-	-
1130 – Cracking (RC and Other)	-	4/10	1/10	-
Bridge MI4 / Assumed Deck for MI2				
12 – RCC Deck				
1080 – Delamination/Spall/Patched Area	-	4/10	5/10	-
1120 – Efflorescence/Rust Staining	-	-	1/10	-
1130 – Cracking (RC and Other)	-	1/10	3/10	-

The defects captured for bridge MI1 and MI2 decks as shown in Table 2-36 constitute the "current condition" for the RCC decks. Therefore, these defects altogether function as the "current condition" attribute for the damage modes of the RCC deck, and each defect individually may function as an attribute for a damage mode affected by these defects. For example, based on the RAP meetings data, spalling/delamination damage mode in RCC decks was indicated to have a higher probability to reach failure (CS 4) in the next 72 months. And for this damage mode, the current condition was listed as an attribute in ID, IL, OR, PA, and WI; and cracking, efflorescence/Rust Staining, patching, delamination, spalling, and map cracking are individually listed as attributes in almost all the eight states. Therefore, either collectively as the “current condition” or defect wise the condition of the bridge does affect the attribute criteria. Similarly, the MBEI defect 1120 – Efflorescence/Rust Staining in Table 2-36 captures the same deterioration as that described in the NCHRP 782 condition attribute for Corrosion-Induced Cracking, but since the two practices use different wording for the same phenomenon it is reported as it is. But the unification of the two practices would clarify the inspection practice and the RBI application.

Based on the above discussion, for bridge MI3, 8/10 inspectors assigned defect 1080 to CS 3, and 1/14 inspectors assigned defect 1130 to CS 3; and 2/10 inspectors assigned defect 1080 and defect 1120 and 4/10 inspectors assigned defect 1130 to CS 2.

Sometimes, the sum across each row in Table 2-36 would not equal the total number of inspectors because the inspectors may not collect the same defect for an element. The defect rate for Michigan inspection exercises will be provided later. The defect rate analysis provides insight on how much inspectors can capture the defects defined for an element in the MBEI and used as the attributes in RBI. The cells with a dash in Table 2-36 indicate that based on the CS method no inspector assigned the RCC deck to that attribute criteria.

2.12.2 PSC Superstructure

The inspection results (attributes’ criteria) for bridge MI1 are provided in the upper and the attributes’ criteria for bridge MI2 are provided in the lower part of Table 2-37. In this table, the attributes for the PSC girder and strip and pourable joint seals are provided. The attributes for the PSC girders contain Agency Developed Elements (ADEs) like 845 – Temporary Support for Beam End and 826 – Beam End Deterioration that were collected by the MI inspectors.

The PSC superstructures were discussed in the RAP meetings held in Idaho, Oregon, and Washington. In these meetings, the damage modes that could be captured by the MBEI were listed among other damage modes outside the scope of the MBEI. The damage mode addressed by the MBEI includes strand corrosion, exposed strand, shear cracking (overload), spalling/delamination, cracking, bearing loss, bearing seat problems, impact, strand damage from impact, and reinforcing steel corrosion.

Table 2-37. Condition Attributes for PSC Superstructure

Condition Attributes	**Attributes' Criteria Ranking - Number of Inspectors**			
	CS 1	**CS 2**	**CS 3**	**CS 4**
Bridge MI1				
109 PSC Girder/Beam				
1080 – Delamination/Spall/Patched Area	-	4/10	4/10	-
1090 – Exposed Reinforcing steel	-	-	2/10	-
1110 – Cracking (PSC)	-	2/10	-	-
845 – Temporary Support for Beam End (ADE)	1/10	-	1/10	-
826 – Beam End Deterioration (ADE)	-	-	1/10	-
300 – Strip Seal MI3				
2350 – Debris Impaction	-	5/10	5/10	-
2360 – Adjacent Deck or Header	-	1/10	-	-
301 – Pourable Joint Seal (MI3)				
2360 – Adjacent Deck or Header	3/10	-	2/10	-
Bridge MI2				
109 PSC Girder/Beam				
1080 – Delamination/Spall/Patched Area	-	4/10	5/10	-
1090 – Exposed Reinforcing steel	-	1/10	1/10	-
1110 – Cracking (PSC)	-	1/10	-	-
826 – Beam End Deterioration (ADE)	-	1/10	1/10	-
7000 – Damage	-	2/10	-	-
300 – Strip Seal MI4				
2330 – Seal Damage	-	1/10	1/10	-
2350 – Debris Impaction	-	2/10	6/10	-
2360 – Adjacent Deck or Header	-	2/10	-	-
301 – Pourable Joint Seal (MI4)				
2350 – Debris Impaction	2/10	2/10	1/10	-
2360 – Adjacent Deck or Header	1/10	2/10	2/10	

Based on the RAP data for the damage mode of delamination/spall for PSC superstructures, the attributes are the deck condition, joint type and condition, spalling, exposed strand, existing damage, and the current condition of the PSC. According to the

MBEI, the current condition of the PSC girder/beam is described using the applicable defects and the CSs. Therefore, the inspection result for PSC girder shown could be analyzed individually or could be summed for each CS to be analyzed as the current condition. For bridge MI1 PSC superstructure, 4/10 inspectors assigned defect 1080 to CS 3, 2/10 inspectors assigned defect 1090 to CS 3, and 1/10 inspector each assigned defect 845 and 826 to CS 3. Similarly, 4/10 inspectors assigned defect 1080 to CS 2, and 2/10 inspectors assigned defect 1110 to CS 2. Only 1/10 inspector assigned defect 845 to CS 1.

Another attribute listed for the damage modes of PSC girder is the joint type and condition. According to the RBI criterion for the attribute of Joint Types shown in Table 2-4, the joints for bridge MI1 are closed system – positive attribute with upgrading effect. For the joint condition attribute, the inspectors assigned defect 2350 and 2360 for the strip seal and defect 2360 for the pourable joint seal. Based on the MBEI conditions mapped to the RBI criteria shown in Table 2-11, 5/10 inspectors assigned defect 2350 to CS 3 and 5/10 inspectors assigned to CS 2 for strip seal which corresponds to the "Moderate" attribute ranking. Similarly, 2/10 inspectors assigned element 301 for 2360 – Adjacent Deck or Header to CS 3. Defect 2360 in CS 2, CS 3, and CS 4 captures delamination and spall surrounding the joint like the deck's defect 1080. Therefore, it should be counted toward the reliability of the deck and if it allows water to reach the superstructure, it should be considered to the reliability of the superstructure as well. Based on this, 2/10 inspectors assigned defect 2360 to CS 3, and 3/10 inspector assigned to CS 1.

The inspection data for bridge MI2 PSC girder could be interpreted similarly.

2.12.3 Substructure

The condition attributes affecting the substructure reliability are reported in Table 2-38. The upper part of Table 2-38 lists the attributes for the MBEI elements comprising the substructure for bridge MI1 and the lower part lists the MBEI elements comprising the substructure for bridge MI2. Based on the RAP meetings data analysis, the substructure reliability is not only affected by the substructure condition itself, but also the condition of the joints and bearings. But since the joints were not inspected for the two PSC bridges, it is substituted from the other two bridges where the joints were inspected. The joints' attributes are listed in Table 2-37 and the attributes for the bearings are listed in Table 2-38.

The damage modes of spalling/delamination, cracking, impact, and settlement were indicated to be the most likely damage modes for substructure to develop and reach failure (CS 4) in the next 72 months. Sometimes, the damage modes of spalling/delamination and cracking were combined under a common heading of Corrosion Damages that will be used here as well.

Table 2-38. Condition Attributes for RCC Substructure

Condition Attributes	**Attributes' Criteria Ranking - Number of Inspectors**			
	CS 1	**CS 2**	**CS 3**	**CS 4**
Bridge MI1				
205 – RCC Column				
1080 – Delamination/Spall/Patched Area	1/10	2/10	7/10	-
1130 – Cracking (RC and Other)	-	1/10	1/10	-
234 RCC Pier Cap				
1080 – Delamination/Spall/Patched Area	4/10	5/10	-	-
1130 – Cracking (RC and Other)	-	1/10	-	-
215 – RCC Abutment				
1080 – Delamination/Spall/Patched Area	-	1/10	-	-
1130 – Cracking (RC and Other)	9/10	1/10	-	-
310 – Elastomeric Bearing				
1000 – Corrosion	-	3/10	-	1/10
2230 – Bulging, Splitting, or Tearing	-	2/10	3/10	-
313 – Fixed Bearing				
1000 – Corrosion	3/10	3/10	-	-
3440 – Effectiveness	-	1/10	-	-
Bridge MI2				
205 – RCC Column				
1080 – Delamination/Spall/Patched Area	1/10	5/10	1/10	-
1130 – Cracking (RC and Other)	-	5/10	-	-
234 – RCC Pier Cap				
1080 – Delamination/Spall/Patched Area	1/10	5/10	4/10	-
215 – RCC Abutment				
1120 – Efflorescence/Rust Staining	-	1/10	-	-
1130 – Cracking (RC and Other)	-	9/10	-	-
310 – Elastomeric Bearing				
1000 - Corrosion	-	2/10	-	-
2210 – Movement	-	1/10	-	-
2230 – Bulging, Splitting, or Tearing	1/10	2/10	3/10	1/10
313 – Fixed Bearing				
1000 - Corrosion	2/10	1/10	6/10	-
3440 – Effectiveness	-	1/10	-	-

The condition and design attributes captured by the MBEI and used as the attributes for the Corrosion Damage are the current condition of the substructures, joint condition (leakage), joint types, and impact damage. The current condition of the substructure is captured by all the defects defined for a substructure and the four CSs. Based on this, for bridge MI1 RCC Column, 7/10 inspectors assigned defect 1080 to CS 3 and 1/10 inspector assigned defect 1130 to CS 3. Similarly, for RCC Column, 2/10 inspectors assigned defect 1080 to CS 2, 1/10 inspectors assigned defect 1130 to CS 2; for RCC Cap, 5/10 inspectors assigned defect 1080 to CS 2, 1/10 inspector assigned defect 1130 to CS 2; and for RCC Abutment, 1/10 inspector assigned defect 1080 to CS 2, and 1/10 inspector assigned defect 1130 to CS 2. For RCC Column, 1/10 inspector assigned defect 1080 to CS 1, for RCC Cap, 4/10 inspectors assigned defect 1080 to CS 1; and for RCC Abutment 9/10 inspectors assigned defect 1130 to CS 1.

The joint condition attribute discussed before for the PSC superstructure applies equally to the substructure Corrosion Damage.

In Table 2-38, the CSs for the Elastomeric and Fixed Bearing is provided too. The inspectors assigned defect 1000 – Corrosion, 2230 – Bulging, Splitting, or Tearing, and 3440 – Effectiveness to these elements. Based on the inspection results, 1/10 inspector assigned element 310 to CS 4 which based on the MBEI “warrants structural review” [12]. Therefore, this CS corresponds to the RBI screening attribute. 3/10 inspectors assigned element 310 for defect 2230 to CS 3. Similarly, 3/10 inspectors assigned element 310 for defect 1000 to CS 2 and defect 2230 to CS 2; and 3/10 inspectors assigned element 313 for defect 1000 to CS 2, and defect 3440 to CS 2. Finally, 3/10 inspectors assigned element 313 for defect 1000 to CS 1.

The inspection data provided for bridge MI2 substructure in Table 2-38 could be interpreted similarly.

2.12.4 Defect Detection Rate for Michigan Inspection Exercise

The defect detection rate for RCC elements and PSC girder/beam is shown in Table 2-39 and Table 2-40, respectively. The defect rate analysis provides insight on how capable the inspectors are to capture the defects defined for an element in the MBEI that corresponds to the RBI damage modes and attributes. For the attributes, Table 2-36, Table 2-37, and Table 2-38 provides the detection rate for each attribute (MBEI defect) for each OF category.

Table 2-39. Defect Detection Rate for RCC Elements in Michigan

Element No./Name	**1080**	**1120**	**1130**
Bridge MI1/MI3			
12 – RCC Deck (MI3)	10/10	2/10	5/10
205 – RCC Column	10/10	-	2/10
215 – RCC Abutment	1/10	-	10/10
234 – RCC Pier Cap	9/10	-	1/10
Bridge MI2/MI4			
12 – RCC Deck (MI4)	9/10	1/10	5/10
205 – RCC Column	7/10	-	5/10
215 – RCC Abutment	-	1/10	10/10
234 – RCC Pier Cap	10/10	-	-
Note: 1080 – Delamination/Spall/Patched Area; 1120 – Efflorescence/Rust Staining; 1130 – Cracking (RC and Other). Cells with a dash indicate that none of the inspectors assigned the defect to the element.			

Table 2-40. Defect Detection Rate for PSC Girders in Michigan

Element No./Name	**1080**	**1090**	**1110**	**1130**	**826**	**845**	**7000**
Bridge MI1							
109 PSC Girder/Beam	8/10	2/10	1/10	1/10	1/10	2/10	-
Bridge MI2							
109 PSC Girder/Beam	9/10	2/10	-	1/10	2/10	1/10	2/10
Note: 1080 – Delamination/Spall/Patched Area; 1090 – Exposed Reinforcing steel; 1110 – Cracking (PSC); 1130 – Cracking (RC and Other); 7000 – Damage; 826 – Beam End Damage (ADE); 845 – Beam End Support (ADE). Cells with a dash indicate that none of the inspectors assigned the defect to the element.							

2.12.5 Michigan Inspection Exercise Conclusion

This section provides a general conclusion for the RBI deck, steel superstructure, and substructure based on the data collected by 10inspectors in Michigan.

As mentioned before, individually the MBEI defects could be an attribute for the damage modes affected by, and collectively the defects define the “current condition” or “existing condition” for an element. And current condition is always an attribute for the damage modes that are likely to develop and reach failure in the next 72 months. Defects as attributes are affected by the detection rate (inspectors’ capability to identify and record a defect for an element) and the CS assignment dispersion between CS 1 – CS 4. For example, for the RCC deck, only one of the three defects reported by the inspectors was identified by all the inspectors, but the other two defects were identified by 20% and 50% of the inspectors. Similarly, for the PSC superstructure only one of the five defects was identified by 80% of the inspectors. As shown in Table 2-36 - Table 2-38, the CS assignment is dispersed for each defect and element as well. The field test showed that there was inconsistency in defects identified by the inspectors. In terms of RBI, these inconsistencies may affect the quality of the risk models that include the presence of specific defects in defining attributes of a family of bridges. Hence, additional training to improve the consistency of defect identification may be needed. Additional analysis of this data can be found in NCHRP 12-104 [36]. The conclusion for the "current condition" attribute of the deck, superstructure, and substructure is provided as follows.

For bridge MI1 deck (substituted deck), 8/10 inspectors assigned the deck to CS 3, and 2/10 inspectors assigned the deck to CS 2.

For bridge MI1 PSC superstructure, 7/10 inspectors assigned the girders to CS 3, and 3/10 inspectors assigned the girders to CS 2.

For bridge MI1 joints, 7/10 inspectors assigned the joints to CS 3, and 3/10 inspectors assigned to CS 2.

For bridge MI substructure, 1/10 inspector assigned the substructure to CS 4 which corresponds to the RBI screening attribute, 7/10 inspector to CS 3, and 2/10 inspectors assigned the substructure to CS 2.

Table 2-41 summarizes the preceding discussions for bridge MI1 deck, superstructure, and substructure. Assuming a CS assignment for a bridge component to be correct if it is assigned by most of the inspectors to that CS. Based on this assumption, most of the inspectors (73%) assigned bridge MI1 deck, superstructure, and substructure to CS 3. Relative to this, about 4% of the inspectors assigned the components to CS 4 (screening attribute), and the other 23% of the inspector to CS 2. Based on the MI1 inspection result, the total error relative to the assumed correct answer is about 27%.

Table 2-41. Number of inspectors assigned the condition attribute criteria for bridge MI1

Attribute's Criteria Ranking	Deck	Superstructure	Substructure
CS 4 (Screening)	-	-	1/10
CS 3	8/10	7/10	7/10
CS 2	2/10	3/10	2/10
CS 1	-	-	-

2.13 Conclusions, Recommendations, and Future Work

This chapter presents the effect of the element-level data quality on RBI. To achieve this objective, three tasks were completed. First, the MBEI elements, defects, and CSs were mapped to the RBI criteria to illuminate the boundaries for each practice and found out the gray areas. Second, data collected from the RAP meetings of the eight states participating in the two RBI projects were compiled and analyzed to find out what and how the MBEI elements and defects are used in RBI practice. Third, two methods were presented to calculate the effect of the element-level data quality on RBI. Using these three steps, element level bridge inspection data collected from Indiana and Michigan were analyzed to quantify the effect of the element-level data quality on RBI.

To generalize the conclusion, the effect of the element-level data quality on RBI presented for Indiana and Michigan separately are combined.

For defects as attributes the field tests demonstrated that the defects identified by the inspectors were inconsistent. In terms of RBI, these inconsistencies may affect the quality of the risk models that include the presence of specific defects in defining attributes of a family of bridges.

For defects as “current condition” or “existing condition” attribute the conclusion is as follows. A CS assignment is assumed to be the correct if most of the inspectors assign that CS for a bridge’s element. Based on this assumption, 73% of the inspectors from Indiana and Michigan exercises assigned the bridges’ elements to CS 3 (high ranking score). Relative to the assumed correct answer, about 9% of the inspectors incorrectly assigned the bridges’ elements to CS 4 (RBI screening attribute), and the remaining 18% of the inspectors incorrectly assigned the bridges’ elements to CS 2 (low ranking score). The total error relative to the assumed correct answer is 27%.

Based on the result of the MBEI elements and defects mapped to the RBI criteria, most of the RBI condition attributes relevant to the MBEI, matches the MBEI elements and defects very well. But some instances need clarification or unification to bring consistency in using the MBEI and RBI together.

Detailed recommendations and the future work for the topics discussed in this chapter are provided in the recommendation section of Chapter 5.

3 Understanding Bridge Components' Reliability based on the National Bridge Inventory Data

3.1 Introduction

Bridges deteriorate. The deterioration occurs more easily than its modeling task. Deterioration modeling is one of the components of every bridge management system (BMS) to forecast the condition of a bridge inventory for short-term and long-term resource allocation and its corresponding activities. Condition of a bridge or a bridge inventory can be forecasted by probability and statistical-based, and structural-based deterioration modeling techniques. A general discussion of the techniques is provided below.

3.2 Probability and Statistical Based Deterioration Modeling

Probability and statistical-based deterioration models employ principles of probability and statistics to model deterioration of a bridge or a bridge inventory. Statistical-based deterioration models are either prospective or retrospective.

In prospective deterioration models, parameters and variables of a deterioration model are either calculated using the available data or it is solicited from the "experts" to predict a bridge or a bridge inventory condition. Once the real condition becomes available, it is used to minimize the difference between the predicted and the actual condition using methods like the least squares. In retrospective deterioration models, inspection data for bridges are used to understand bridge performance based on the data. Therefore, the data type is a controlling factor and requires attention to find a statistical method conforming with the data type, otherwise spurious information could be drawn from the data.

Markov chain, a probability-based deterioration model is one of the earliest and most used techniques employed by Pontis, the first bridge management system software in the US [37, 38]. American Association of State Highway and Transportation Officials' (AASHTO) Bridge Management (BrM) software, the renamed version of Pontis is used in about 40 states in the US [39]. In BrM, deterioration modeling is applied for different types of data, in terms of granularity, such as, the component level (deck, superstructure, and substructure) CR and element level condition state (CS) – those that were developed with Pontis itself and the current Manual for Bridge Element Inspection (MBEI) elements. The Markov chain deterioration model is built using bridge initial condition vector and the transition probability matrix (TPM). The TPM is constructed either based on "expert judgment," or using several cycles of inspection data. For the "expert judgment," experts assign a median number of years for a bridge component or element to stay in a given CR/CS and for the latter, bridge inspection data from several years are used to determine the number of years a bridge component/element would stay in a CR/CS. Deterioration probability, as reported separately by Thompson and Sobanjo overestimates the deterioration probability and underestimates the transition times with an error of "1.6 for railings and 3.3 for deck slabs" [40, 41].

To accommodate the probability and statistical models for different conditions and to enhance deterioration models, several studies were completed. The conclusions from these studies are presented as follows. The Markov chain in its original form has a faster deterioration rate in the early years after bridge construction which is the opposite of a structure's real deterioration [42]. To overcome the constant and faster deterioration rate in the early years, Sobanjo proposed a semi-Markov deterioration model [42]. Markov chain deterioration model using transition intensity matrix - to account for the irregular inspection interval is applied for bridges in Portugal [43]. Markov deterioration hazard model applied to find deterioration factors for an RC slab found that length of the span, annual average use of deicing chemicals, the annual average of heavy traffic, structural type, and joints of concrete are factors affecting RC deterioration [25]. Similarly, to reduce human subjectivity on CRs used in the Markov chain, the fuzzy set was applied to evaluate bridge conditions [44].

Other statistical methods such as polynomial regression, Bayesian inference, and Weibull distribution are also applied to model bridge deterioration. The polynomial regression was used to model average bridge CR within CR 9 – 3, and bridge age to predict bridge service life [44]. The Bayesian inference was applied by using the visual inspection (VI) data to forecast the deterioration of bridges [39]. Using the Bayesian inference, it was found that the larger the number of inspection cycles' data for a bridge, the more accurate the deterioration curve [39]. Two separate studies [45, 46] applied Weibull distribution to extract information from bridge components' time in condition rating (TICR) data, the number of years a bridge component stayed in each CR. Both studies compared the goodness-of-fit criteria such as Anderson Darling (AD) statistics among distributions to choose the best fit, but goodness-of-fit tests "are not designed to choose which among these distributions best fit the data" [47]. The papers mentioned that "lower values of AD statistic generally indicate a better fit" and "the better the fit the smaller the AD statistic will be." [45, 46] But none of the papers mentioned how much smaller AD statistics indicate better fit. According to D'Agostino et al., the AD statistic for a two parameter Weibull distribution with both parameters unknown, and a significance level $\alpha = 0.05$ as used by the two papers is 0.757 multiplied by a modification term of $(1+\frac{0.2}{\sqrt{n}})$, where n is the sample size used to calculate the AD statistic[48]. As seen in the modification term, the smallest sample size $n=1$ gives an upper bound for the AD statistics equal to 0.908. Based on this threshold, the AD statistics reported by Nasrollahi et al., is 2 to 27 times of the threshold, and a higher order of magnitude is reported by Sobanjo et al. Similarly, in both studies the p-values reported for fit of the data were less than 0.01, for 31 of the 40 data sets (the rest of the samples were with appropriate AD statistic and p-value but all samples sizes were less than 30) and 15 of the 15 data sets, respectively [45, 46]. That means the p-values were less than 0.05 (α level) which indicates to reject the hypothesis that the sample data "agree with a given distribution as its population" [48]. Therefore, the parameters of the Weibull reported by the above-mentioned papers may not provide accurate information about bridge components performance.

Also, distributional assumptions about the data have reasons like; "compactness of the description for the data" using the distribution parameters, using "useful statistical procedures" such as using the Weibull hazard rate or failure rate for CRs, "characterize the sampling distribution of statistics computed during the analysis and thereby make inferences and probabilistic statements about the unknown aspect of the underlying distribution", and "shed light on the physical mechanisms involved in generating the data"[49]. Based on the last reason, a review of the literature shows that the random processes exhibited Weibull property (yield strength of steel, the size distribution of fly ash, fiber strength of Indian cotton, length of Cyrtoideae, fatigue life of steel, and engine failure) are natural phenomena not interfered by human subjectivity [50, 51]. But bridge CRs are subjective definitions to capture a bridge condition and when inspectors collect the data, results are affected by the subjectivity of the inspector and how accurate a bridge condition conforms with the CR definition. Therefore, from the CR definition to data collection, no inherent performance characteristics of a bridge component contributes to the claim that the data follow a Weibull distribution. A detailed discussion on the nature of the National Bridge Inventory (NBI) CR data and its collection process is provided in the subsequent sections.

3.3 Structural Based Deterioration Modeling

Structural-based deterioration techniques are the second type of deterioration modeling. These techniques employ principles of structural analysis, structural material properties, and interaction between different materials to forecast deterioration and remaining life of a bridge or a bridge component. For example, Nonlinear Finite Element (FE) analysis combined with the visual inspection data has been used to model delaminated bridge deck deterioration [52]. The nonlinear FE analysis found that given equal delamination areas of a bridge deck, “scattered patterns result in more severe degradation in the overall performance of the system” than delamination concentrated in one spot [52]. The FE model could be updated using visual inspection data every two years to monitor the structural performance and to extrapolate the remaining service life of the bridge. [52].

Hybrid deterioration models, the combined versions of probability, statistical, and structural-based deterioration models alsofound in the literature that have been applied for different purposes. In one study, the distribution of pitting corrosion of prestressing strands modeled based on probability was combined with a probabilistic nonlinear FE model for a prestressed concrete girder to estimate “structural strength, time to failure and structural reliability” [53]. Similarly, visual inspection results using Bayesian networks has been used to update the safety and serviceability of bridges in quantitatively and qualitatively within Building Information Modeling (BIM) [54].

Finally, “despite the type of deterioration and the implemented detection method, the basic question that still needs to be answered is how the collected damage data can be used to correlate the impact of existing deteriorating conditions on the structural performance of highway bridges” [52]. The following section discusses the characteristics of CRs and data collection.

3.4 Condition Rating and Data Collection Nature

This section describes the nature of the condition rating (CR) and how the data are collected. The National Bridge Inventory (NBI) database operated by Federal Highway Administration (FHWA) stores data for all public bridges in the US. The data are available online from 1992 to the present. The information stored for each bridge contains 137 parameters, including CR for bridge components – superstructure, deck, and substructure. CRs for bridge components are single digit numbers (0 – failed condition to 9 – excellent condition) used to describe the as-is condition of the component. Table 3-1 provides the qualitative descriptions attached to these ordinal discrete number CRs. In other words, CRs are mutually exclusive or disjointed condition descriptions because each CR definition is unique. In each two-year inspection cycle, an inspector evaluates bridge components against the qualitative descriptions and assigns a CR which conforms to the as-is condition of the component. This task is affected by the subjectivity of the inspector on how closely a bridge's condition conforms with the CR definition.

Bridge deterioration is a gradual and continuous phenomenon throughout a bridge's life. But the way a bridge component CR is recorded is grouped in discrete time intervals. That is, a bridge deteriorates every day during the two-year inspection interval, but a bridge component's condition is recorded only once, therefore the deterioration is subdivided into discrete time intervals between successive inspection cycles [1992, 1994), [1994, 1996), …, [2015, 2017), [2017, ∞) [55]. Also, a bridge component CR may drop to a lower one any time after the last inspection, but it will be recorded and reported only when the next inspection cycle is reached.

Bridge components' CRs are reported to FHWA annually and therefore, every other inspection is just a repetition of the last inspection cycle. For example, a bridge component inspected in 1995 and rated an 8 would have a CR 8 for the 1996 data submission, and this component would be inspected and rated again in 1997 and so on. Therefore, the data acquired from the FHWA database have duplicate CRs for each bridge component assuming the bridge component was not rehabilitated since the last inspection.

Table 3-1. NBI Condition Rating for Bridge Components [56]

Code	Description
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION – no problem 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 action is taken.
1	"IMMINENT" FAILURE CONDITION – major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	FAILED CONDITION - out of service - beyond corrective action.

The qualitative CR descriptions are mutually exclusive – each CR is unique, and a bridge could be in only one of the CRs at any given time. Also, the way the CR is collected can be defined as discrete time intervals. A probability plot for CR data against Weibull distribution illustrate the discrete nature of the CR data. The percent – percent (PP) plot of the theoretical Weibull distribution (y-axis) against TICR for CR 8 for bridge substructures in Missouri is shown in Figure 3-1. To construct the PP plot, the TICR data were used to calculate the parameters of the Weibull distribution. Then the cumulative distribution function (CDF) of the Weibull distribution with calculated parameters are plotted against the ordered TICR data. If the sample data (TICR for CR 8) against the theoretical Weibull quantile function follow the straight line, it shows that the TICR data has come from the Weibull distribution. Even if the data deviated a small amount, say within the confidence interval, a Weibull distribution assumption would describe the data. But Figure 3-1 shows that the TICR for CR 8 does not follow the straight line. Also, Figure 3-1 reveals the discrete nature of the TICR data – the data are stacked in chunks and there is a gap within each chunk of the data. The graph depiction that the data do not follow a Weibull distribution is supplemented with the AD statistic and the p-value calculated from the data. As seen in Figure 3-1, the AD statistic is 71.68 and the p-value is less than 0.01 which indicates to reject the null hypothesis that the data come from a Weibull distribution.

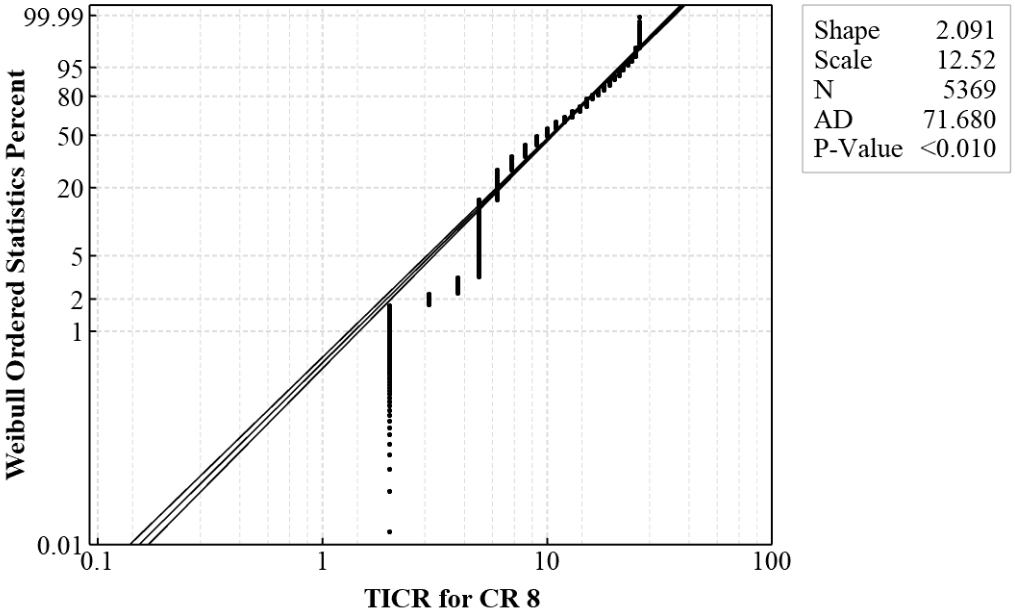


Figure 3-1. PP plot for Weibull distribution and TICR for Missouri Substructures in CR 8

The CR 4 – 8 for deck, superstructures (PSC, RCC, and steel), and substructure of the seven states (175 data sets) were analyzed similarly, and none of the data sets fitted to the Weibull distribution. That is, neither the TICR data type conforms to the Weibull distribution (continuous distribution), nor the data fit to this continuous distribution. Therefore, a statistical method to match the data type and fulfill any statistical assumption was sought. This statistical method is discussed after defining the origin of time for bridge CRs.

3.5 The origin of time for TICR

The NBI CRs for bridge components of the seven states from 1992 – 2017 were included in this study. These data show four different types of bridge records as shown in Figure 3-2. First, bridges for which CR reports are available for each year from 1992 to 2017 (Bridge A). Second, bridges that CR reports begin after 1992, but the record is available as of 2017 inspection cycle (Bridge B). Third are those bridges for which the CR reports are available for a period from 1992 – 2017 (e.g., 1995 – 2015, 1997 – 2013) (Bridge C). Fourth are those bridges for which the CR reports are available beginning 1992 but were discontinued before 2017 (Bridge D).

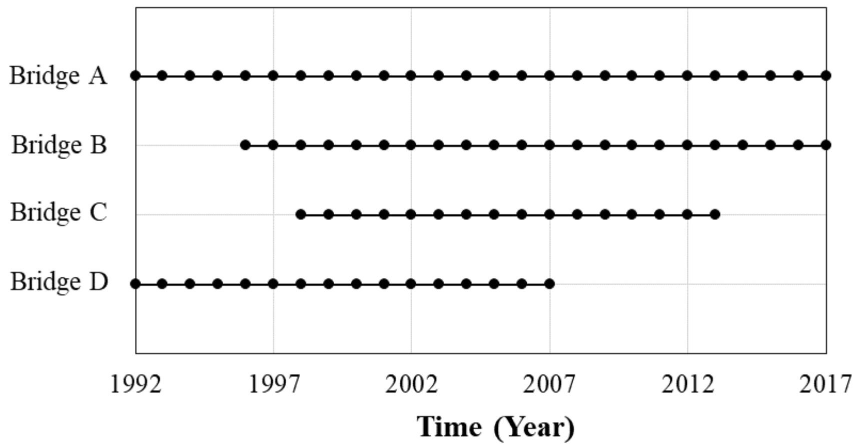


Figure 3-2. Graphic representation for bridges' CR record

As will be discussed later, CRs 4 – 8 are included in the analysis, and those bridges that passed the data preparation steps fall in one of the above four data types. The origin of time for a bridge component TICR analysis is not accounted for, but TICR durations are compared between the bridge components. For example, if a bridge component is reported in CR 8 in 1992 and stayed in this CR for eight years, then it has a TICR of eight years for CR 8. Similarly, if another bridge component is reported in CR 8 in 2000 and stayed in that CR for six years, then it has TICR of six years in CR 8. And the bridge reported in 2000 has shorter TICR compared to the bridge reported in 1992. Therefore, TICRs are compared between bridges, but not the calendar year a bridge component has been in a CR.

If a bridge component is rehabilitated and thus the CR is upgraded, the TICR for the upgraded CR is accounted among bridge components with the same CR. For example, if a bridge deck being several years in CR 4 is renewed and the CR is now recorded 8 for seven years – TICR equal to 7 in CR 8. Then this TICR is analyzed with those bridge decks in CR 8. Therefore, all higher CRs due to the rehabilitation and renovation of bridge components are accounted for in the analysis.

The four bridge record types described above bear special names in reliability or time-to-event analysis – censoring. Censoring happens when a bridge component's CR is recorded later than the actual transition time to that CR, or the last recorded CR is used for the study, but the bridge component would stay in that CR for unknown duration beyond the last recorded time. For example, the NBI data used for this research are those reported during 1992 – 2017; any bridge reported at a given CR in 1992 is left censored, because the exact time it transitioned to that CR is unknown, and any bridge reported in 2017 in a given CR is right censored, because the duration a bridge component would stay in that CR beyond 2017 is unknown. In reliability analysis, CRs not completely observed are identified using the censoring indicator $\delta = 0$ and CRs fully observed (uncensored) are identified using indicator $\delta = 1$. And censored bridge components are excluded from the data analysis. Due to time boundaries (1992 – 2017) for the data, all bridge components' CRs would be either left – or right – censored or if a bridge component is both left and right censored then it is termed interval censored. And this makes the data set of uncensored components extremely small – less than 10% of those analyzed here. To avoid such a huge loss of data utility, a conservative approach was used. Any bridge component with less than five years of similar CRs in the beginning, or the end of the available data for a bridge component were deleted from the data set. And components fulfilling this criterion were assumed not to be censored - CRs were assumed to transition to the next lower CR. In this way, most of the available data was utilized in the analysis. The effect of this modified censoring was previously studied and found to produce data suitable for analysis [46]. The next section provides a short overview of the reliability analysis used in this chapter.

3.6 Reliability Analysis

Survival analysis, known in engineering as reliability analysis or time to failure analysis, employs statistical methods to study the incidence and time of events [57]. Some of these methods first emerged in applications by demographers to study deaths, but nowadays it is applied to both "social and natural sciences, including disease onset, equipment failures, earthquakes, automobile accidents, stock market crashes, revolutions, …" [55, 57]. One of the methods for time-to-failure analysis is the Kaplan-Meier estimator or the product-limit method. Kaplan-Meier method, a nonparametric maximum likelihood estimator of time-to-event data is the most common method for uncensored and only right censored reliability data [57, 58]. The time-to-event for a bridge component could be defined as deteriorating and dropping to the next lower CR.

One way to describe the reliability distribution of a random variable (bridge component duration in a CR) is using the CDF [57]. The CDF for a randomly selected bridge component T is the probability that the bridge component stays in each CR less than or equal to a selected time *t*, written as;

$$F(t) = P(T \leq t) \tag{3-1}$$

The reliability function describes the probability of staying or surviving in each CR beyond time *t*, and written as;

$$S(t) = P(T > t) = 1 - F(t) \tag{3-2}$$

F(t) and *S(t)* are the complement of each other, that is, knowing one of them could be used to calculate the other one.

When the reliability data are uncensored or only right censored, the reliability could be calculated using the Kaplan-Meier estimator by the following equation.

$$S(t) = \prod_{j:t_j \le t} (1 - \frac{d_j}{n_j}) \text{ for } t_1 \le t \le t_k \qquad (3\text{-}3)$$

In the above equation, $S(t)$ is the Kaplan-Meier estimator, d_j is the number of bridge components for which the event occurred (transitioned to the lower CR) at time t_j, n_j is the number of bridge components at risk of the event at the time t_j, and t_1 and t_k are the boundary for *k* distinct event times.

The $\prod$ (capital P) in the above equation means that the survival probability at time t for bridge components is the product of the quantity within the parenthesis calculated for all the events that occurred at times less than or equal to time *t* [57]. The $\prod$ notation can also be interpreted as estimating the conditional probability of surviving to time t_{j+1} given that a bridge component has survived to time t_j [57]. For times less than t_1 (before the first event), $S(t)$ is equal to 1 (all bridge components are staying in a given CR) and $S(t)$ is equal to 0 for the case of no censored data for $t > t_k$ (all bridge components transitioned to lower CR) [57].

The Kaplan-Meier estimator is accompanied by statistics such as the mean, median, confidence interval for the median, standard error of the mean, and hazard rate. The mean, median, and confidence interval for the median of KM can be calculated by methods outlined in Bakker and Brookmeyer et al. [59, 60]. The standard error of the mean known as the Greenwood's formula is the square root of the variance of the estimate and indicates how far the sample mean would be from the true population mean [61, 62]. The standard error of the mean is shown below.

$$se(S(t)) = \{S(t)[1 - S(t)] / n_1\}^{1/2} \tag{3-4}$$

It is assumed there is no censored reliability data in the above standard error equation. That is, all TICRs are observed and bridge components transitioned to the next lower CR during the study. The standard error of the mean can be used to construct a confidence interval for the mean using $\mp 1.96 \cdot se(S(t))$. In the presence of censoring, the mean is not a good measure of the central tendency because the data are "skewed to the right" and the median provides superior statistics for the central tendency [63]. As discussed previously, the data are prepared with a conservative assumption that TICRs are not censored, but any bridge component with less than five years of similar CRs in the beginning or the end of the available data were deleted from the data set. Hence, the mean and the median should provide almost similar measures of the central tendency.

The hazard rate or failure rate, the number of bridge components per unit of time (year) to transition from one CR to the lower one (assuming the rate is constant during the year) could be computed instantaneously, cumulatively, or averaged within a time interval [64]. The instantaneous hazard rate is the number of bridge components transition to lower CR in a unit of time (year) and this quantity varies from one year to the next. This estimate can be computed for $t_j \leq t \leq t_{j+1}$ using the following equation in which $\tau_j = t_{j+1} - t_j$ [62].

$$h(t) = \frac{d_j}{n_j \cdot \tau_j} \tag{3-5}$$

The cumulative failure rate is the integral of the instantaneous hazard rate within the interval of 0 to *t*, and this quantity could be computed as $H(t) = -\ln(S(t))$. Similarly, average failure rate (AFR) could be computed within any two time-intervals as;

$$AFR(t_1, t_2) = \frac{\int_{t_1}^{t_2} h(t)dt}{t_2 - t_1} = \frac{H(t_2) - H(t_1)}{t_2 - t_1} = \frac{\ln S(t_1) - \ln S(t_2)}{t_2 - t_1} \tag{3-6}$$

Since the instantaneous failure rate is variable and changes in each unit of time, the AFR could be used to give a single number to indicate the average number of bridge components in a given CR per year to transition to the lower one during the years the data are available for analysis.

Another statistic reported for reliability analysis of TICR is tests of homogeneity across CRs – bridge components have equal TICR for CRs 4 – 8. The null hypothesis asserts that there is no difference in TICR among CRs 4 – 8 for a bridge component, and the alternate hypothesis asserts that there is a difference among TICR for CRs 4 – 8. Distribution free tests like Log-Rank, and Wilcoxon are reported to demonstrate whether bridge components would stay equally in CRs 4 – 8.

Like the tests of homogeneity across CRs, the KM estimator can be used to study the effect of time-invariant covariates (explanatory variables) on bridge performance such as bridge families with different average daily traffic (ADT), continuous vs. simply supported bridges, bridge families with different environmental conditions and so on. For example, bridge superstructures can be grouped to study the effect of continuous vs.

simply supported bridges or prestressed bridges vs. steel bridges. Or bridges can be grouped based on the construction era (1980 – 2000 vs. 2000 – 2017) by time blocking to study the effect of a higher standard and improved construction material on bridge performance with those of the old standards and lower quality material.

3.7 Data preparation

Data preparation, the first step to get the data ready for analysis is an important part of the data analysis and this section provides a short description for it. Also, this section identifies several issues that affect data quality such as duplicate data for bridges each year, bridge CR continuity due to an extra space or dash in a bridge name, or even bridge name change. Data preparation steps apply equally to all states reported in this chapter, except as mentioned specifically and the steps are numbered in the order that were applied to prepare data for the analysis.

1. The NBI data were acquired from the Federal Highway Administration (FHWA) online database from 1992-2017. The State Code, the first two digits from the Federal Information Processing Standards (FIPS) was used to compile NBI data for each participating state in the research project [65]. The NBI data were compiled and renamed using the state's name abbreviation and inspection year in separate folders. For example, the NBI data file for Missouri bridges in 1992 was renamed as MO1992.txt.

2. For each participating state, only data columns appropriate for data analysis were extracted from the NBI data file, and an "Inspection Year" variable corresponding to the NBI data submission year to FHWA was added for each bridge in the data

set. The variables extracted were Structure Number_008, Year Built_027, Structure Kind_43A, Structure Type_043B, Deck Condition_058, Superstructure Condition_059, and Substructure Condition_060.

3. For every state, all the data from 1992 – 2017 were combined into a single SAS data file. The data were sorted based on the structure number and Inspection Year to collect all inspection cycles for each bridge in an ascending order of the year.

4. The columns' names from each year data set accumulated in the SAS file were deleted because the SAS generated columns' name itself.

5. The structure numbers in STRUCTURE_NUMBER_008 column was made consistent across the available data by removing any blank space, dash, parenthesis, and question mark. Then, all structure numbers were made 15 digit/character long by adding leading zeros for shorter names. After this step, the sorted data were searched for any duplicate bridge inspection for a given year and the duplicates were deleted from the data set.

During the NBI data analysis for Missouri, a discontinuity in CR was observed. The data discontinuity caused bridge components to have only 16 years of NBI data instead of 26 years (1992 – 2017). Therefore, this paragraph only applies to Missouri bridges. The data discontinuity was shared with the Missouri Department of Transportation (MoDOT) and the issue was identified as renaming the Missouri bridges in 2002. MoDOT provided the research team with an Excel file containing the correlation between the old and the new federal bridge IDs. The Excel file was used to match bridge components with the “Old Federal ID” to those with new “Federal ID”. After resolving the CR discontinuity, steps 4 and 5 were applied for Missouri NBI data like other participating states.

After step 5, data preparation for deck, superstructure, and substructure components were completed separately which is discussed in the following sections. The data set generated from the step 5 was used for further data preparation for each component.

3.8 Data preparation for deck, superstructures, and substructure

According to the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges (SI&A) Item 43, the superstructure component is divided into different types, partially shown in Table 3-2. In this table, the detailed subdivision of reinforced concrete (RCC) –, steel –, and prestressed concrete (PSC) – superstructure is provided. The structure type main – 43A is the kind of material and/or design and – 43B is the type of design and/or construction. Post-tensioned concrete is coded as PSC. As shown in Table 3-2, all superstructures fulfilling the subdivisions in Structure Type Main – 43A and – 43B are captured under RCC –, Steel –, and PSC – superstructures. As mentioned previously, these subdivisions could be used as a covariate to study the performance of each bridge type separately, but this was not done for this research.

Table 3-2. SI&A Superstructures' Types and Subdivisions

Bridge Component Material	Structure Type Main (43A)		Structure Type Main (43B)	
	Code	Description	Code	Description
RCC Superstructure	1	Concrete	02	Stringer/ Multi-beam or girder
			03	Girder and Floor beam System
	2	Concrete Continues		
			04	Tee Beam
Steel Superstructure	3	Steel	02	Stringer/ Multi-beam or girder
	4	Steel Continues	03	Girder and Floor beam System
PSC Superstructure	5	Prestressed Concrete	02	Stringer/ Multi-beam or girder
	6	PSC continues	03	Girder and Floor beam System

After dividing the superstructure component to RCC –, steel –, and PSC – data sets, each data set was further processed individually. All substructures and decks for RCC –, PSC –, and steel – superstructures shown in Table 3-2 were prepared separately for TICR analysis. The following paragraphs apply equally to deck, superstructures (RCC, PSC, and Steel), and substructure's TICR data sets.

Only CRs 4 – 8 were selected for data analysis, because a newly constructed bridge would not stay long in CR 9, and bridges with CRs lower than CR 4 are not expected to be in service. Therefore, CR 9, CRs 3, 2, 1, 0, any missing CR, and cells with an "N" for a CR in any given year were deleted from the data sets. After selecting CRs 4 – 8 for each data set, the frequency of inspection cycles for each component was calculated by counting the number of times a bridge’s structure number appeared in a component data set. Any component with less than five records was deleted from the data set. That is, the shortest period for a bridge component to qualify for inclusion in the analysis was five years. This approach was previously verified [46].

If a CR for a component was changed within five years in the beginning and/or the end of the sorted data, those data points were also deleted. This step was completed because a bridge component’s exact transition time to the CR recorded for the first time and the last time in the available data is unknown. That is, if a bridge component CR is recorded 7 in 1992, it is unknown how long it has been in this CR before 1992. Similarly, if a bridge component is rated in CR 6 in 2017, it is unknown how long it will stay in this CR beyond 2017. Therefore, it is assumed that if a bridge component stayed in a given CR for a minimum of five years and then transitioned to the next lower CR, the duration that the bridge component stayed in that CR is fully observed and in reliability analysis terminology, it is not censored as discussed in section 3.5.

As a last step in data preparation for each component, The TICR was calculated for each bridge component by counting the number for each CR as shown in Table 3-3. Bridge components with only one year in each CR was deleted from the data set. This was done because bridges are inspected every two-year but reported annually to FHWA. Being only one year in each CR means that a component might have been rehabilitated just after the last inspection which only occurs for lower CRs – CR 4 or there is an error in the CR data entry. After this step, the TICR data for bridge components were ready for analysis which is discussed in the data analysis section.

Table 3-3. Relation between time in condition ration (TICR) and condition rating (CR)

Year	Superstructure A		Substructure B		Deck C	
	Bridge CR	TICR	Bridge CR	TICR	Bridge CR	TICR
1992	8	10 yrs in CR 8	CR is not reported.		7	9 yrs in CR 7
1993	8				7	
1994	8				7	
1995	8				7	
1996	8				7	
1997	8				7	
1998	8				7	
1998	8				7	
1999	8				7	
2000	8		7	5 yrs in CR 7	6	6 yrs in CR 6
2001	7	8 yrs in CR 7	7		6	
2002	7		7		6	
2003	7		7		6	
2004	7		7		6	
2005	7		6	5 yrs in CR 6	6	
2006	7		6		5	5 yrs in CR 5
2007	7		6		5	
2008	7		6		5	
2009	6	9 yrs in CR 6	6		5	
2010	6		5	5 yrs in CR 5	5	
2011	6		5		CR is not reported.	
2012	6		5			
2013	6		5			
2014	6		5			
2015	6		4	3 yrs in CR 4		
2016	6		4			
2017	6		4			

3.9 Data Analysis Result

The TICR data sets for decks, superstructures (RCC, PSC, and steel), and substructures that fulfilled the data preparation criteria were analyzed using the KM method using the SAS software. The TICR data were analyzed for Idaho, Illinois, Missouri, New York, Pennsylvania, Washington, and Wisconsin.

Table 3-4 shows the number of bridge components and the number of bridge components in each CR for Idaho and Pennsylvania. The number of bridge components is the count of the components, but a bridge component that stayed in several CRs would be counted as many times as the component’s different CRs. Therefore, these counts are different. As seen in Table 3-4, for Idaho, the total number of bridge decks is 2964, the total number of superstructures is 2946 (1627 + 610 + 709), and the total number of substructures is 2918. The reason for the difference between the number of components is that each component is rated individually and some CRs were either out of range of CRs 4 – 8 or missing in the original data files and did not fulfill the data preparation criteria. Table 3-4 is provided to show participating states with the highest and lowest number of bridge components qualified for data analysis.

Table 3-4. Number of Bridge Components for Idaho and Pennsylvania

Bridge Components	**# of Bridge Components**	**# of Bridge Components in each CR**				
		CR 4	**CR 5**	**CR 6**	**CR 7**	**CR 8**
Idaho Bridge Components						
Deck	2964	120	427	1524	1984	631
PSC Superstructure	1627	45	152	624	1015	690
RCC Superstructure	610	33	107	365	402	83
Steel Superstructure	709	32	89	344	436	200
Substructure	2918	157	695	1605	1688	597
Pennsylvania Bridge Components						
Deck	21417	3132	7046	7795	6804	2036
PSC Superstructure	2814	45	335	845	1289	793
RCC Superstructure	6083	1677	2965	1658	777	67
Steel Superstructure	12465	1907	4632	4309	3234	1550
Substructure	21569	3617	8281	7784	6065	1181

The analysis results – the statistics reported for the median TICR, the confidence interval for the median, mean TICR, the standard error for the mean, reliability and deterioration graphs, cumulative hazard rate, and AFR are reported for Idaho as a sample. Then the analysis results for the seven states are used to provide a data driven research conclusion.

The analysis result for bridge components in Idaho is shown in Table 3-5. In Table 3-5, the CRs are listed in the first column, median TICR in the second column, 95 % confidence interval for the median TICR in the third column, mean TICR in the fourth column, and the standard error for the mean TICR in the last column. As discussed in the reliability analysis review section, for right skewed data, the median is the better choice for measuring the central tendency than the mean. As seen in Table 3-5, the mean is always greater than the median, and this was the case for the other six states as well.

Therefore, the median is used for showing the central tendency for bridge components' TICR.

Table 3-5. Kaplan-Meier analysis result for Bridge Components in Idaho

CR	Median TICR	95% CI for Median TICR		Mean TICR	Standard Error for the mean TICR
		Lower CI	Upper CI		
Deck					
4	8	6	8	8.13	0.41
5	8	7	8	9.32	0.28
6	12	12	13	13.36	0.17
7	14	13	14	14.23	0.16
8	10	9	10	11.04	0.22
Prestressed Concrete Superstructure					
4	8	6	11	9.18	0.76
5	9	8	10	10.51	0.48
6	11	10	12	12.58	0.27
7	14	13	14	14.40	0.23
8	13	12	14	13.87	0.26
Reinforced Concrete Superstructure					
4	10	7	12	11.52	1.20
5	10	9	13	11.71	0.63
6	15	14	16	14.12	0.31
7	10	10	12	12.92	0.33
8	10	8	11	11.27	0.66
Steel Superstructure					
4	7.5	6	9	8.62	0.86
5	8	7	10	10.93	0.68
6	9	9	10	12.10	0.38
7	13	12	14	13.59	0.33
8	10	9	11	11.15	0.36
Substructure					
4	7	7	8	9.00	0.47
5	9	9	10	10.64	0.23
6	14	13	15	13.87	0.17
7	12	11	12	13.29	0.17
8	9	9	10	10.71	0.22

The KM analysis, also provides reliability and deterioration graphs that depict bridge components' performance, captured by CRs 4 – 8. The reliability graph shows the probability for a bridge component in each CR (y-axis) to stay in that CR beyond a selected time (number of years) in the x-axis. The reliability graph for Idaho bridge decks is shown in Figure 3-3. For example, the probability for a bridge deck in CR 8 to stay in this CR for more than 10 years (x-axis) is about 50% (y-axis). In other words, given a bridge stayed in each CR for some time (say 15 years), the probability to stay in this CR beyond this time can be read from the reliability graph. In this manner, the reliability graph for a bridge family can be used to determine individual bridge performance and determine the underlying reliability reasons, like better construction quality, lower ADT, mild environment, and so on. Also, as seen in Figure 3-3, the reliability for bridge decks in CR 4 is the lowest (deteriorating faster) compared to those in CR 7, which is the highest (deteriorating slower). This paradigm may not always conform to the CRs order, as observed for the other six states' bridge components, but CRs could be compared with each other this way. The difference in TICR for CRs are reported using the Log-Rank and Wilcoxon homogeneity tests in the analysis output. The tests indicate whether a bridge component's TICR are equal across the CR 4 – 8. These test for Idaho bridge decks were equal to $p < 0.0001$ which indicates different TICRs at $\alpha=0.05$ significance level.

The essence of the reliability graph using the KM estimator is in its rise and run – step graph that conforms with the discrete nature of the CR data collection. Each rise shows a percentage of bridge decks transitioned to the next lower CR (an event) and each run shows the number of years the remaining bridge decks would stay in each CR. Therefore, the higher the rise, the higher the percentage of the bridge decks transitioned to the next lower CR in that TICR, and the longer the run, the higher the TICR for the remaining bridge decks to stay in that CR.

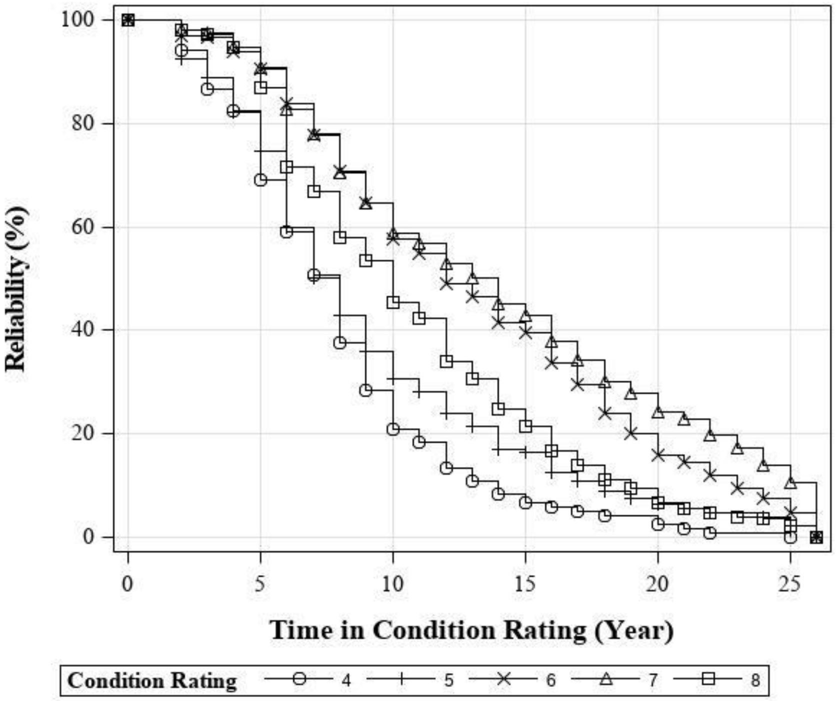


Figure 3-3. Reliability graph for bridge decks in Idaho

The deterioration graph, essentially (1 – reliability) shows the probability for deterioration of a bridge component – the probability that a bridge component would transition to the next lower CR until and including a given number of years. The deterioration graph for bridge decks in Idaho is shown in Figure 3-4. For example, the probability for a bridge deck in CR 5 to deteriorate to CR 4 (lower CR) until and including 10 years (x-axis) is about 70% (y-axis). This can be verified by the reliability graph that shows the probability for bridge decks in CR 5 to stay in this CR beyond 10 years is about 30%.

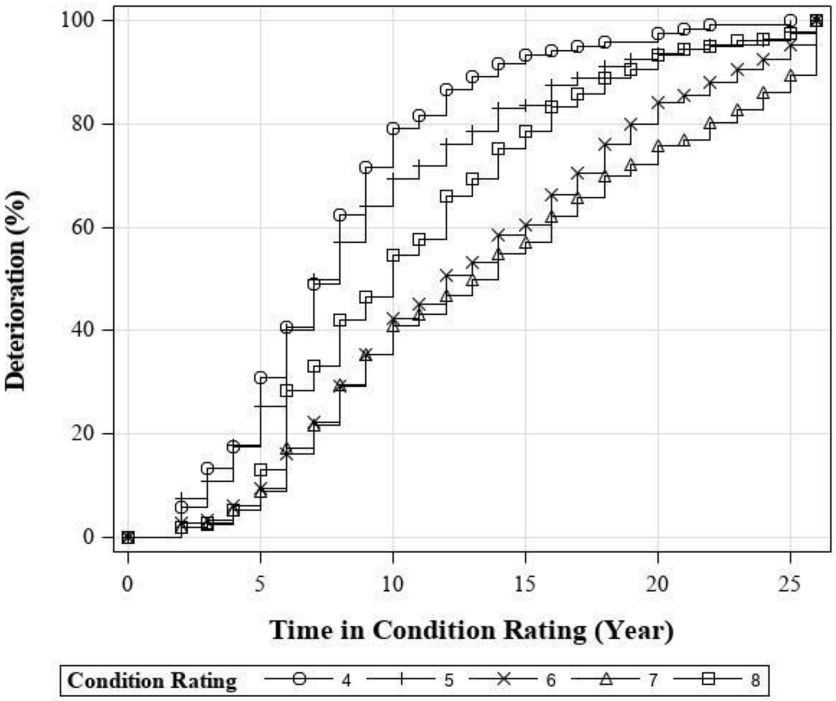


Figure 3-4. Deterioration graph for bridge decks in Idaho

The cumulative hazard graph is shown in Figure 3-5. As seen, all the hazard functions are concave upward which indicates that the failure rate increases with time for all CRs. After TICR 5, the cumulative hazards sharpen for each CR – the highest slope being for CR 4 followed by CR 5, 8, 6, and 7 respectively. As seen in Figure 3-5, bridge decks in CR 4 accumulate more hazard than other CRs – bridge decks in CR 4 deteriorate faster. In other words, a bridge deck in CR 4 would transition to CR 3 during the 25 years 4.79 times to CR 3, provided each time it is renovated to CR 4 and put back to service. A similar interpretation could be made for CR 5 to transition 3.75 times to CR 4, CR 6 3.03 times to CR 5, CR 7 2.25 times to CR 6, and CR 8 3.74 times to CR 7. This type of interpretation of the cumulative hazard rate is called count data interpretation [66].

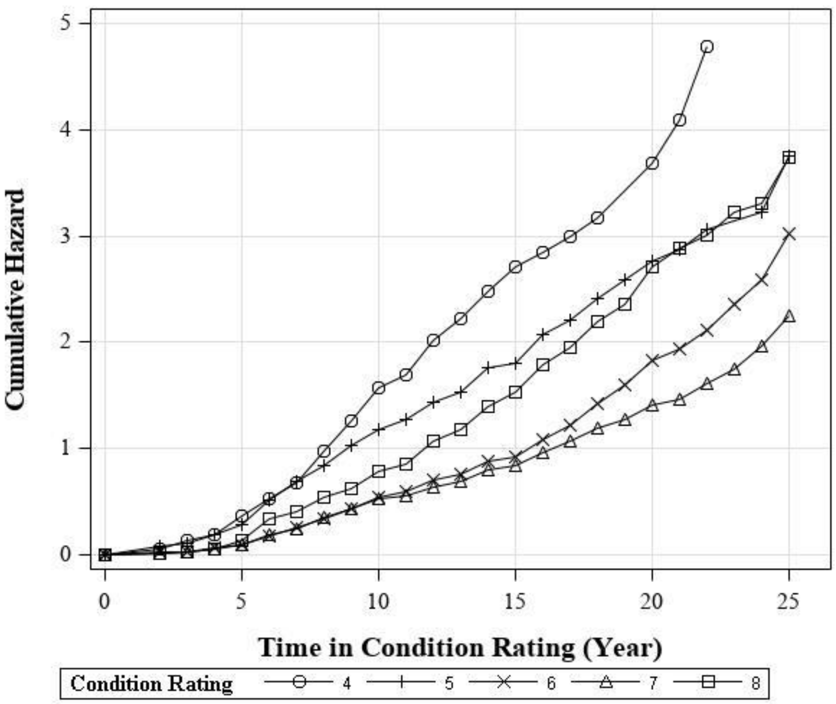


Figure 3-5. Cumulative Hazard graph for bridge decks in Idaho

The analysis using the KM estimator can be updated when CR data for another year become available. Comparison of the two analysis reveal the actual percentage of reliability, deterioration, and failure rate. For example, in 2017, it was assumed that any bridge stayed in the same CR for five years, its TICR was fully observed and the bridge component transitioned to the next lower CR. When the data for 2018 become available, the analysis is rerun by including the 2018 data. And a comparison of reliability, deterioration, and failure rate between the two analysis reveal the trend.

The bridge components' CRs for each state can be viewed in two different ways. First, for a state, the bridge components' CRs passed the data preparation criteria is approximately the population for the bridge families analyzed, and the estimates could be viewed as the true value for the population parameters. Therefore, the median and mean TICRs, and the reliability and deterioration graphs show the performance of the bridge families in those states. Second, for the US bridge population, every state's bridge components' CRs serves as a sample, and the calculated statistics such as the mean and median TICR would serve as an estimate for the US bridge population TICR parameters. In this case, the estimates will vary from one state to another – every state will provide a different estimate for the US bridge population TICR parameters. The varying behavior of the estimates for each state is described by the term called the sampling distribution [67]. Therefore, the statistics for each of the seven states estimate the values for the US bridge population parameters. Given the number of states included in this chapter were more than 30 states, the sampling distribution provides a chance to use the Central Limit Theorem for the median TICR and calculate their asymptotically normal distributions [67]. But, with the seven states, this calculation would result in an unreliable conclusion.

Table 3-6 shows the summary of the TICR analysis for the seven states. Based on the analysis result, the mean TICR was greater than the median TICR for every bridge component which indicates right skewed data. In this case, the median is a better choice for showing the central tendency for TICR. Therefore, the second column in Table 3-6 provides the range for the median TICR for CRs 4 – 8 for each component. The third and fourth columns in Table 3-6 show the highest and the lowest median TICR used to calculate the range. The states for which the highest and the lowest median TICR was observed are listed in the last two columns. Also, if the highest or lowest median TICR was observed in one state only, the number of bridge components for that CR is provided as well. This information is provided to show that the number of bridge components does not affect the statistics. For example, in Table 3-6, for bridge decks in CR 4, the highest median TICR is from Idaho with 120 bridge decks and the lowest median TICR is from Missouri with 1282 bridge decks.

Table 3-6. TICR analysis result for the seven states' bridge components CRs

CR	**Median TICR Range**	**Highest and Lowest Median TICR**		**State Name & # of Bridge Components in CR for Median TICR**	
		Highest	**Lowest**	**Highest**	**Lowest**
Deck					
4	2	8	6	ID (120)	MO (1282)
5	1	8	7	ID (427)	All 6 states
6	5	12	7	ID, WA	PA (7795)
7	9	16	7	WA (3018)	PA (6804)
8	4	10	6	ID, WA	PA (2036)
PSC Superstructure					
4	5	8	3	ID (45)	WA (25)
5	3	9	6	ID (152)	IL (101)
6	5	11	6	ID, MO	IL (360)
7	11	18	7	WA (1924)	PA (1289)
8	8	15	7	WI (2682)	PA (793)
RCC Superstructure					
4	4	10	6	ID (33)	WA (50)
5	3	10	7	ID, MO, WA	PA (2965)
6	8	15	7	ID (365)	PA (1658)
7	10	16	6	WA (636)	WI (194)
8	7	13	6	MO (155)	NY, WA
Steel Superstructure					
4	2.5	7.5	5	ID (32)	WA (31)
5	2	8	6	ID, IL, WI	NY, WA
6	5	12	7	WA (310)	NY, PA
7	6	13	8	ID, IL	NY (5188)
8	4	11	7	MO (4426)	PA, WI
Substructure					
4	1	7	6	ID, IL, PA, WI	MO, NY, WA
5	2	9	7	ID (695)	NY, PA
6	7	14	7	ID (1605)	NY, PA
7	11	18	7	WA (2968)	PA (6065)
8	4	11	7	IL (3216)	PA (1181)

Table 3-6 contains 25 individual comparisons for bridge components (deck, PSC-, RCC-, and steel superstructures, and substructure) in CR 4 – 8 made between the seven states. The result of these comparisons in the last two columns of Table 3-6 shows that bridge components in Idaho has the highest median TICR for 16 of the 25 cases, followed by Washington with 8 of the 25 cases. Similarly, bridge components in Pennsylvania has the lowest median TICR for 14 of the 25 cases followed by New York with 8 of the 25 cases. These comparisons between bridge components' median TICR show two states with higher TICR and two states with lower TICR.

The median TICR ranges shown in Table 3-6 are less than and equal to five years 16/25 times, less than 10 years 6/25 times, and equal and greater than 10 years 3/25 times. Higher range for median TICR is for "CR 7 – Good Condition – some minor problems" which indicate a different interpretation of this CR by the states. But once the bridge components are affected by damage, the states mostly agree on CRs' interpretation, as shown by the smaller median TICR ranges for CRs 4 – 6 in Table 3-6.

Table 3-6, provides another piece of information about the applicability of risk-based inspection to determine bridge inspection interval as well. As seen in this table, the shortest median TICRs are 3 and 5 for CR 4 for PSC –, and steel – superstructures, respectively. The rest of the median TICRs are at least 6, which indicates that bridge components stay in each CR well beyond 24 months inspection interval. Therefore, applying risk-based bridge inspection would optimize and direct the resources to the bridges in need.

Finally, the data from Table 3-6 could be used as a guide for “expert elicitation,” and “engineering judgment,” to provide median TICR for constructing prospective deterioration models, like the TPM for Markov chain.

3.10 Conclusion

This chapter was written with three objectives – introduce a statistical method that conforms to the NBI CR type, provide data driven results to support the applicability of risk-based inspection practice, and provide a data driven benchmark for “expert elicitation,” and “engineering judgment,” used to construct prospective deterioration models. To reach the objectives, NBI CRs and its collection nature were described and supplemented with CR data percent – percent plot to demonstrate that the CR data are discrete and that is why it does not fit to continuous distribution such as Weibull. Then bridge components’ CR data for seven states were analyzed using the KM estimator without masking the data with unmet statistical assumptions. Based on the analysis result, it was shown that the bridge components stay in each CR from six to 18 years. That is, risk-based inspection could be implemented reliably. Furthermore, the TICR calculated for each component could serve as a guide for “expert elicitation,” and “engineering judgment,” used to construct prospective deterioration models, like the transition probability matrix for Markov chain.

4 Determining the Probability of Failure for RBI Occurrence Factor

4.1 Background

The RBI practice combines the occurrence factor (OF) and the consequence factor (CF) to calculate the risk matrix and estimate the inspection interval. Each of the four OF levels has an estimated theoretical probability of failure (POF). For a bridge component in the RBI context, failure is defined as reaching to CR 3. The theoretical POF for the "remote" OF is estimated to be less than 1/10,000, the POF for the "low" OF is estimated to be 1/10,000 – 1/1,000, the POF for the "moderate" OF is estimated to be 1/1,000 – 1/100, and the POF for the "high" OF is estimated to be greater than 1/100 [14]. The component level inspection data for a bridge population could be used to determine a condition based POF. The condition based POF would provide another piece of information about a bridge family performance and reduce the notion of the "one size fit all" estimated POF that may not be the same for a bridge family with better condition bridges compared to an aged and lower condition family. Markov chain, a probability-based prospective deterioration modeling technique was employed to do this.

The Markov chain deterioration model discussed in chapter 3 in detail is built using bridges' initial condition vector (CV) and the transition probability matrix (TPM) as shown below.

$$CV_{Future} = CV_{Initial} \cdot TPM^{n} \tag{4-1}$$

The CVinitial is the current proportion of the bridge components in each CR as below.

$$CV_{Initial} = (\%_8 \quad \%_7 \quad \%_6 \quad \%_5 \quad \%_4 \quad \%_3) \tag{4-2}$$

And the TPM is an *n x n* (square) matrix in which each element is either the probability of staying in a CR or the probability of transitioning to other CRs as shown in matrix 4-3 below.

$$TPM = \begin{pmatrix} P_{8,8} & P_{8,7} & P_{8,6} & P_{8,5} & P_{8,4} & P_{8,3} \\ P_{7,8} & P_{7,7} & P_{7,6} & P_{7,5} & P_{7,4} & P_{7,3} \\ P_{6,8} & P_{6,7} & P_{6,6} & P_{6,5} & P_{6,4} & P_{6,3} \\ P_{5,8} & P_{5,7} & P_{5,6} & P_{5,5} & P_{5,4} & P_{5,3} \\ P_{4,8} & P_{4,7} & P_{4,6} & P_{4,5} & P_{4,4} & P_{4,3} \\ P_{3,8} & P_{3,7} & P_{3,6} & P_{3,5} & P_{3,4} & P_{3,3} \end{pmatrix} \tag{4-3}$$

The TPM elements with the same subscript as shown above are the probability of staying in that CR. The elements with different subscripts show the probability of transitioning from one CR to the next. For example $P_{8,4}$ is the probability of transitioning from CR 8 to CR 4 and $P_{3,7}$ is the probability for a bridge component in CR 3 to be upgraded and put to CR 7 – rehabilitation and repair effect.

The TPM power *n* is the number of inspection cycles desired to predict the future CRs of the bridge family and in the case of RBI application, this is equal to POF – how much of the bridge family will reach CR 3 by the end of the RBI inspection interval.

The TPM could be constructed either by using the Kaplan-Meier reliability and deterioration graphs or plugging the median TICR from the Kaplan-Meier reliability graphs in each CR to the Pontis popular equation - $P_{Stay} = 0.5^{1/T}$, where T is the median TICR for each CR. The following section applies the Markov chain to calculate the POF.

4.2 Determining POF using the Markov chain

As stated in section 4.1, the two elements of the Markov chain are the initial CV and the TPM. These two elements are calculated here for bridge decks in Idaho shown in Table 4-1. In this table, the number of components in each CR is the count of the components stayed in every CR.

Table 4-1. Number of bridge components in each CR for Idaho

Bridge Components	**Total # of Components**	**# of Bridge Components in each CR**				
		CR 4	**CR 5**	**CR 6**	**CR 7**	**CR 8**
Deck	4686	120	427	1524	1984	631
PSC Superstructure	2526	45	152	624	1015	690
RCC Superstructure	990	33	107	365	402	83
Steel Superstructure	1101	32	89	344	436	200
Substructure	4742	157	695	1605	1688	597

To calculate the initial CV for the Idaho bridge decks, the number of bridge components in each CR is divided into the total number of components shown in the second column of Table 4-1.

$$CV_{Deck\_ID} = (0.135 \quad 0.423 \quad 0.325 \quad 0.091 \quad 0.026 \quad 0) \qquad (4\text{-}4)$$

The CV elements – the current proportion of the decks in each CR from CR 8 - 3 are positioned from left to right. As seen, the current CR proportion of the deck in CR 3 is equal to 0 – no bridge deck in CR 3 now.

For the TPM elements, it is assumed that a bridge component would not transition more than one CR in every inspection cycle and the effect of repair is not accounted for.

Based on these two assumptions, only the diagonal elements and one lower CR of the TPM would remain to be completed and the remaining elements are equal to zero.

As mentioned before, the TPM elements could be determined in two ways. 1) The probability of staying in each CR for a specific TICR could be read from the reliability and deterioration graphs generated from the Kaplan-Meier method as shown in Figure 4-1. The Kaplan-Meier method is discussed in Chapter 3. For example, for TICR equal to 6, the reliability for CR 8 is 0.71 and the probability of transition to CR 7 is equal to 0.29. In this manner the TPM is filled out from the reliability graph as shown in matrix 4-5.

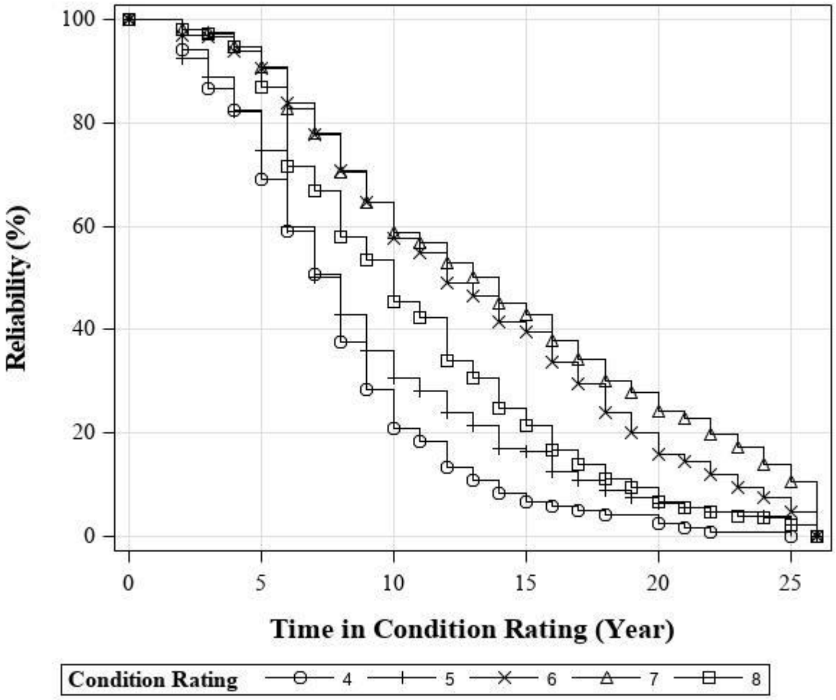


Figure 4-1. Reliability graph for bridge decks in Idaho

$$TPM_{TICR=6} = \begin{pmatrix} 0.71 & 0.29 & 0 & 0 & 0 & 0 \\ 0 & 0.83 & 0.17 & 0 & 0 & 0 \\ 0 & 0 & 0.83 & 0.17 & 0 & 0 \\ 0 & 0 & 0 & 0.59 & 0.41 & 0 \\ 0 & 0 & 0 & 0 & 0.69 & 0.31 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{4-5}$$

2) The other way to calculate the elements of the TPM for Idaho bridge decks is to use the median TICR calculated for decks in each CR and plug it in the Pontis equation - $P_{Stay} = 0.5^{1/T}$ - to determine the probability of staying in a CR. The median TICR for Idaho decks is provided in Table 3-5 and the probability of transitioning to the lower CR is $1 - P_{stay}$. The TPM using the median TICR is given in the matrix 4-6.

$$TPM_{Median\_TICR} = \begin{pmatrix} 0.93 & 0.07 & 0 & 0 & 0 & 0 \\ 0 & 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0 & 0.94 & 0.06 & 0 & 0 \\ 0 & 0 & 0 & 0.92 & 0.08 & 0 \\ 0 & 0 & 0 & 0 & 0.92 & 0.08 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{4-6}$$

As seen in matrix 4-5, and 4-6, there are differences between the elements of the TPM calculated using the two different ways, especially that the probability of staying in a CR for the second method is larger than those calculated by the first method.

To calculate the POF for the bridge decks – the percentage to reach CR 3 after six years - the maximum RBI inspection interval, each TPM could be raised to the power three or six. If it is assumed that the elements of the TMP are filled out using the data collected every two years, therefore the six years inspection interval is reached by raising the TPM to the power of three. In this case the TPM raised to the power of three is shown in matrix 4-7.

$$TPM^{3}_{TICR=6} = \begin{pmatrix} 0.358 & 0.517 & 0.117 & 0.0083 & 0 & 0 \\ 0 & 0.572 & 0.351 & 0.065 & 0.012 & 0 \\ 0 & 0 & 0.572 & 0.26 & 0.147 & 0.022 \\ 0 & 0 & 0 & 0.205 & 0.505 & 0.29 \\ 0 & 0 & 0 & 0 & 0.329 & 0.671 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \qquad (4\text{-}7)$$

Matrix 4-7 shows the proportion of the bridge components in each CR after 3 inspection cycles – 6 years. For example, 2.2% of the decks would reach CR 3 from those initially were in CR 6 – the $P_{6,3} = 0.022$ (the third row and last right column) and so on. To get the proportion of the decks in each CR after six years is to multiply the initial CV to the TPM raised to the power of three. The result of this step is shown below.

$$CV_{6\_years} = (0.048 \quad 0.312 \quad 0.350 \quad 0.132 \quad 0.107 \quad 0.051) \qquad (4\text{-}8)$$

As shown in CV 4-8, 5.1% of the bridge decks would reach CR 3 after six years or three inspection cycles compared to the current proportion of the bridges given in CV 4-4. Certainly, all the population would not be a candidate for the six years inspection interval and therefore a lot of the bridges reaching CR 3 would be inspected in shorter interval and appropriate intervention would be planned to prevent the bridges to reach CR 3.

To predict the proportion of the bridge components reaching CR 3 based on the median number of TICR for each CR and the Pontis equation, matrix 4-6 is raised to the power of three and the result is shown below in matrix 4-9.

$$TPM^{3}_{Med\_TICR} = \begin{pmatrix} 0.804 & 0.186 & 0.00987 & 0.00021 & 0 & 0 \\ 0 & 0.857 & 0.134 & 0.00843 & 0.00024 & 0 \\ 0 & 0 & 0.831 & 0.156 & 0.013 & 0.000384 \\ 0 & 0 & 0 & 0.779 & 0.203 & 0.018 \\ 0 & 0 & 0 & 0 & 0..779 & 0.221 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{4-9}$$

As seen in matrix 4-9 above, the proportion of the bridge decks reaching CR 3 is smaller than those calculated using the matrix directly filled from the reliability and deterioration graphs shown before. The total proportion of the bridge decks reaching CR 3, in this case, is shown in CV 4-10 below. Based on this method, 0.75% of the bridge decks would reach CR 3 after six years which is much lower than the value presented before.

$$CV_{median\_6\_years} = (0.108 \quad 0.388 \quad 0.328 \quad 0.125 \quad 0.043 \quad 0.0075) \tag{4-10}$$

If it is assumed that the bridges are inspected every two years, but the inspection task is distributed over the two years (a portion of the bridge population is inspected every year). In this case, a power of six would provide the prediction for the POF.

4.3 Conclusion

This chapter provided a condition-based way to calculate the POF – the probability for a bridge population to reach CR 3 by the end of the inspection interval determined by RBI – using the Markov chain. Two ways were presented to determine the elements of the TPM – using the reliability and deterioration graphs directly or using the median TICR from the Kaplan-Meier method and the popular Pontis equation. The POF calculation though mere condition-based would provide information about the proportion of the bridge components to reach CR 3 by the end of the inspection interval based on the current condition of the bridge components population. The technique could be applied to each component population (deck, superstructure, and substructure) separately to gain insight about the performance of a bridge inventory. Roughly, if it is assumed that bridges in better CRs (CR 8, 7, and 6) are candidates for the RBI longer inspection interval, then the method would provide information about the proportion of the bridges in better CRs currently candidate for longer inspection interval and how the proportions will change in the future.

5 Conclusions, Recommendations, and Future Work

5.1 Conclusions

The goal of the study is to increase the safety and serviceability of bridges by optimizing the use of inspection resources through a risk-based inspection (RBI) approach.

The objective of the study is to determine the effect of inspection quality on risk-based inspection (RBI). To achieve this objective, the study sought:

1. To determine how inspection variability in condition state (CS) assignment and defect quantification affect the attributes in RBI practice.
2. How inspection variability affects deterioration modeling (Markov, Weibull, and Kaplan-Meier).

To attain the first objective, the research compiled and analyzed the design and condition attributes collected from the reliability assessment panel (RAP) meetings from the eight states participating in the RBI projects, mapped the Manual for Bridge Element Inspection (MBEI) content (elements, defect, and CSs) to the NCHRP 782 RBI criteria, proposed two ways to account for the element-level inspection data quality on RBI, and analyzed the element-level data collected from Indiana and Michigan inspection exercises as part of the NCHRP 12-104 project. It was found that the MBEI defects individually could function as the RBI attributes and altogether as the “current condition” or “existing condition” for a damage mode. For defects as attributes the field tests demonstrated that the defects identified by the inspectors were inconsistent. In terms of RBI, these inconsistencies may affect the quality of the risk models that include the presence of specific defects in defining attributes of a family of bridges.

For defects as “current condition” or “existing condition” attribute the following conclusion could be made. Based on the analysis result of the element-level data, it was found that about 9% of the inspectors incorrectly assigned the bridges’ elements to CS 4 (RBI screening attribute), and 18% of the inspectors incorrectly assigned the bridges’ elements to CS 2 (low ranking score). This conclusion assumes that if most of the inspectors assign the same CS for a bridge’s element, it is the correct CS assignment. Based on this assumption, 73% of the inspectors from Indiana and Michigan exercises assigned the bridges’ elements to CS 3 (high ranking score). Chapter 2 contains the details for this objective.

To attain the second objective, National Bridge Inventory (NBI) data for seven states participating in the Pooled Fund Project “Developing Implementation Strategies for Risk Based Inspection” were prepared and during the analysis it was found that the NBI data do not fit the Weibull distribution. A detailed literature was provided on why the NBI data do not fit the Weibull distribution. The Kaplan-Meier method, an alternative for the Weibull distribution was proposed and the NBI data for the seven states were analyzed using this method. The result of the NBI data showed that the NBI data variability would either shorten or extend the median TICR, the recommended statistics for the skewed NBI data. The median TICR was shortened whenever a bridge component was assigned to a CR where the bridge component had never been in that CR before. That is because a bridge component with a single CR in a population would cause the reliability to drop early on which shortens the median TICR. And the median TICR was extended whenever a component was assigned to a CR where it had been in that CR before. This happens because the incorrectly assigned CR is summed with the previous CR and increases the reliability or extends the median TICR. Chapter 3 contains the details for this objective.

Built on the result of the detailed background information provided in Chapter 3, the Markov chain deterioration model was used to calculate the probability of failure (POF) – the probability to reach CR 3 – for the RBI occurrence factor (OF). This mere condition based POF provides information about the performance of a bridge family based on the bridge family's current condition and guards against the "one size fit all" theoretical foundation available for the four levels of the OF.

5.2 Contributions

This section enumerates the contributions made to attain the research objectives. For determining the effect of the element-level data quality on RBI, the MBEI content (elements, defects, and CS) were mapped to the RBI criteria, RAP data collected from eight states were compiled and analyzed to find how the MBEI content is discussed in an RBI context, and two ways to account for the effect of the element level data on RBI was proposed. Using these three steps, the effect of the element level data quality on RBI was determined using the data collected from Indiana and Michigan inspection exercises as part of the NCHRP 12-104 project. The result and recommendations from this d contribution would bring consistency in RBI application and would reduce agencies' resistance to RBI practice as over 90% of the element-level data currently collected by the states provide input for RBI application. This contribution is provided in Chapter 2.

For determining the effect of inspection data variability on deterioration models the following contributions were made. Using 175 NBI data sets from the seven states it was shown that the NBI data do not fit to Weibull distribution and proposed an alternative method – the Kaplan-Meier method – and analyzed the NBI data for the seven states participating in the Pooled Fund Project "Developing Implementation Strategies for Risk Based Inspection". This contribution put an end to an incorrect statistical distribution that was applied to analyze the NBI data previously – the Weibull distribution. The Kaplan-Meier method is consistent with the NBI data type, determining the reliability and deterioration of a single bridge stayed in a CR for several years is straightforward from the graphs compared to the Weibull distribution.

Built on the result of the detailed background for deterioration models, Markov chain deterioration model was used to calculate the probability of failure (POF) – the probability to reach CR 3 – for the RBI occurrence factor (OF). This contribution provides information about the performance of a bridge family based on the bridge family's current condition and guards against the "one size fit all" theoretical foundation available for the four OF levels. Similarly, if bridges in better CRs (CR 8, 7, and 6) are candidates for RBI longer inspection intervals, determining the POF provides information about the proportion of the bridges suitable for different inspection intervals and how this would change in the future.

5.3 Recommendations

This section provides recommendations for the topics covered in each chapter. The recommendations to enhance the RBI application process and its consistency based on the damage modes and attributes compiled from the eight states' RAP meetings are as follows.

1. The RBI damage modes and attributes could be standardized by using the data collected from the eight states in terms of terminology and extra items could be added if new damage modes or attributes arise. This can be done by printing the damage modes and attributes' tables in large pads and providing extra blank cells to collect new damage modes and attributes during the RAP meetings. Hence, to bring consistency, alike terminology would spread for this practice from the beginning.
2. As shown before for defects as attributes, the defects identified and the CSs assigned by the inspectors was inconsistent. Since defect identification and correct CS assignment is needed to support RBI analysis, inspectors' training to improve the consistency of defect identification and CS assignment will be needed.
3. In several instances, the "current condition" or "existing condition" for an MBEI element is used as an attribute in addition to some defects from the same element used as attributes for a damage mode as well. Based on the MBEI, the current condition is made of the CSs of the defects applicable to the element. Therefore, if a defect is listed as an attribute, it should be scrutinized individually, and its quantity should be accounted for separately. Hence, the defect and its quantity would not be counted twice. This also suggests that collecting MBEI defects would be responsive for both cases whether the "current condition" is needed or the individual defects, but not collecting the MBEI defects would not be the same.

4. Using the MBEI defects' number and name in RBI application would help to differentiate between the MBEI defects used as RBI attributes and those that are RBI attributes.

Based on the MBEI elements and defects mapped to the RBI criteria, the following recommendations are proposed.

1. The screening attribute for the current condition only applies to NBEs. Therefore, the NCHRP 782 Appendix E, S.1 Current Condition Rating should be revised to only include NBEs, but not the BMEs.
2. The RBI condition attributes "C.9 – General Cracking", C.14 – Flexural Cracking", "C.15 – Shear Cracking", and "C.16 – Longitudinal Cracking" refine the MBEI defects 1130 – Cracking (RC and other) and defect 1110 – Cracking (PSC) for RCC and PSC members. Therefore, to apply RBI for determining the inspection interval and scope, agencies should collect the refined RBI attributes than the MBEI defects.
3. The RBI condition attributes "C.10 – Delamination", "C.11 – Presence of Repaired Areas", and "C.12 – Presence of Spalling" refine the MBEI defect – 1080 – Delamination/Spall/Patched Area. But, since MBEI is a standard, the three RBI attributes could be coalesced into one attribute (MBEI defect) for data collection and RBI application purposes. This recommendation favors MBEI over the individual RBI criteria because the MBEI defect 1080 captures the development process of this defect accurately. That is, cracks would cause delamination, delamination would ultimately become spalls, and spalls would be repaired or patched.

4. The RBI condition attribute “C.21 – Presence of Active Corrosion” recommends differentiating between active and inactive corrosion which is generalized by the MBEI defect 1000 – Corrosion. Therefore, to apply RBI for determining the inspection interval and scope, agencies should differentiate between active and inactive corrosion and collect it according to the criteria set by the RBI.
5. The RBI condition attribute “C.8 – Corrosion-Induced Cracking” captures the same deterioration as the MBEI defect 1120 – Efflorescence/Rust Staining. But the RBI condition attribute “C13 – Efflorescence/Staining” duplicates the same deterioration. This RBI duplication is like the MBEI recommendation to record the most severe defect in case two defects occur on the same spot. For example, if Cracking and Efflorescence/Rust Staining occur on the same spot, the most severe one is preferred to be recorded. More information is needed on how these two RBI deterioration types are different and if not different, their unification would bring consistency in data collection and RBI application.
6. The RBI condition attribute “C.22 – Presence of Debris” addresses the detrimental effect of debris accumulation and stays for a long time on “flanges, bearings, connections, or other details” that causes accelerated deterioration [14]. This attribute only corresponds to the MBEI defect 2350 – Debris Impaction for joints. Therefore, to apply RBI for determining the inspection interval and scope, agencies should collect this RBI attribute for other bridge elements as well. Though, it is an MBEI applicable defect for joints only. Or debris impaction could be added as a new defect for all other MBEI elements in which debris accumulation is possible.

Using the Kaplan-Meier method is recommended for NBI data analysis. This method is consistent with the NBI data type, the data are not masked with unmet statistical assumptions, and straightforward in determining the reliability and deterioration of a bridge stayed in a CR for several years.

Using the Markov chain is recommended to calculate a data driven POF for the four levels of the OF. The data driven POF reduces the notion of “one size fits all” theoretically provided for the four OF levels. This calculation would provide information about the proportion of the bridges qualified for different RBI inspection intervals and how it will change in the future as well.

5.4 Future work

This dissertation presented three distinct contributions: the effect of element-level data quality on RBI, the Kaplan-Meier method to analyze the NBI data, and the Markov chain to calculate the POF for the OF levels. The future research for the effect of the element-level data quality on RBI is to apply the recommendations provided in the above section to improve the RBI application and practice and conduct more bridge inspection exercises in other states to validate the conclusion made about the effect of the element level data quality on RBI. Especially, more training is needed for inspectors to improve defect identification and CS assignment for supporting the RBI. The future research for the Kaplan-Meier method is to analyze the NBI data for other states to determine the reliability and deterioration patterns. The future work for calculation of the POF consists of verifying whether the TPM using the reliability and deterioration graphs provides accurate POF or using the median TICR in the Pontis equation.

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Appendix A Reliability Assessment Panel Data Tables

This appendix contains the detailed reliability assessment panel (RAP) data for damage modes and attributes used in Chapter 2 and are shown in the following tables.

Table A-1. RCC Bridge Deck Damage modes

Table A-2. RCC Bridge Deck Attributes

Table A-3. PSC Superstructure Damage modes

Table A-4. PSC Superstructure Attributes

Table A-5. Steel Superstructure Damage modes

Table A-6. Steel Superstructure Attributes

Table A-7. Substructure Damage Modes

Table A-8. Substructure Attributes

These data provide insight on how and which MBEI elements and defects were discussed in the RBI. In another step, the inspection data for these elements and defects collected by the inspectors in the NCHRP 12-104 project bridge inspection task were analyzed to determine the effect of visual inspection data quality on RBI.

The damage modes for RCC deck, steel and prestressed superstructures, and substructures are listed individually. Each table lists the damage modes exactly as discussed and their severity. The damage mode severity is captured by recording the number of participants indicated a percentage point to cause the failure. For example, in Table A-1, for the damage mode of Spalling/Delamination, two people indicated 30% likelihood, one person 40% likelihood, and two other people 60% likelihood that this damage mode would be the cause of reaching a bridge deck to failure (CR 3 or CS 4).

The MBEI equivalent element’s number and name is provided for each damage mode in the first column as well.

Similarly, the condition attributes are recorded and shown in tables for RCC deck, steel and prestressed superstructures, and substructures. For each attribute, the number of people indicated each of the four severity ranks (High, Moderate, Low, and Screening) is recorded. For example, in Table A-2, one person indicated that the severity of Efflorescence/Rust Staining to be moderate and four people indicated to be low. The grayed cells in the attribute tables of Appendix A indicate the severity assigned for assessing the attributes to determine the OF for a damage mode. Cells with a dash in the attribute tables show that the number of voters was not recorded during the RAP meetings.

Table A-1. RCC Bridge Deck Damage modes

Defect Number and Name in the MBEI	**Defects name documented in RBI RAP meeting**	**Damage mode severity percentage (# of people)**									**State**
		10	20	30	40	50	60	70	80	90	
Damage modes											
1080 Delamination/Spall/Patched Area	Spalling/ Delamination			2	1		2				ID
7000 Damage	Impact	1									ID
1190 Abrasion/ Wear (PSC, RCC)	Wear/Abrasion (screening)	1									ID
1130 Cracking (RC and Other)	Cracking	1	1	3							ID
1120 Efflorescence/ Rust	Efflorescence / Rust Staining	2	2								ID
1090 Exposed Reinforcing steel	Exposed Reinforcing steel without corrosion	3	1								ID
1080 Delamination/Spall/Patched Area	Spall/ Delamination			2	3						IL
1130 Cracking (RC and Other)	Cracking /leaching				4						IL
	Long cracking	3	1								IL
	Soffit – Map / Saturation		3	2							IL
1090 Exposed Reinforcing steel	Section loss on Reinforcing steel			3							IL
7000 Damage	Impact damage										IL
1080 Delamination/Spall/Patched Area	Spalling		1	1			1	1		1	WI
1080 Delamination/Spall/Patched Area	Delamination			1		1					WI
1130 Cracking (RC and Other)	Cracking	2	1	2	1						WI
1190 Abrasion/ Wear (PSC, RCC)	Abrasion	1									WI
1090 Exposed Reinforcing steel contains section loss not corrosion	Corrosion / Section loss		2								WI
Railing has several types and for each condition is defined using the applicable defects and quantities	Railing deterioration		1								WI
1130 Cracking (RC and Other)	Cracking		1		4	1					PA

Defect Number and Name in the MBEI	Defects name documented in RBI RAP meeting	Damage mode severity percentage (# of people)									State
		10	20	30	40	50	60	70	80	90	
Damage modes											
1080 Delamination/Spall/Patched Area	Spalls				1	4	1				PA
1080 Delamination/Spall/Patched Area	Delamination	1	1	4							PA
1190 Abrasion/ Wear (PSC, RCC) only for abrasion	Rutting / Abrasion	2									PA
1080 Delamination/Spall/Patched Area, 1090 Exposed Reinforcing steel	Spalling/ Delamination / Reinforcing steel Corrosion				2		1	3			WA
1090 Exposed Reinforcing steel	Exposed reinforcing steel	4	1	1							WA
	Rutting	3	1								WA
1080 Delamination/Spall/Patched Area	Spalling										OR
	Rutting										OR
1130 Cracking (RC and Other)	Cracking										OR
1080 Delamination/Spall/Patched Area	Spalling										TX
	Punch through										TX
1130 Cracking (RC and Other)	Cracking										TX
1080 Delamination/Spall/Patched Area	Delamination										TX

Table A-2. RCC Bridge Deck Attributes

Defect Number and Name in the MBEI	Defects name documented in RBI	Attributes' Ranking				State
		H	M	L	Scr	
Attributes						
1120 Efflorescence/ Rust Staining	Efflorescence / Rust Staining		1	4		ID
This is defined using 4 CS and applicable defects in MBEI	Joint Condition (Header, adjacent)	1	1	2		ID
This is defined using 4 CS and applicable defects in MBEI	Current Condition	5				ID
This is quantified in CS 2 and 3 of MBEI	Quantity of Spalls/ Patches	5				ID
This is defined using 4 CS and applicable defects in MBEI	Existing Condition	4	1			IL
7000 damage	Impact damage			2		WI
1130 Cracking (RC and Other)	Cracking	1	4			WI
7000 damage	Plow damage			1		WI
This is defined using 4 CS and applicable defects in MBEI	Current Condition	1				WI
This is defined using 4 CS and applicable defects in MBEI	Current Condition	6				PA
1130 Cracking (RC and Other)	Cracking		4	2		WA
1080 Delamination/Spall/Patched Area	Prior Patching	5	1			WA
This is defined 4 CSs and the applicable defects.	Current Condition		-			WA
Wearing Surface is an element and it has its applicable defects	Asphalt Patches / Bad Patches	4	2			WA
1130 Cracking (RC and Other)	Cracking/ spalling		-			OR
1080 Delamination/Spall/Patched Area	Delamination Patches	-				OR
1090 Exposed Reinforcing steel	Reinforcing steel Corrosion	-				OR

Defect Number and Name in the MBEI	**Defects name documented in RBI**	**Attributes' Ranking**				**State**
		H	**M**	**L**	**Scr**	
Attributes						
This is defined 4 CSs and the applicable defects.	Current Condition	4-H, 4-M				OR
1130 Cracking (RC and Other)	Cracking	-				OR
510 – Wearing Surfaces	Wearing Surface Type		-			OR
1080 Delamination/Spall/Patched Area	Delamination	-				TX
1130 Cracking (RC and Other)	Cracking (Map dense)		-			TX
1080 Delamination/Spall/Patched Area	Map Cracking	-				TX
1080 Delamination/Spall/Patched Area	Delamination / Spall to bar		-			TX
1130 Cracking (RC and Other)	Existing Cracking	-				TX
1080 Delamination/Spall/Patched Area	Spalling	-				TX
1080 Delamination/Spall/Patched Area	Delamination	-				TX
1130 Cracking (RC and Other)	Cracking (Map dense)		-			TX

Table A-3. PSC Superstructure Damage modes

Defect Number and Name in the MBEI	**Defects name documented in RBI RAP Meeting**	**Damage mode severity percentage (# of people)**							**State**
		10	20	30	40	50	60	70	
Damage modes									
7000 Damage	Impact	1	2			1	1	1	ID
1080 Delamination/Spall/Patched Area	Spalling/ Delamination			2		1	2	1	ID
	Overload Shear Cracking	2	3	1					ID
1100 Exposed Prestressing	Exposed Strand (screening)	1			1				ID
1100 Exposed Prestressing	Strand Corrosion		3	1	1				WA
7000 Damage	Strand Damage from Impact		1			3	1		WA
1110 Cracking (PSC)	Cracking	1	1	1					WA
1080 Delamination/Spall/Patched Area	Spalling/ Delamination	2		1					WA
2240 Loss of Bearing Area, ADE	Bearing Loss/ Beam end damage	2		1					WA
1110 Cracking (PSC)	Cracking (Shear)								OR
1100 Exposed Prestressing	Strand Corrosion								OR
7000 Damage	Impact								OR
1090 Exposed Reinforcing steel	Reinforcing steel Corrosion within the Span								OR
	Bearing Seat Problems								OR

Table A-4. PSC Superstructure Attributes

Defect Number and Name in the MBEI	Defects name documented in RBI RAP Meeting	Attributes' Ranking				State
		H	Mode	Low	Scr	
Attributes						
It is defined by 4 CSs and the applicable defects	Deck Condition			3	3	ID
MBEI	Joint Type	2	-	3		ID
It is defined by 4 CSs and the applicable defects	Joint Condition	5	1			ID
It is defined by 4 CSs and the applicable defects	Current Condition	6	-		<=cr 4	ID
300 Strip Seal Expansion Joint	Expansion Joint	6			-	WA
1080 Delamination/Spall/Patched Area	Spalling / Exposed Strand	3	1	2		WA
2350 Debris Impaction	Debris Impaction	2	3	2		WA
7000 Damage	Existing Damage	-				OR
It is defined by 4 CSs and the applicable defects	Current Condition	-				OR
7000 Damage	Existing Damage	-				OR
1100 Exposed Prestressing, 1090 Exposed Reinforcing steel	Corrosion	-+				OR
2350 Debris Impaction	Debris			-		OR
CS 4	Failed Joint	-				OR
7000 Damage	Existing Damage	-				OR

Table A-5. Steel Superstructure Damage modes

Defect Number and Name in the MBEI	Defects name documented in RBI RAP Meeting	Damage mode severity percentage (# of people)								State
		10	20	30	40	50	60	70	80	
Damage modes										
1000 Corrosion	Section loss/ Corrosion						1	2	2	IL
	Cracking - Fatigue	2	1	1						IL
7000 - Damage	Impact	3	2							IL
1000 Corrosion	Corrosion/ section loss				1		1		4	MO
	Fatigue cracking	2	2	1						MO
7000 Damage	Impact	4		1						MO
1020 Connections	Connection Issues									MO
2210 Movement	Movement / Bearing	1								MO
1000 Corrosion	Corrosion / Section loss					1	3	2		WI
7000 Damage,	Impact / distortion	1		3	1					WI
	Fatigue Cracking	5	1							WI
1020 Connection	Connection Damage	2								WI
1000 Corrosion	Section loss / Corrosion					3	1	3		PA
	Fatigue Cracking	1	3	2	1					PA
7000 Damage	Impact	2	5							PA
1000 Corrosion	Section loss									TX
7000 Damage	Impact									TX
	Fatigue Cracking									TX
	Fire Damage									TX
	Deflection overload									TX

Table A-6. Steel Superstructure Attributes

Defect Number and Name in the MBEI	Defects name documented in RBI RAP Meeting	Attributes' Ranking				State
		H	Mod	Lo	Scr	
Attributes						
515 Steel Protective Coating	Coating	5				IL
300 – 306 Joints	Joints	4	1			IL
It is defined by 4 CSs and the applicable defects.	Deck Condition	1	3	1		IL
7000 Damage	Existing damage (Section loss)		5			IL
	Expansion joint / jointless - leaking	5				MO
It is defined by 4 CSs and the applicable defects.	Coating Condition	3	1			MO
1000 Corrosion	Corrosion – damaged area	2	4			MO
1010 Cracking	Current condition (cracks)	3	2		1	MO
7000 Damage, 7000, …	Impact Damage / Collision / Fire				-	MO
1020 Connection	Connection Issues	-				MO
2210 Movement	Movement Bearing				-	MO
It is defined by 4 CSs and the applicable defects.	Joint condition	6				WI
515 Steel Protective Coating	Coating / Weathering	2	4			WI
ADE	Embedded girder ends		2	1		WI
It is defined by 4 CSs and the applicable defects.	Current Condition	2	4			WI
515 Steel Protective Coating	Coating Type	5	1			PA
300 – 306 Joints	Joint Type	5				PA
2310 Leakage	Joint Condition leaking / not leaking	5				PA

Defect Number and Name in the MBEI	Defects name documented in RBI RAP Meeting	Attributes' Ranking				State
		H	Mod	Lo	Scr	
Attributes						
It is defined by 4 CSs and the applicable defects.	Coating Condition	4	2			PA
It is defined by 4 CSs and the applicable defects.	Current Condition	3	2			PA
1020 Connection	Connections / Multi plate		3	3		PA
1000 Corrosion	Existing section loss	-				TX
2350 Debris Impaction	Debris			-		TX
2310 Leakage	Joint Leakage			-		TX
1000 Corrosion	Corrosion			-		TX
7000 Damage	Existing Impact	-				TX
1010 Cracking	History of previous cracking		-			TX
	Load Posting	-				TX
7000 Damage	Previous overload damage	-				TX

Table A-7. Substructure Damage Modes

Defect Number and Name in the MBEI	**Defects name documented in RBI RAP Meeting**	**Damage mode severity percentage (# of people)**								**States**
		10	20	30	40	50	60	70	80	
Damage modes										
1080 Delamination/Spall/Patched Area	Spalling / Delamination									IL
1130 Cracking	Cracking									IL
1090 Exposed Reinforcing steel	Reinforcing steel Loss									IL
7000 Damage	Impact Damage									IL
4000 Settlement	Settlement									IL
1000 Corrosion, 228 Timber Pile,225 Steel Pile	Pile Corrosion, Exposed Timber piles, Exposed Steel Piles									IL
1080 Delamination/Spall/Patched Area, 1090 Exposed Reinforcing steel	Spalling / Reinforcing steel corrosion				1		3	1	1	WA
7000 Damage	Impact Damage	2	3							WA
4000 Settlement	Settlement 360/361	2	1	1	1					WA
1080 Delamination/Spall/Patched Area	Spalling / Delamination			2		3	1			WI
1130 Cracking	Cracking – settlement, shear, loading	2	3							WI
1140 Decay/Section Loss, 1000 Corrosion	Section loss – timber, steel	1		2	2					WI
7000 Damage	Impact	1								WI
4000 Settlement	Settlement	2	1							WI
4000 Settlement	Settlement									OR
1080 Delamination/Spall/Patched Area	Corrosion damage (Spalling/ delamination/ cracking / rust)									OR
1080 Delamination/Spall/Patched Area	Corrosion Damage (Spalling, delamination/ cracking/ rust)									TX

Defect Number and Name in the MBEI	**Defects name documented in RBI RAP Meeting**	**Damage mode severity percentage (# of people)**								**States**
		10	20	30	40	50	60	70	80	
Damage modes										
4000 Settlement	Settlement									TX

Table A-8. Substructure Attributes

Defect Number and Name in the MBEI	Defects name documented in RBI	Attributes' Ranking				State
		H	Mod	Lo	Scr	
Attributes						
300 - 3006	Joint above					IL
1130 Cracking	Settlement Cracks CS 2, 3	-				IL
	Mass concrete consolidation cracking					IL
300 - 3006	Joint Above					IL
7000 Damage	Barge impact					IL
7000 Damage	Vehicle impact					IL
300 - 306	Deck Joints					IL
7000 Damage	Debris Damage					IL
It is defined by 4 CSs and the applicable defects.	Existing Condition					IL
300- 3006	Deck Joints	5	1			WA
7000 Damage	Debris Damage	2	3	1		WA
It is defined by 4 CSs and the applicable defects.	Existing Condition	3	2	1		WA
310 Elastomeric Bearing, has 4 CSs and Several defined defects	Substructure Elastomeric Bearing Failure (CS2, CS3, CS4)					WA
1080 Delamination/Spall/Patched Area	Spalling/Reinforcing steel Corrosion	-				WA
2310 Leakage	Leakage joints	4	2			WI
	Subsurface condition	-				OR
4000 Settlement	Existing settlement	-				OR
It is defined by 4 CSs and the applicable defects.	Current Condition	-				OR
7000 Damage	Existing damage	-				OR

Defect Number and Name in the MBEI	**Defects name documented in RBI**	**Attributes' Ranking**				**State**
		H	**Mod**	**Lo**	**Scr**	
Attributes						
It is defined by 4 CSs and the applicable defects.	Failed Joint	-				OR
7000 Damage	Existing Damage	-				TX
It is defined by 4 CSs and the applicable defects.	Current Condition	-				TX
It is defined by 4 CSs and the applicable defects.	Joint Condition	-				TX
	Subsurface condition	-				TX
4000 Settlement	Existing settlement	-				TX

Appendix B SAS Code for NBI Data Analysis

This appendix contains the complete SAS code for the NBI data preparation and analysis using the Kaplan-Meier method. For each piece of the code, a detailed comment is provided on how to use the code or manipulate the code to fit a specific need. Each complete line of the SAS code ends with a semicolon (;) and each comment block always in green color starts with a combination of a forward slash and an asterisk (/*) and ends with an asterisk and a forward slash (*/). Single line comments could be inserted by putting the asterisk (*) at the beginning and ending the comment line with a semicolon (;).

The most important thing in running the SAS code is to make sure the folder location to read the data and the data file name is specified correctly.

The codes are divided into small chunks to easily follow, execute, and debug in case of an error. To generate the reliability graphs available in Appendix C, the following steps should be followed. From the SAS menu, select Tools >ODS Graphics Designer. From the Graph Gallery, select Analytical >Survival.

```
/*This appendix provides the code for NBI data preparation and analysis.
The code is provided in the order that was applied.The following code
reads Idaho NBI data downloaded from the FHWA website from the
ID_Original_Data folder. The NBI data files in the ID_Original_Data
folder are named as ID1992, ID1993, ...,ID2017. In reading the NBI data
files, only the variables required for the data analysis are extracted
from the original NBI data files and an "Inspection_Year" variable
corresponding to the year the NBI data were submitted to the FHWA are
added to every bridge. The varibles extracted are listed in the "keep"
section of the code. The files with specific variables are written in
another folder - ID_Added_Inspection_Year.
To use the code for other states or to include more data in the
analysis, the code should be revised to accommodate such changes. To
apply the code for other states, the Idaho abbreviation (ID) in the
following code should be replaced with state's name abbreviation.
To include more number of years, the NBI data file should be added to
the ID_Original_Data folder and the code section %runner(yy=1992)
should be revised to include the new number of years at the end of the
code after %runner(yy=2017). Also, the folder to read the NBI data
and the folder to write the data output should be specified clearly.
*/

%Let path =D:\Idaho\ID_Original_Data;
%macro runner(yy=);
    proc import datafile ="D:\Idaho\ID_Original_Data\ID&yy..txt"
        dbms=dlm out=work.test (keep = STRUCTURE_NUMBER_008
        YEAR_BUILT_027 STRUCTURE_KIND_043A STRUCTURE_TYPE_043B
        DECK_STRUCTURE_TYPE_107 DECK_COND_058 SUPERSTRUCTURE_COND_059
        SUBSTRUCTURE_COND_060);
        delimiter =",";
        getnames=yes;
        guessingrows=1000000;
    run;
    data Work.ID&yy.ay;
        set test;
        Inspection_year=&yy.;
    run;
    proc export data=Work.ID&yy.ay replace
        outfile ="D:\Idaho\ID_Added_Inspection_Year\ID&yy..txt"
        dbms=dlm;
        delimiter=",";
    run;
proc datasets lib=work;
delete test;
quit;
```

```
%mend runner;
%runner(yy=1992);
%runner(yy=1993);
%runner(yy=1994);
%runner(yy=1995);
%runner(yy=1996);
%runner(yy=1997);
%runner(yy=1998);
%runner(yy=1999);
%runner(yy=2000);
%runner(yy=2001);
%runner(yy=2002);
%runner(yy=2003);
%runner(yy=2004);
%runner(yy=2005);
%runner(yy=2006);
%runner(yy=2007);
%runner(yy=2008);
%runner(yy=2009);
%runner(yy=2010);
%runner(yy=2011);
%runner(yy=2012);
%runner(yy=2013);
%runner(yy=2014);
%runner(yy=2015);
%runner(yy=2016);
%runner(yy=2017);

/*The NBI data with the "Inspection_Year" variable are combined into a
signle SAS file named ID_NBI_Data. This file would be used for the sub-
sequent data preparation and analysis.*/

libname xx 'D:\Idaho\ID_Added_Inspection_Year';
proc import datafile='D:\Idaho\ID_Added_Inspection_Year\*.txt'
dbms=dlm out=xx.ID_NBI_Data replace;
delimiter =',';
getnames=yes;
guessingrows=1000000;
run;

/*The SAS ID_NBI_Data file is sorted based on the STRUCTURE_NUMBER_008
and Inspection_Year to collect every bridge's data in once place and
order them in an ascending fashion.*/

libname xx 'D:\Idaho\ID_Added_Inspection_Year';
proc sort data=xx.ID_NBI_Data;
```

```
by STRUCTURE_NUMBER_008 Inspection_Year;
RUN;

/*The SAS data file contains the column names from every year NBI
data. These names are deleted from the data file by the following code.
The data file is saved with a new name ID_NBI_Data02. */

data xx.ID_NBIB_Data02;
set xx.ID_NBI_Data;
if STRUCTURE_NUMBER_008 = "STRUCTURE_NUMBER_008" then delete;
run;

/* During the data preparation, it was found that some of the bridge IDs
was changed by an extra space, dash, parathesis, or other non-digit and
non-character identifiers through the years. These changes resulted in
discontinued data, because SAS counts the bridge IDs different if not
exactly the same. Therefore, the following code removes any space, dash,
(), and ? in order to make the bridge IDs consistent. The data file is
saved as ID_NBI_Data03. */

data xx.ID_NBI_Data03;
set xx.ID_NBI_Data02;
new_STRUCTURE_NUMBER_008 = compress(STRUCTURE_NUMBER_008, '- () ?');
drop STRUCTURE_NUMBER_008;
rename new_STRUCTURE_NUMBER_008=STRUCTURE_NUMBER_008;
run;

/* STRUCTURE_NUMBER_008 is set to 15 digits/character long by adding
leading zeros to make the bridge IDs look aesthitically pleasant.
The data file is saved as ID_NBI_Data04.*/

data xx.ID_NBI_Data04;
set xx.ID_NBI_Data03;
length new_STRUCTURE_NUMBER_008 $15;
new_STRUCTURE_NUMBER_008='000000000000000';
substr(new_STRUCTURE_NUMBER_008, 16-length(STRUCTURE_NUMBER_008))=
        STRUCTURE_NUMBER_008;
drop STRUCTURE_NUMBER_008;
rename new_STRUCTURE_NUMBER_008=STRUCTURE_NUMBER_008;
run;

/* The data file columns were missed up during the last two steps,
therefore the columns are reordered using the "retain" in the
following code. The file is saved as ID_NBI_Data05. */

data xx.ID_NBI_Data05;
```

```
retain STRUCTURE_NUMBER_008 YEAR_BUILT_027 STRUCTURE_KIND_043A
        STRUCTURE_TYPE_043B DECK_COND_058 SUPERSTRUCTURE_COND_059
        SUBSTRUCTURE_COND_060 Inspection_Year;
set xx.ID_NBI_Data04;
run;

/* During the data preparation, it was found that some bridges had
duplicated inspection data. The duplicated data were removed from
the data set by the following code using the STRUCTURE_NUMBER_008
and Inspection_year variables. The data file was saved as
ID_NBI_Data06. */

proc sort data=xx.ID_NBI_Data05 nodupkey out=xx.ID_NBI_Data06;
by STRUCTURE_NUMBER_008 Inspection_year;
run;

/* In order to have the count of the number of bridges the data pre-
paration started, the varibale "Censor" is defined based on the year a
bridge is built - YEAR_BUILT_027>1800. All bridges would have a column
"Censor = 1", and this would be used to count the number of bridges.
This step uses tthe ID_NBI_Data02 where only the column headings were
removed from the data set. The bridge counts file is saved as
ID_NBI_Data_BridgeCount. */

data  xx.ID_NBI_Data_BridgeCount;
set  xx.ID_NBI_Data02;
 if YEAR_BUILT_027 >1800  then Censor=1;
 else Censor=0;
run;

/*The following code counts the number of bridges (distinct bridge IDs)
and the count is saved in ID_Bridge_Count file. */

proc freq data=xx.ID_NBI_Data_BridgeCount;
tables STRUCTURE_NUMBER_008*Censor/ out=xx.ID_Bridge_Count;
run;
quit;

/*The following code separates reinforced concrete (RCC) bridges - concr
and concrete continuous based on the STRUCTURE_KIND_043A criteria. In th
step, the ID_NBI_Data06 file is used to select the RCC bridges. The RCC
bridges are saved in ID_NBI_RCC file. */

libname xx "D:\Idaho\ID_Added_Inspection_Year";
data xx.ID_NBI_RCC;
set xx.ID_NBI_Data06;
```

```
if 0<STRUCTURE_KIND_043A <=2;
run;

/* The following code separates steel bridges - steel and steel continuc
based on the STRUCTURE_KIND_043A criteria. In this step, the ID_NBI_Datє
file is used to select the steel bridges. The steel bridges are saved ir
ID_NBI_Steel file. */

data xx.ID_NBI_Steel;
set xx.ID_NBI_Data06;
if  2<STRUCTURE_KIND_043A<=4;
run;

/* The following code separates prestressed (PSC) bridges - prestressed
and prestressed continuous based on the STRUCTURE_KIND_043A criteria. Ir
this step, the ID_NBI_Data06 file is used to select the steel bridges.
The steel bridges are saved in ID_NBI_PSC file. */

data xx.ID_NBI_PSC;
set xx.ID_NBI_Data06;
if  4<STRUCTURE_KIND_043A<=6;
run;

/* The following code separates Other bridges - bridges other than RCC
PSC, and steel based on the STRUCTURE_KIND_043A criteria. In this step,
the ID_NBI_Data06 file is used to select Other bridges.  The Other
bridges are saved in ID_NBI_Other file. */

data xx.ID_NBI_Other;
set xx.ID_NBI_Data06;
if STRUCTURE_KIND_043A>6 or STRUCTURE_KIND_043A=0;
run;

/*The following code selects RCC superstructures using STRUCTURE_TYPE_04
for RCC equal to 02, 03, and 04 and superstructure condition rating usir
SUPERSTRUCTURE_COND_059 = 4 - 8. In this step, any bridge with
SUPERSTRUCTURE_COND_059 cell that is missing or with an 'N' are deleted
from the data set. Also, in this step DECK_COND_058 and
SUBSTRUCTURE_COND_060 columns are removed from the data set. For this
step the data file ID_NBI_RCC is used and The RCC superstructures are
saved in ID_NBI_RCC_Super file. */

data xx.ID_NBI_RCC_Super;
set xx.ID_NBI_RCC;
if 2<=STRUCTURE_TYPE_043B<=4;
if 4<=SUPERSTRUCTURE_COND_059<=8;
```

```
drop DECK_COND_058 SUBSTRUCTURE_COND_060;
if missing(SUPERSTRUCTURE_COND_059) then  delete;
if SUPERSTRUCTURE_COND_059='N' then  delete;
run;

/*The following code selects steel superstructures using
STRUCTURE_TYPE_043B for steel equal to 02, 03, and 04 and superstructure
condition rating using SUPERSTRUCTURE_COND_059 = 4 - 8. In this step,
any bridge with SUPERSTRUCTURE_COND_059 cell that is missing or with an
'N' are deleted from the data set. Also, in this step DECK_COND_058 and
SUBSTRUCTURE_COND_060 columns are removed from the data set. For this
step the data file ID_NBI_Steel is used and The steel superstructures
are saved in ID_NBI_Steel_Super file. */

data xx.ID_NBI_Steel_Super;
set xx.ID_NBI_Steel;
if 2<=STRUCTURE_TYPE_043B<=3;
if 4<=SUPERSTRUCTURE_COND_059<=8;
drop DECK_COND_058 SUBSTRUCTURE_COND_060;
if missing(SUPERSTRUCTURE_COND_059) then  delete;
if SUPERSTRUCTURE_COND_059='N' then  delete;
run;

/*The following code selects PSC superstructures using STRUCTURE_TYPE_04
for RCC equal to 02, 03, and 04 and superstructure condition rating usin
SUPERSTRUCTURE_COND_059 = 4 - 8. In this step, any bridge with
SUPERSTRUCTURE_COND_059 cell that is missing or with an 'N' are deleted
from the data set. Also, in this step DECK_COND_058 and
SUBSTRUCTURE_COND_060 columns are removed from the data set. For this
step the data file ID_NBI_PSC is used and the PSC superstructures are
saved in ID_NBI_PSC_Super file. */

data xx.ID_NBI_PSC_super;
set xx.ID_NBI_PSC;
if 2<=STRUCTURE_TYPE_043B<=4;
if 4<=SUPERSTRUCTURE_COND_059<=8;
drop DECK_COND_058 SUBSTRUCTURE_COND_060;
if missing(SUPERSTRUCTURE_COND_059) then  delete;
if SUPERSTRUCTURE_COND_059='N' then  delete;
run;

/*The following code selects bridge decks for RCC, PSC, and steel
superstructures that fulfill the STRUCTURE_KIND_043A and _043B Criteria.
The CR for DECK_COND_058 = 4 - 8 is selected and any bridge deck CR cell
with missing data or an 'N' is deleted from the data file. For this step
ID_NBI_Data06 file is used and the data is saved in ID_NBI_Deck file. */
```

```
data xx.ID_NBI_Deck;
set xx.ID_NBI_Data06;
if 1=<STRUCTURE_KIND_043A<=6;
if 2<=STRUCTURE_TYPE_043B<=4;
/* Delete Deck with 9 <conditin_rating< 4, missing data and unavailable
data. */
if 4=<DECK_COND_058<=8;
if missing(DECK_COND_058) then  delete;
if DECK_COND_058='N' then  delete;
/*Gives concrete and conrete continous code of 1,
steel and steel con. code 3 and psc and psc cont. code of 5. */
if  1=<STRUCTURE_KIND_043A<=2 then newSTRUCTURE_KIND_043A=1;
if  3=<STRUCTURE_KIND_043A<=4 then newSTRUCTURE_KIND_043A=3;
if  5=<STRUCTURE_KIND_043A<=6 then newSTRUCTURE_KIND_043A=5;
drop STRUCTURE_KIND_043A;
rename newSTRUCTURE_KIND_043A=STRUCTURE_KIND_043A;
drop  YEAR_BUILT_027 SUBSTRUCTURE_COND_060 SUPERSTRUCTURE_COND_059;
run;

/*The following code orders the deck data columns as shown in the "retai
section of the code and rewrites the file with the same name- ID_NBI_Dec
*/

data xx.ID_NBI_Deck;
retain STRUCTURE_NUMBER_008 STRUCTURE_KIND_043A STRUCTURE_TYPE_043B
        DECK_COND_058 Inspection_year;
set xx.ID_NBI_Deck;
run;

/*The following code selects bridge substructures for RCC, PSC, and stee
superstructures that fulfill the STRUCTURE_KIND_043A and _043B Criteria.
The CR for SUBSTRUCTURE_COND_060 = 4 - 8 is selected and any bridge subs
structure CR cell with missing data or an 'N' is deleted from the data
file. For this step ID_NBI_Data06 file is used and the data are saved ir
ID_NBI_Substructure file. */

data xx.ID_NBI_Substructure;
set xx.ID_NBI_Data06;
/* Delete substructure with 9 <conditin_state< 4, missing data and
unavailable data. */
if missing(SUBSTRUCTURE_COND_060) then  delete;
if SUBSTRUCTURE_COND_060='N' then  delete;
if 4=<SUBSTRUCTURE_COND_060<=8;
 /* Selects only substructure with 043A and 043B Criteria. */
if 1=<STRUCTURE_KIND_043A<=6;
```

```
if 2<=STRUCTURE_TYPE_043B<=4;
/* Gives noncontinous code of 1, and continous 2. */
if  STRUCTURE_KIND_043A=1 then newSTRUCTURE_KIND_043A=1;
if  STRUCTURE_KIND_043A=3 then newSTRUCTURE_KIND_043A=1;
if  STRUCTURE_KIND_043A=5 then newSTRUCTURE_KIND_043A=1;
if  STRUCTURE_KIND_043A=2 then newSTRUCTURE_KIND_043A=2;
if  STRUCTURE_KIND_043A=4 then newSTRUCTURE_KIND_043A=2;
if  STRUCTURE_KIND_043A=6 then newSTRUCTURE_KIND_043A=2;
drop STRUCTURE_KIND_043A;
rename newSTRUCTURE_KIND_043A=STRUCTURE_KIND_043A;
drop  YEAR_BUILT_027 SUPERSTRUCTURE_COND_059 DECK_COND_058;
run;

/* The following code orders the substructure data columns as shown in
the "retain" section of the code and rewrites the file with the same nam
-  ID_NBI_Substructure. */

data xx.ID_NBI_Substructure;
retain STRUCTURE_NUMBER_008 STRUCTURE_KIND_043A STRUCTURE_TYPE_043B
        SUBSTRUCTURE_COND_060 Inspection_year;
set xx.ID_NBI_Substructure;
run;

/* The following code calculates the number of years a bridge data is
availble in the dataset for RCC, PSC, Steel, deck and substructure.
The data for RCC superstructures are read from the ID_NBI_RCC_Super file
and is saved in ID_NBI_RCC_Super_Count file.*/

proc sql;
create table xx.ID_NBI_RCC_Super_Count as
select *, count(STRUCTURE_NUMBER_008) as Freq
from xx.ID_NBI_RCC_super
group by STRUCTURE_NUMBER_008;
quit;

/* The data for Steel superstructures are read from the ID_NBI_RCC_Super
file and is saved in ID_NBI_Steel_Super_Count file.*/

proc sql;
create table xx.ID_NBI_Steel_Super_Count as
select *, count(STRUCTURE_NUMBER_008) as Freq
from xx.ID_NBI_Steel_Super
group by STRUCTURE_NUMBER_008;
quit;

/* The data for PSC superstructures are read from the ID_NBI_PSC_Super
```

```
file and is saved in ID_NBI_PSC_Super_Count file.*/

proc sql;
create table xx.ID_NBI_PSC_Super_Count as
select *, count(STRUCTURE_NUMBER_008) as Freq
from xx.ID_NBI_PSC_Super
group by STRUCTURE_NUMBER_008;
quit;

/*The data for bridge decks are read from the ID_NBI_Deck file and is
saved in ID_NBI_Deck_Count file.*/

proc sql;
create table xx.ID_NBI_Deck_Count as
select *, count(STRUCTURE_NUMBER_008) as Freq
from xx.ID_NBI_Deck
group by STRUCTURE_NUMBER_008;
quit;

/*The data for substructures are read from the ID_NBI_Substructure file
and is saved in ID_NBI_Substructure_Count file.*/

proc sql;
create table xx.ID_NBI_Substructure_Count as
select *, count(STRUCTURE_NUMBER_008) as Freq
from xx.ID_NBI_Substructure
group by STRUCTURE_NUMBER_008;
quit;

/*The following code sorts RCC, PSC, Steel, Deck, and substructure data
files based on the STRUCTURE_NUMBER_008 and Inspection_Year. This step
reads the data from the respective data files and sorts the data in the
same file. */

libname xx "D:\Idaho\ID_Added_Inspection_Year";
proc sort data=xx.ID_NBI_RCC_Super_Count;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

proc sort data=xx.ID_NBI_Steel_Super_Count;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

proc sort data=xx.ID_NBI_PSC_Super_Count;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;
```

```
proc sort data=xx.ID_NBI_Deck_Count;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

proc sort data=xx.ID_NBI_Substructure_Count;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

/* The following code trims the sorted data for RCC-, PSC-, and Steel-
superstructures, Deck, and substructure if the CR is changed during
five years in the beginning, end or both. The trimmed data are saved in
a new file by adding 02 at the end of the files the data were read.
The following code is for RCC superstructure, followed by Steel
superstructure, PSC superstructure, decks, and substructures. */

data xx.ID_NBI_RCC_Super_Count02;
array cond{99} $23 _temporary_;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_RCC_Super_Count; by STRUCTURE_NUMBER_008;
    cond{count} = SUPERSTRUCTURE_COND_059;
    end;
if count ge 5 then do;
    do cb = 4 to 1 by -1;
        if cond{cb} ne cond{5} then leave;
        end;
    begin = cb + 1;
    do ce = count-3 to count;
        if cond{ce} ne cond{count-4} then leave;
        end;
    end = ce - 1;
    end;
else do; /* Don't touch if begin and end sequence overlap */
    begin = 1;
    end = count;
    end;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_RCC_Super_Count; by STRUCTURE_NUMBER_008;
    if count >= begin and count <= end then output;
    end;
drop cb ce count begin end;
run;

**********************;

data xx.ID_NBI_Steel_Super_Count02;
```

```
array cond{99} $23 _temporary_;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_Steel_Super_Count; by STRUCTURE_NUMBER_008;
    cond{count} = SUPERSTRUCTURE_COND_059;
    end;
if count ge 5 then do;
    do cb = 4 to 1 by -1;
        if cond{cb} ne cond{5} then leave;
        end;
    begin = cb + 1;
    do ce = count-3 to count;
        if cond{ce} ne cond{count-4} then leave;
        end;
    end = ce - 1;
    end;
else do; /* Don't touch if begin and end sequence overlap */
    begin = 1;
    end = count;
    end;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_Steel_Super_Count; by STRUCTURE_NUMBER_008;
    if count >= begin and count <= end then output;
    end;
drop cb ce count begin end;
run;

**********************;

data xx.ID_NBI_PSC_Super_Count02;
array cond{99} $23 _temporary_;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_PSC_Super_Count; by STRUCTURE_NUMBER_008;
    cond{count} = SUPERSTRUCTURE_COND_059;
    end;
if count ge 5 then do;
    do cb = 4 to 1 by -1;
        if cond{cb} ne cond{5} then leave;
        end;
    begin = cb + 1;
    do ce = count-3 to count;
        if cond{ce} ne cond{count-4} then leave;
        end;
    end = ce - 1;
    end;
else do; /* Don't touch if begin and end sequence overlap */
    begin = 1;
```

```
    end = count;
    end;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_PSC_Super_Count; by STRUCTURE_NUMBER_008;
    if count >= begin and count <= end then output;
    end;
drop cb ce count begin end;
run;

***********************;

data xx.ID_NBI_Deck_Count02;
array cond{99} $23 _temporary_;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_Deck_Count; by STRUCTURE_NUMBER_008;
    cond{count} = DECK_COND_058;
    end;
if count ge 5 then do;
    do cb = 4 to 1 by -1;
        if cond{cb} ne cond{5} then leave;
        end;
    begin = cb + 1;
    do ce = count-3 to count;
        if cond{ce} ne cond{count-4} then leave;
        end;
    end = ce - 1;
    end;
else do; /* Don't touch if begin and end sequence overlap */
    begin = 1;
    end = count;
    end;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_Deck_Count; by STRUCTURE_NUMBER_008;
    if count >= begin and count <= end then output;
    end;
drop cb ce count begin end;
run;

***********************;

data xx.ID_NBI_Substructure_Count02;
array cond{99} $23 _temporary_;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_Substructure_Count; by STRUCTURE_NUMBER_008;
    cond{count} = SUBSTRUCTURE_COND_060;
    end;
```

```
if count ge 5 then do;
    do cb = 4 to 1 by -1;
        if cond{cb} ne cond{5} then leave;
        end;
    begin = cb + 1;
    do ce = count-3 to count;
        if cond{ce} ne cond{count-4} then leave;
        end;
    end = ce - 1;
    end;
else do; /* Don't touch if begin and end sequence overlap */
    begin = 1;
    end = count;
    end;
do count = 1 by 1 until(last.STRUCTURE_NUMBER_008);
    set xx.ID_NBI_Substructure_Count; by STRUCTURE_NUMBER_008;
    if count >= begin and count <= end then output;
    end;
drop cb ce count begin end;
run;

/* The following code counts the number of bridge's CRs availble in the
data set after trimming the five observation in the beginning, end, or
both for each bridge. This step would enable us to remove bridge with or
one CR record, because bridges are inspected every two years and every
other year is just a duplication of the previous year inspection report.
Therefore, only one CR record is impractical and is deleted from the
files. The file for RCC superstructures are read from
ID_NBI_RCC_Super_Count02 and is saved as to the same file. */

libname xx "D:\Idaho\ID_Added_Inspection_Year";
proc sql;
create table xx.ID_NBI_RCC_Super_Count02 as
select *, count(STRUCTURE_NUMBER_008) as Freq2
from xx.ID_NBI_RCC_Super_Count02
group by STRUCTURE_NUMBER_008;
quit;

/* The file for Steel superstructures are read from the
ID_NBI_Steel_Super_Count02 file and is saved as to the same file. */

proc sql;
create table xx.ID_NBI_Steel_Super_Count02 as
select *, count(STRUCTURE_NUMBER_008) as Freq2
from xx.ID_NBI_Steel_Super_Count02
group by STRUCTURE_NUMBER_008;
```

```
quit;

/* The file for Steel superstructures are read from the
ID_NBI_PSC_Super_Count02 file and is saved as to the same file. */

proc sql;
create table xx.ID_NBI_PSC_Super_Count02 as
select *, count(STRUCTURE_NUMBER_008) as Freq2
from xx.ID_NBI_PSC_Super_Count02
group by STRUCTURE_NUMBER_008;
quit;

/* The file for Steel superstructures are read from the
ID_NBI_Deck_Count02 file and is saved as to the same file. */

proc sql;
create table xx.ID_NBI_Deck_Count02 as
select *, count(STRUCTURE_NUMBER_008) as Freq2
from xx.ID_NBI_Deck_Count02
group by STRUCTURE_NUMBER_008;
quit;

/* The file for Steel superstructures are read from the
ID_NBI_Substructure_Count02 file and is saved as to the same file. */

proc sql;
create table xx.ID_NBI_Substructure_Count02 as
select *, count(STRUCTURE_NUMBER_008) as Freq2
from xx.ID_NBI_Substructure_Count02
group by STRUCTURE_NUMBER_008;
quit;

/* The following code deletes single CR records for RCC superstructures.

data xx.ID_NBI_RCC_Super_Count02;
set xx.ID_NBI_RCC_Super_Count02;
if freq2 = 1 then  delete;
drop freq;
rename freq2=freq;
run;

/*The following code deletes single CR records for Steel superstructures

data xx.ID_NBI_Steel_Super_Count02;
set xx.ID_NBI_Steel_Super_Count02;
if freq2 = 1 then  delete;
```

```
drop freq;
rename freq2=freq;
run;

/* The following code deletes single CR records for PSC superstructures.

data xx.ID_NBI_PSC_Super_Count02;
set xx.ID_NBI_PSC_Super_Count02;
if freq2 = 1 then  delete;
drop freq;
rename freq2=freq;
run;

/* The following code deletes single CR records for Decks.*/

data xx.ID_NBI_Deck_Count02;
set xx.ID_NBI_Deck_Count02;
if freq2 = 1 then  delete;
drop freq;
rename freq2=freq;
run;

/* The following code deletes single CR records for Substructures.*/

data xx.ID_NBI_Substructure_Count02;
set xx.ID_NBI_Substructure_Count02;
if freq2 = 1 then  delete;
drop freq;
rename freq2=freq;
run;

/* The following code sorts the above data set for RCC superstructure
to be used for time in condition rating (TICR) calculation.*/

proc sort data=xx.ID_NBI_RCC_Super_Count02;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

/* The following code sorts the above data set for Steel superstructure
to be used for time in condition rating (TICR) calculation.*/

proc sort data=xx.ID_NBI_Steel_Super_Count02;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

/* The following code sorts the above data set for PSC superstructure
```

```
to be used for time in condition rating (TICR) calculation.*/

proc sort data=xx.ID_NBI_PSC_Super_Count02;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

/* The following code sorts the above data set for Decks  to be used
for time in condition rating (TICR) calculation.*/

proc sort data=xx.ID_NBI_Deck_Count02;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

/* The following code sorts the above data set for subrstructures
to be used for time in condition rating (TICR) calculation.*/

proc sort data=xx.ID_NBI_Substructure_Count02;
by STRUCTURE_NUMBER_008 Inspection_Year;
run;

/* The following code calculates the TICR, number of years a bridge
component stayed in each CR. The code reads the data from the file
ID_NBI_RCC_Super_Count02 and saves in ID_NBI_RCC_Super_TICR file. */

proc freq data=xx.ID_NBI_RCC_Super_Count02;
tables STRUCTURE_NUMBER_008*SUPERSTRUCTURE_COND_059/
out=xx.ID_NBI_RCC_Super_TICR;
run;
quit;

/* The following code calculates the TICR, number of years a bridge
component stayed in each CR. The code reads the data from the file
ID_NBI_Steel_Super_Count02 and saves in ID_NBI_Steel_Super_TICR file.*/

proc freq data=xx.ID_NBI_Steel_Super_Count02;
tables STRUCTURE_NUMBER_008*SUPERSTRUCTURE_COND_059/
out=xx.ID_NBI_Steel_Super_TICR;
run;
quit;

/* The following code calculates the TICR, number of years a bridge
component stayed in each CR. The code reads the data from the file
ID_NBI_PSC_Super_Count02 and saves in ID_NBI_PSC_Super_TICR file. */

proc freq data=xx.ID_NBI_PSC_Super_Count02;
tables STRUCTURE_NUMBER_008*SUPERSTRUCTURE_COND_059/
```

```
out=xx.ID_NBI_PSC_Super_TICR;
run;
quit;

/* The following code calculates the TICR, number of years a bridge
component stayed in each CR. The code reads the data from the file
ID_NBI_Deck_Count02 and saves in ID_NBI_Deck_TICR file. */

proc freq data=xx.ID_NBI_Deck_Count02;
tables STRUCTURE_NUMBER_008*DECK_COND_058/
out=xx.ID_NBI_Deck_TICR;
run;
quit;

/* The following code calculates the TICR, number of years a bridge
component stayed in each CR. The code reads the data from the file
ID_NBI_Substructure_Count02 and saves in ID_NBI_Substructure_TICR
file. */

proc freq data=xx.ID_NBI_Substructure_Count02;
tables STRUCTURE_NUMBER_008*SUBSTRUCTURE_COND_060/
out=xx.ID_NBI_Substructure_TICR;
run;
quit;

/* As seen in the previous sections of th code, the five CR records
in the beginning and the end of the availble data were searched and
deleted from the data sets if changed during this period. The CRs
fulfilled this criteria are assumed to be observed event - the CR
transitioned to the next lower CR. Therefore, a 'Censor' column is
added using the followin code. The file is read from the file and
saved in the same file. */

libname xx "D:\Idaho\ID_Added_Inspection_Year";
data xx.ID_NBI_RCC_Super_TICR;
set xx.ID_NBI_RCC_Super_TICR;
 if count > 26  then CENSOR=0;
 else CENSOR=1;
run;

**********************;

data xx.ID_NBI_Steel_Super_TICR;
set xx.ID_NBI_Steel_Super_TICR;
 if count > 26  then CENSOR=0;
 else CENSOR=1;
```

```
run;

**********************;

data xx.ID_NBI_PSC_Super_TICR;
set xx.ID_NBI_PSC_Super_TICR;
 if count > 26  then CENSOR=0;
 else CENSOR=1;
run;

**********************;

data xx.ID_NBI_Deck_TICR;
set xx.ID_NBI_Deck_TICR;
 if count > 26  then CENSOR=0;
 else CENSOR=1;
run;

**********************;

data xx.ID_NBI_Substructure_TICR;
set xx.ID_NBI_Substructure_TICR;
 if count > 26  then CENSOR=0;
 else CENSOR=1;
run;

/*The following code uses Kaplan-Meier method to analyze the realiabi-
lity of bridge components. The code read the data from the TICR file
saved in the previous step and saves the analyzed data in a new file.
This step for PSC superstructure is saved in ID_KM_PSC_Super file.
Another step to calculate bridge components' deterioration and cumu-
lative hazard is implemented as well. Another lines of codes are used
to smooth the reliability and deterioration curves for producing gra-
phs. */

title;
proc LIFETEST method=km data=xx.ID_NBI_PSC_Super_TICR plots=s(cb=ep)
            OUTSURV=xx.ID_KM_PSC_Super;
TIME count*CENSOR(0);
strata SUPERSTRUCTURE_COND_059;
label count="Time in Condition Rating (Year)";
run;

data xx.ID_KM_PSC_Super;
        set xx.ID_KM_PSC_Super;
        Survival_Percent=survival*100;
```

```
        Deterioration = 100-Survival_Percent;
        Cumulative_hazard=-log(Survival_Percent);
    run;

/* The following code smooths the KM reliability and Deterioration
    curves by taking the average of each steps across the data. */

data xx.ID_KM_PSC_Super;
set xx.ID_KM_PSC_Super;
by SUPERSTRUCTURE_COND_059;
lagS = lag(Survival_percent);
lagD = lag(Deterioration);
if First.SUPERSTRUCTURE_COND_059
then do;
SmoothedS = survival_Percent;
SmoothedD = Deterioration;
end;
else do;
SmoothedS =(LagS+Survival_Percent)*0.5;
SmoothedD =(LagD+Deterioration)*0.5;
end;
run;

/*This step for RCC superstructure is saved in ID_KM_RCC_Super file.*/

title;
proc LIFETEST method=km data=xx.ID_NBI_RCC_Super_ticr plots=s(cb=ep)
        OUTSURV=xx.ID_KM_RCC_Super;
TIME count*CENSOR(0);
strata SUPERSTRUCTURE_COND_059;
label count="Time in Condition Rating (Year)";
run;

data xx.ID_KM_RCC_Super;
        set xx.ID_KM_RCC_Super;
        Survival_Percent=survival*100;
        Deterioration = 100-Survival_Percent;
    run;

/* The following code smooths the KM Survival and Deterioration curves
by taking average of each steps across the data. */

data xx.ID_KM_RCC_Super;
set xx.ID_KM_RCC_Super;
by SUPERSTRUCTURE_COND_059;
lagS = lag(Survival_percent);
```

```
lagD = lag(Deterioration);
if First.SUPERSTRUCTURE_COND_059
then do;
SmoothedS = survival_Percent;
SmoothedD = Deterioration;
end;
else do;
SmoothedS =(LagS+Survival_Percent)*0.5;
SmoothedD =(LagD+Deterioration)*0.5;
end;
run;

/*This step for Steel superstructure is saved in ID_KM_Steel_Super file.
*/

title;
proc LIFETEST method=km data=xx.ID_NBI_Steel_Super_ticr plots=s(cb=ep)
            OUTSURV=xx.ID_KM_Steel_Super;
TIME count*CENSOR(0);
strata SUPERSTRUCTURE_COND_059;
label count="Time in Condition Rating (Year)";
run;

data xx.ID_KM_Steel_Super;
        set xx.ID_KM_Steel_Super;
        Survival_Percent=survival*100;
        Deterioration = 100-Survival_Percent;
    run;

/*The following code smooths the KM Survival and Deterioration curves
by taking average of each steps across the data. */

data xx.ID_KM_Steel_Super;
set xx.ID_KM_Steel_Super;
by SUPERSTRUCTURE_COND_059;
lagS = lag(Survival_percent);
lagD = lag(Deterioration);
if First.SUPERSTRUCTURE_COND_059
then do;
SmoothedS = survival_Percent;
SmoothedD = Deterioration;
end;
else do;
SmoothedS =(LagS+Survival_Percent)*0.5;
SmoothedD =(LagD+Deterioration)*0.5;
end;
```

```
run;

/*This step for Decks is saved in ID_KM_Deck file.*/

title;
proc LIFETEST method=km data=xx.ID_NBI_Deck_TICR plots=s(cb=ep)
                OUTSURV=xx.ID_KM_Deck;
TIME count*CENSOR(0);
strata DECK_COND_058;
label count="Time in Condition Rating (Year)";
run;

data xx.ID_KM_Deck;
        set xx.ID_KM_Deck;
        Survival_Percent=survival*100;
        Deterioration = 100-Survival_Percent;
        Cumulative_hazard=-log(Survival);
    run;

/*The following code smooths the KM Survival and Deterioration curves
by taking average of each steps across the data. */

data xx.ID_KM_Deck;
set xx.ID_KM_Deck;
by DECK_COND_058;
lagS = lag(Survival_percent);
lagD = lag(Deterioration);
if First.DECK_COND_058
then do;
SmoothedS = Survival_Percent;
SmoothedD = Deterioration;
end;
else do;
SmoothedS =(LagS+Survival_Percent)*0.5;
SmoothedD =(LagD+Deterioration)*0.5;
drop lagS lagD;
end;
run;

/*/*This step for Substructures is saved in ID_KM_Substructure file.*/

title;
proc LIFETEST method=km data=xx.ID_NBI_Substructure_TICR plots=s(cb=ep)
            OUTSURV=xx.ID_KM_Substructure;
TIME count*CENSOR(0);
strata SUBSTRUCTURE_COND_060;
```

```
label count="Time in Condition Rating (Year)";
run;

data xx.ID_KM_Substructure;
        set xx.ID_KM_Substructure;
        Survival_Percent=survival*100;
        Deterioration = 100-Survival_Percent;
    run;

/* The following code smooths the KM Survival and Deterioration curves
by taking average of each steps across the data. */

data xx.ID_KM_Substructure;
set xx.ID_KM_Substructure;
by SUBSTRUCTURE_COND_060;
lagS = lag(Survival_percent);
lagD = lag(Deterioration);
if First.SUBSTRUCTURE_COND_060
then do;
SmoothedS = survival_Percent;
SmoothedD = Deterioration;
end;
else do;
SmoothedS =(LagS+Survival_Percent)*0.5;
SmoothedD =(LagD+Deterioration)*0.5;
end;
run;

/*The following codes cuculates the number of bridge components availa-
ble in each data set. The data are read from the files
ID_NBI_RCC_Super_TICR, ID_NBI_PSC_Super_TICR, ID_NBI_Steel_Super_TICR,
ID_NBI_Deck_TICR, and ID_NBI_Substructure_TICR and is saved as in new
file. */

proc freq data=xx.ID_NBI_RCC_Super_TICR;
tables STRUCTURE_NUMBER_008*Censor/ out=xx.ID_NBI_RCC_Super_Number;
run;
quit;

proc freq data=xx.ID_NBI_Steel_Super_TICR;
tables STRUCTURE_NUMBER_008*Censor/ out=xx.ID_NBI_Steel_Super_Number;
run;
quit;

proc freq data=xx.ID_NBI_PSC_Super_TICR;
tables STRUCTURE_NUMBER_008*Censor/ out=xx.ID_NBI_PSC_Super_Number;
```

```
run;
quit;

proc freq data=xx.ID_NBI_Deck_TICR;
tables STRUCTURE_NUMBER_008*Censor/ out=xx.ID_NBI_Deck_Number;
run;
quit;

proc freq data=xx.ID_NBI_Substructure_TICR;
tables STRUCTURE_NUMBER_008*Censor/ out=xx.ID_NBI_Substructure_Number;
run;
quit;

/*The following code calculates the number of bridge components per year
for producing bar graphs showing the number of bridge components against
each year. For RCC superstructures the data are read from
ID_NBI_RCC_Super_Count02 and saved in ID_NBI_RCC_Super_CR_Year file.
*/

libname xx "D:\Idaho\ID_Added_Inspection_Year";
proc freq data=xx.ID_NBI_RCC_Super_Count02;
tables Inspection_Year*SUPERSTRUCTURE_COND_059/
out=xx.ID_NBI_RCC_Super_CR_Year;
run;
quit;

/* For PSC superstructures the data are read from ID_NBI_PSC_Super_Count
and saved in ID_NBI_PSC_Super_CR_Year file.*/

proc freq data=xx.ID_NBI_PSC_Super_Count02;
tables Inspection_Year*SUPERSTRUCTURE_COND_059/
out=xx.ID_NBI_PSC_Super_CR_Year;
run;
quit;

/* For Steel superstructures the data are read from
ID_NBI_Steel_Super_Count02 and saved in ID_NBI_Steel_Super_CR_Year file.

proc freq data=xx.ID_NBI_Steel_Super_Count02;
tables Inspection_Year*SUPERSTRUCTURE_COND_059/
out=xx.ID_NBI_Steel_Super_CR_Year;
run;
quit;

/* For Substructures the data are read from ID_NBI_Substructure_Count02
and saved in ID_NBI_Substructure_CR_Year file.*/
```

```
proc freq data=xx.ID_NBI_Substructure_Count02;
tables Inspection_Year*SUBSTRUCTURE_COND_060/
out=xx.ID_NBI_Substructure_CR_Year;
run;
quit;

/* For decks the data are read from ID_NBI_Deck_Count02 and saved in
ID_NBI_Deck_CR_Year file.*/

proc freq data=xx.ID_NBI_Deck_Count02;
tables Inspection_Year*DECK_COND_058/
out=xx.ID_NBI_Deck_CR_Year;
run;
quit;
```

Appendix C NBI Data Analysis Graphs

C.1 General information for using this appendix

This appendix contains the table for the number of bridge components (deck, superstructure, and substructure) used for the time in condition rating (TICR) analysis, tables for the number of bridge components in each condition rating (CR), and tables for bridge components' statistics. Bar graphs and reliability and deterioration graphs for bridge components for each participating state are provided as well. The states are ordered alphabetically – Idaho, Illinois, Missouri, New York, Pennsylvania, Washington, and Wisconsin.

The number of bridge components is the count of the components (distinct bridge ID) available in the data set, but a bridge component that stayed in several CRs would be counted as many times as the component's different CRs for CR 4 – 8. Therefore, these counts are different.

TICR statistics for bridge components – deck, superstructures (prestressed concrete (PSC), reinforced concrete (RCC), and steel), and substructure are calculated using the Kaplan-Meier method and is reported in tables for each state separately. In each table the CRs are listed in the first column, median TICR in the second column, 95 % confidence interval (CI) for the median TICR in the third column, mean TICR in the fourth column and standard error for the mean TICR in the last column.

The bar graphs are generated for bridge components submitted to Federal Highway Administration (FHWA) before data processing – no bridge component is deleted from the data set except those out of CR 4 – 8 range and any missing CR or an

“N” in CR cell. The bar graphs depict the number of bridge components in CR 4 – 8 in the y-axis against inspection year in the x-axis from 1992 – 2017.

The reliability graph shows the reliability percentage in the y-axis against TICR, the number of years a bridge component stayed in each CR based on the available data. The reliability graph shows the probability for a bridge component in each CR (y-axis) to stay beyond the number of years selected in the x-axis.

The deterioration graph, essentially (1 – reliability) shows the probability for bridge components (percentage) in a given CR (y-axis) that transitioned to the next lower CR until and including the year selected in the x-axis.

APPENDIX C LIST OF TABLES

APPENDIX C LIST OF FIGURES

C.2 Idaho Bridge Components' graphs

This section contains the tables and graphs for Idaho bridge components. The tables are presented first, followed by the bar graphs and reliability and deterioration graphs. How to read graphs are presented in the general information section.

Table C-1. Number of bridge components in Idaho for TICR analysis

Bridge Components	**# of Bridge Components**	**# of Bridge Components in each CR**				
		CR 4	**CR 5**	**CR 6**	**CR 7**	**CR 8**
Deck	2964	120	427	1524	1984	631
PSC Superstructure	1627	45	152	624	1015	690
RCC Superstructure	610	33	107	365	402	83
Steel Superstructure	709	32	89	344	436	200
Substructure	2918	157	695	1605	1688	597

Table C-2. Kaplan-Meier statistics for Idaho's bridge components

CR	**Median TICR**	**95% CI for Median TICR**		**Mean TICR**	**Standard Error of the mean TICR**
		Lower CI	**Upper CI**		
Deck					
4	8	6	8	8.13	0.41
5	8	7	8	9.32	0.28
6	12	12	13	13.36	0.17
7	14	13	14	14.23	0.16
8	10	9	10	11.04	0.22
Prestressed Concrete Superstructure					
4	8	6	11	9.18	0.76
5	9	8	10	10.51	0.48
6	11	10	12	12.58	0.27
7	14	13	14	14.40	0.23
8	13	12	14	13.87	0.26
Reinforced Concrete Superstructure					
4	10	7	12	11.52	1.20
5	10	9	13	11.71	0.63
6	15	14	16	14.12	0.31
7	10	10	12	12.92	0.33
8	10	8	11	11.27	0.66
Steel Superstructure					
4	7.5	6	9	8.62	0.86
5	8	7	10	10.93	0.68
6	9	9	10	12.10	0.38
7	13	12	14	13.59	0.33
8	10	9	11	11.15	0.36
Substructure					
4	7	7	8	9.00	0.47
5	9	9	10	10.64	0.23
6	14	13	15	13.87	0.17
7	12	11	12	13.29	0.17
8	9	9	10	10.71	0.22

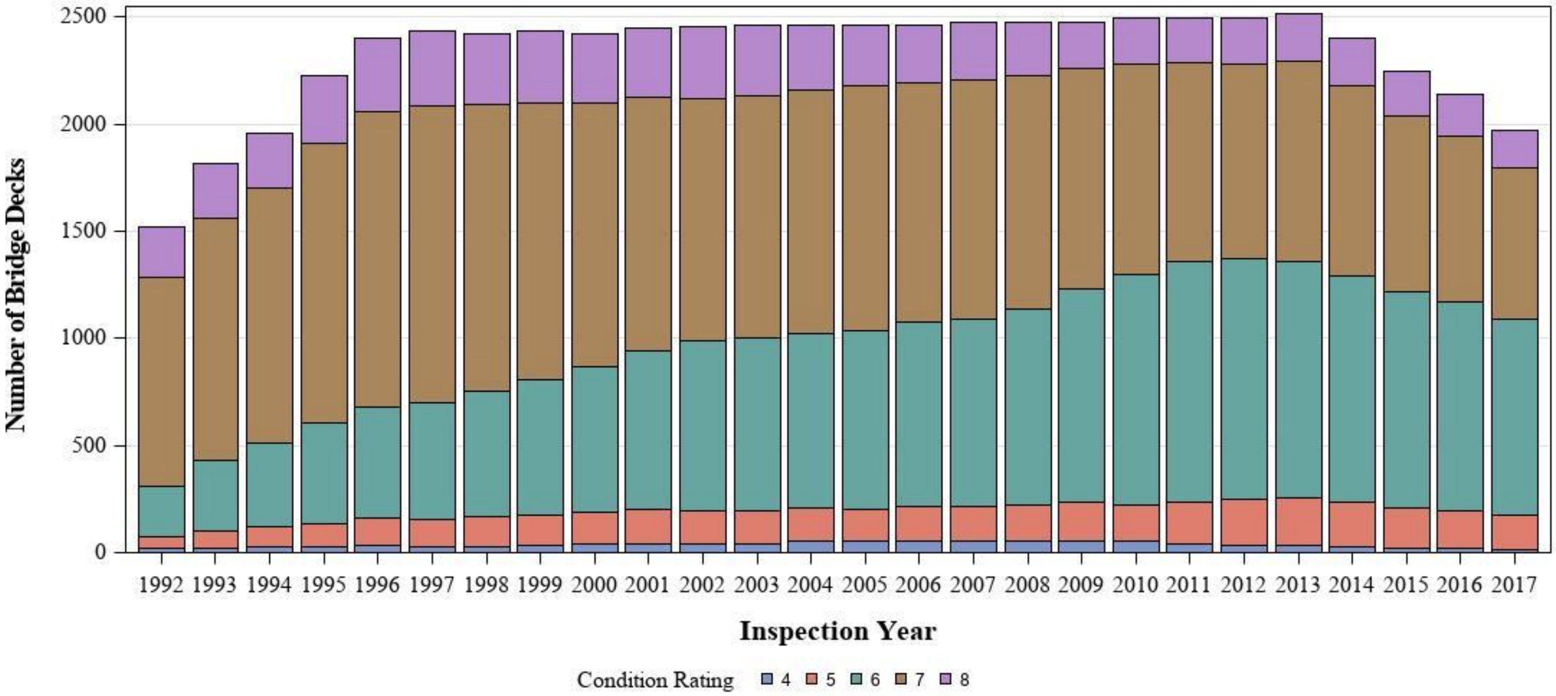

Figure C-1. Bar graph showing the number of bridge Decks in Idaho

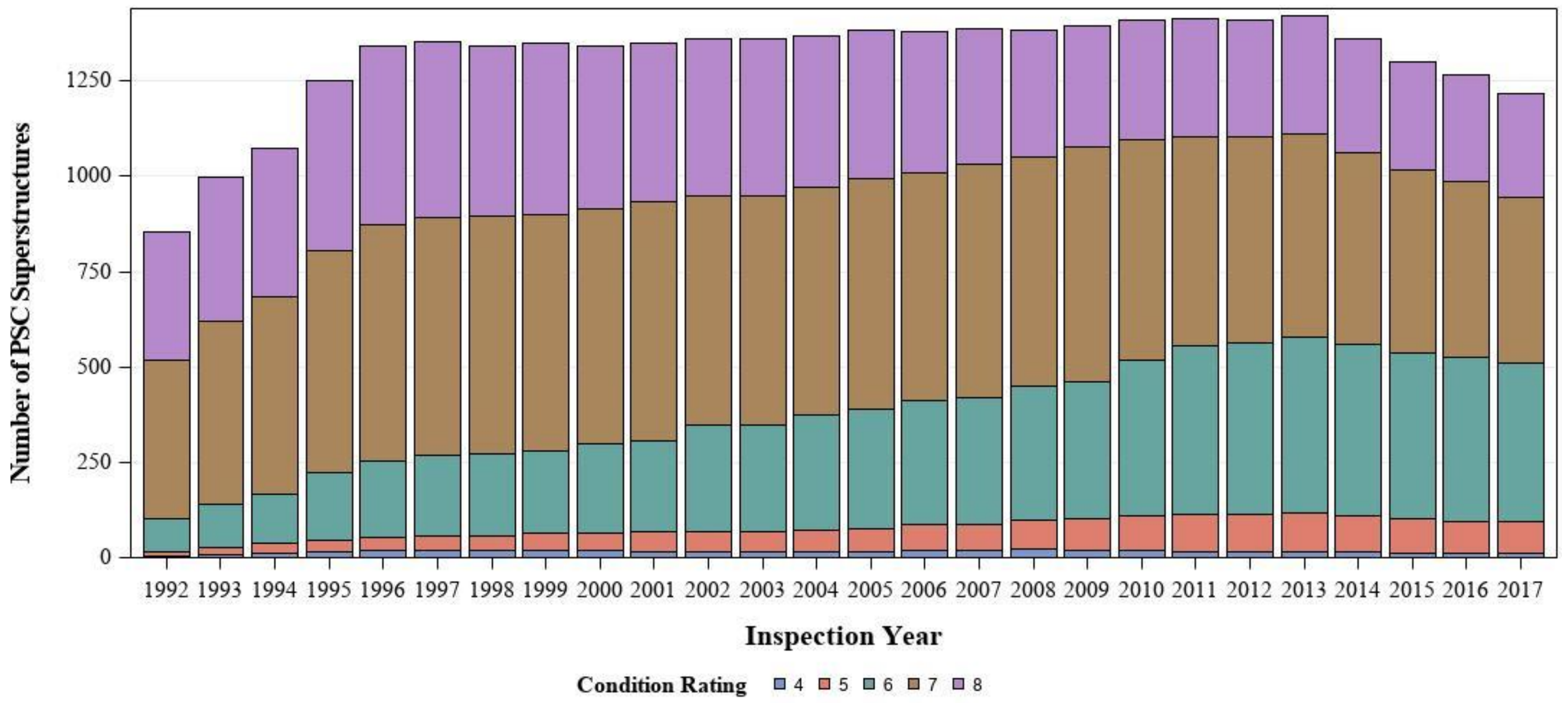

Figure C-2. Bar graph showing the number of PSC Superstructures in Idaho

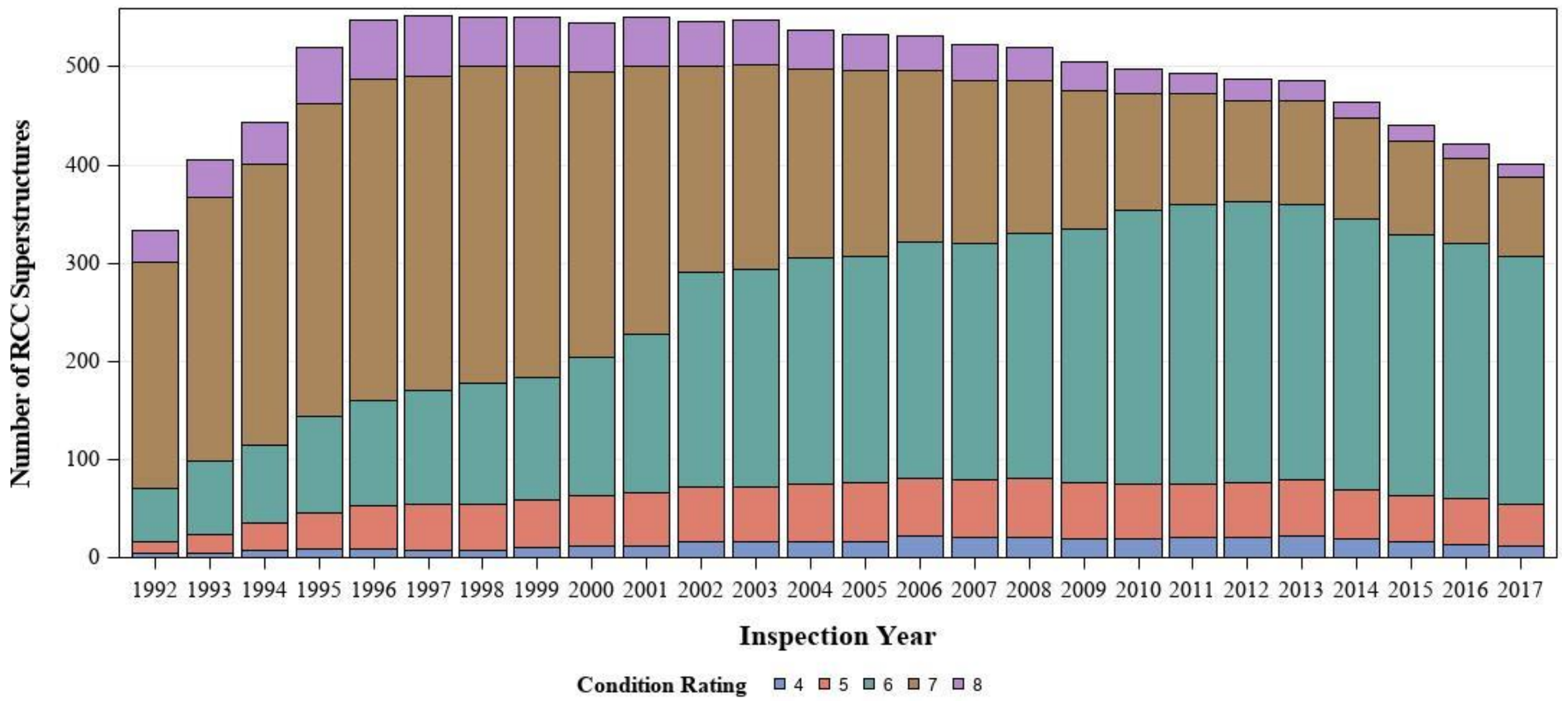

Figure C-3. Bar graph showing the number of RCC Superstructures in Idaho

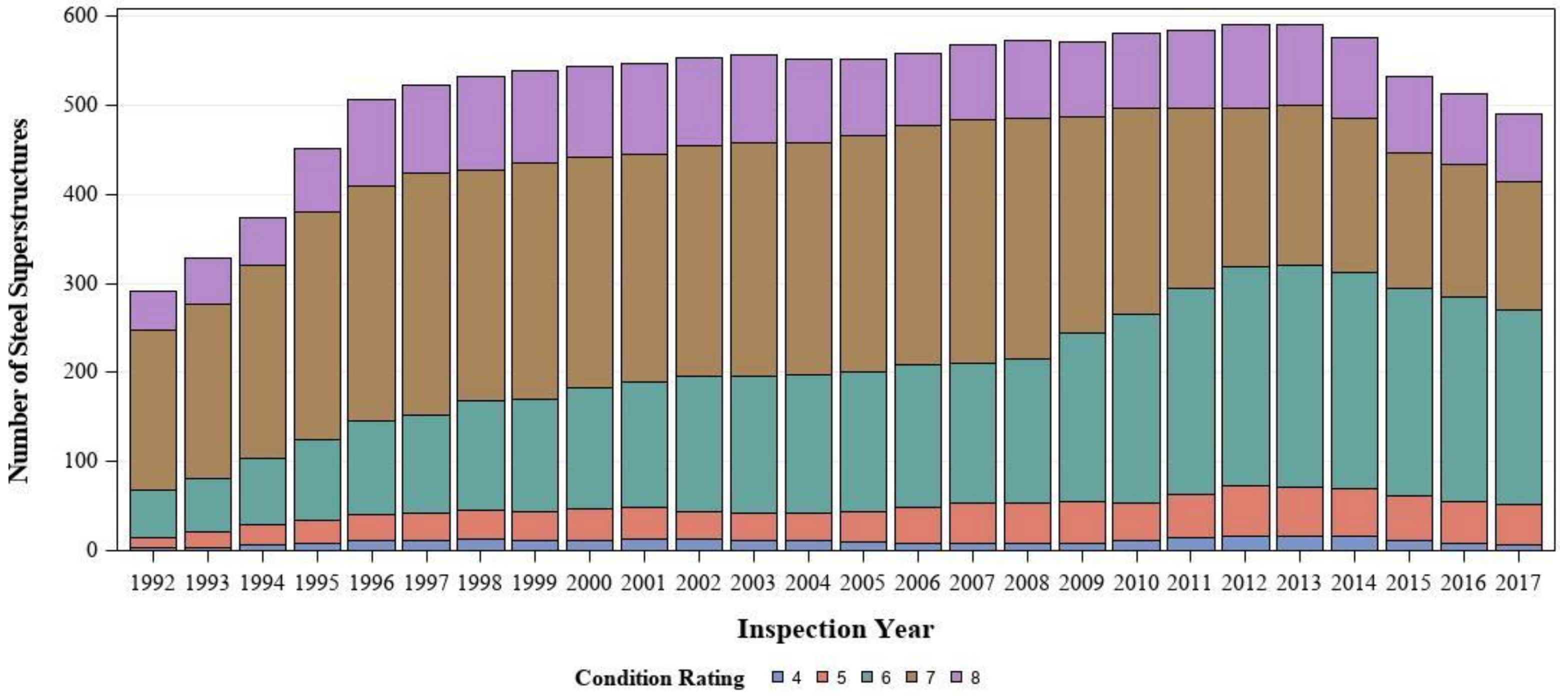

Figure C-4. Bar graph showing the number of Steel Superstructures in Idaho

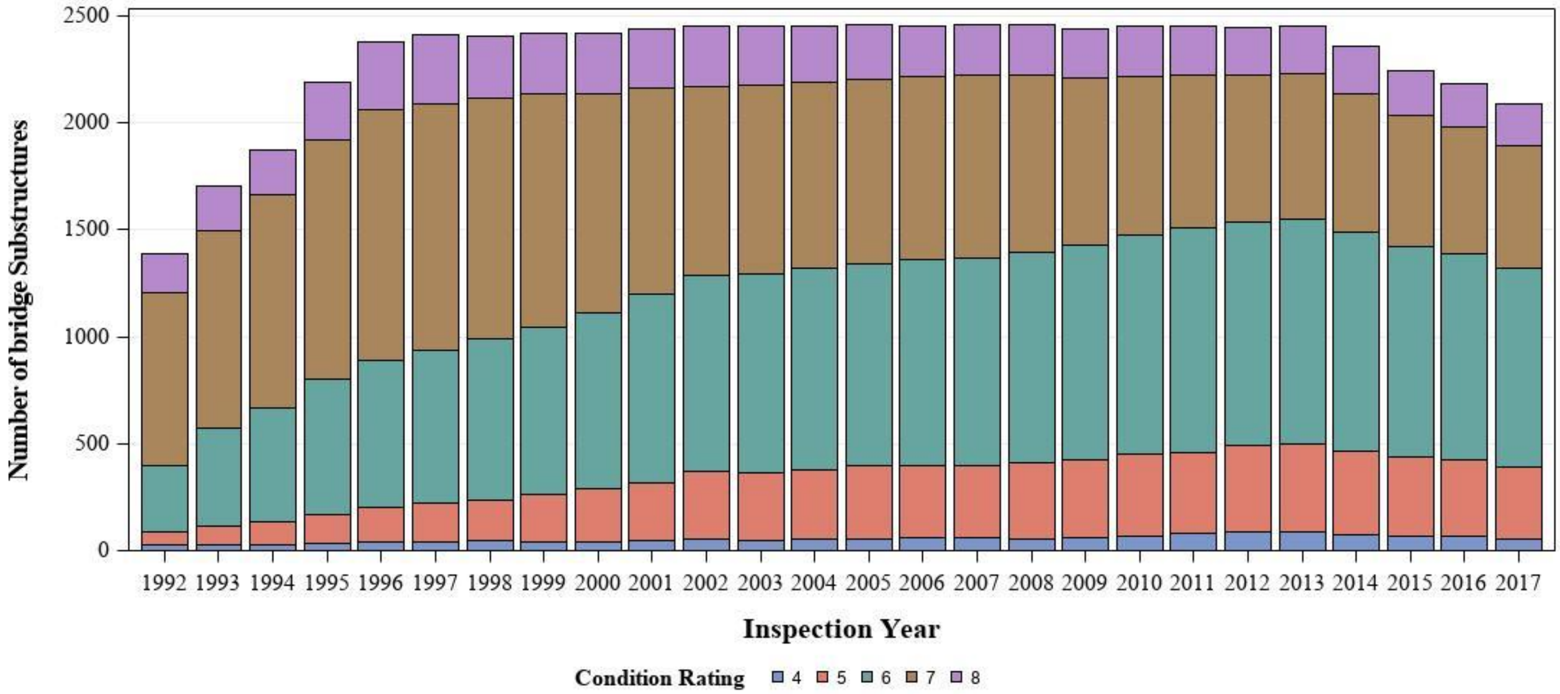

Figure C-5. Bar graph showing the number of bridge Substructures in Idaho

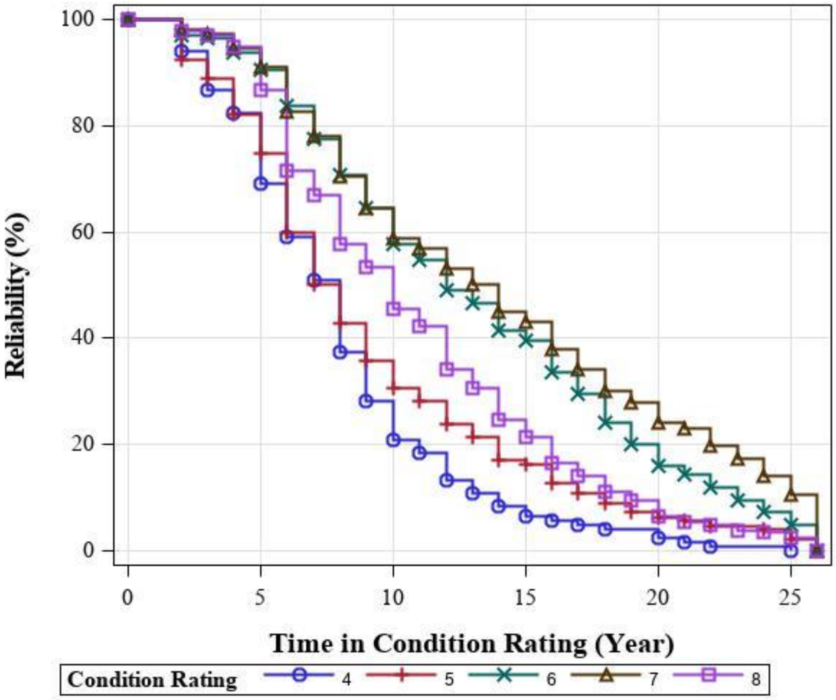

Figure C-6. Reliability graph for bridge Decks in Idaho

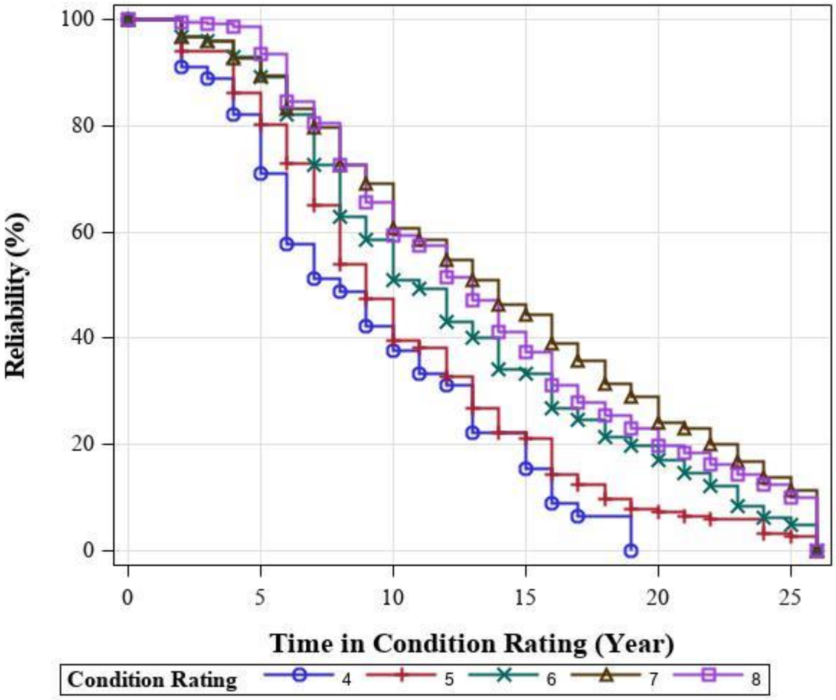

Figure C-7. Reliability graph for PSC Superstructures in Idaho

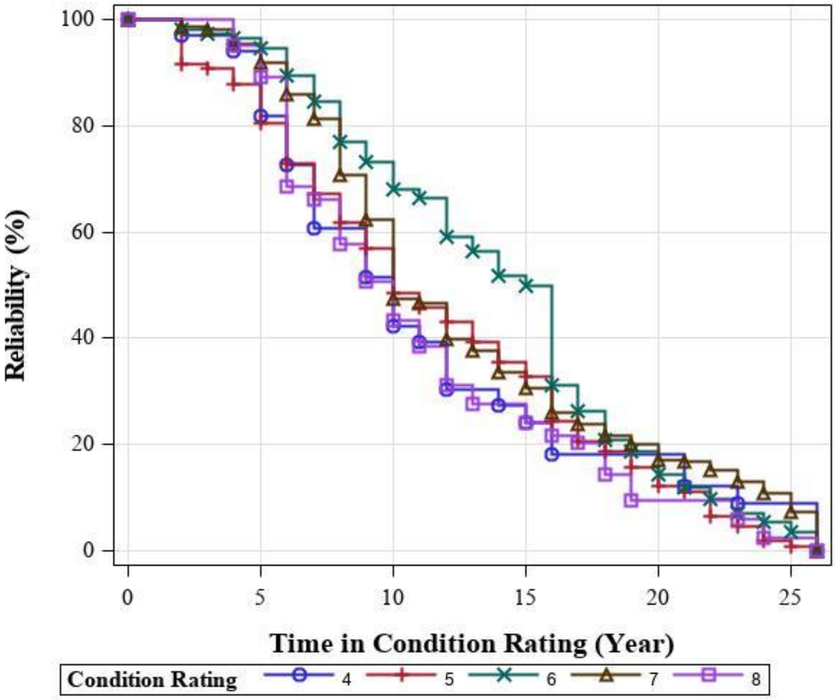

Figure C-8. Reliability graph for RCC Superstructures in Idaho

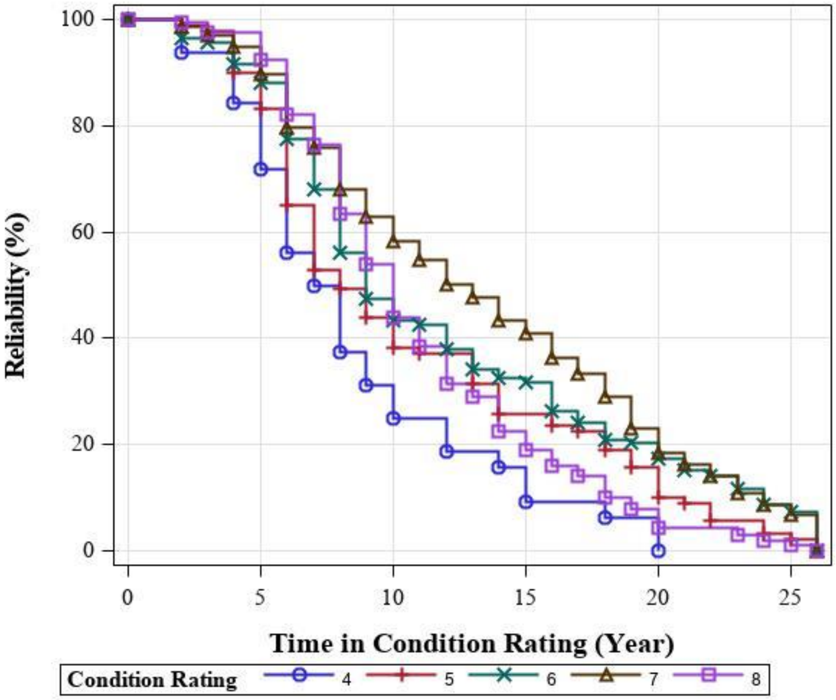

Figure C-9. Reliability graph for Steel Superstructures in Idaho

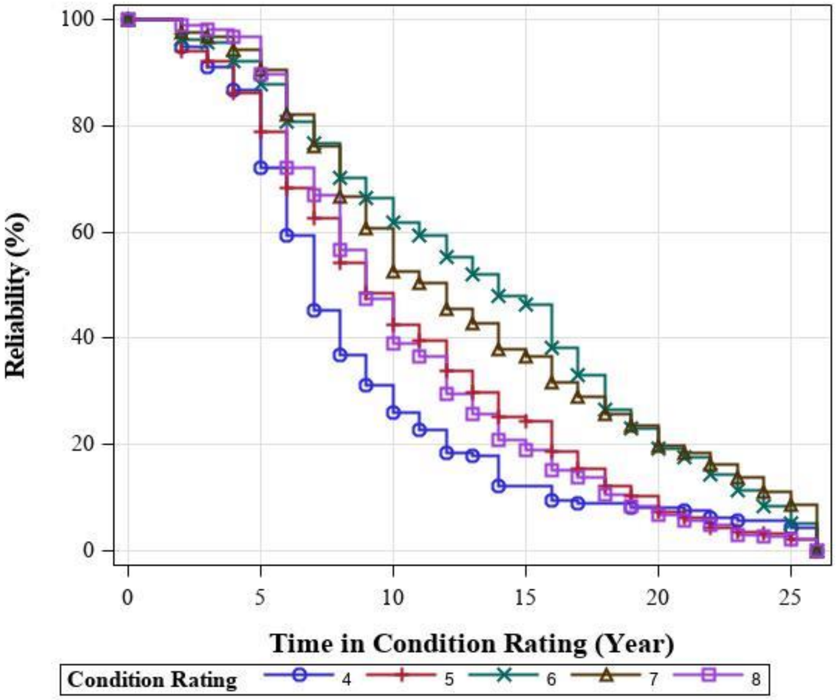

Figure C-10. Reliability graph for bridge Substructure in Idaho

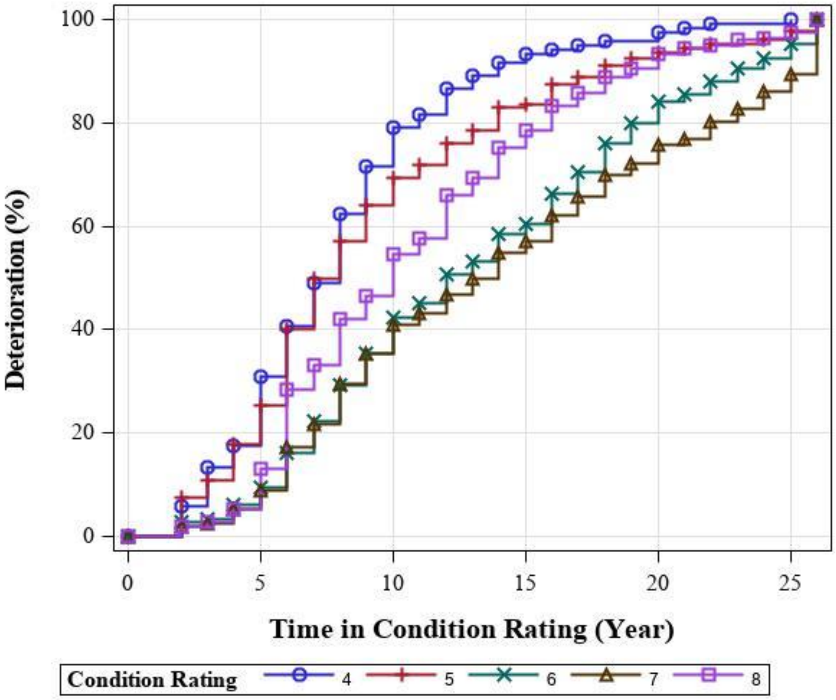

Figure C-11. Deterioration graph for bridge Decks in Idaho

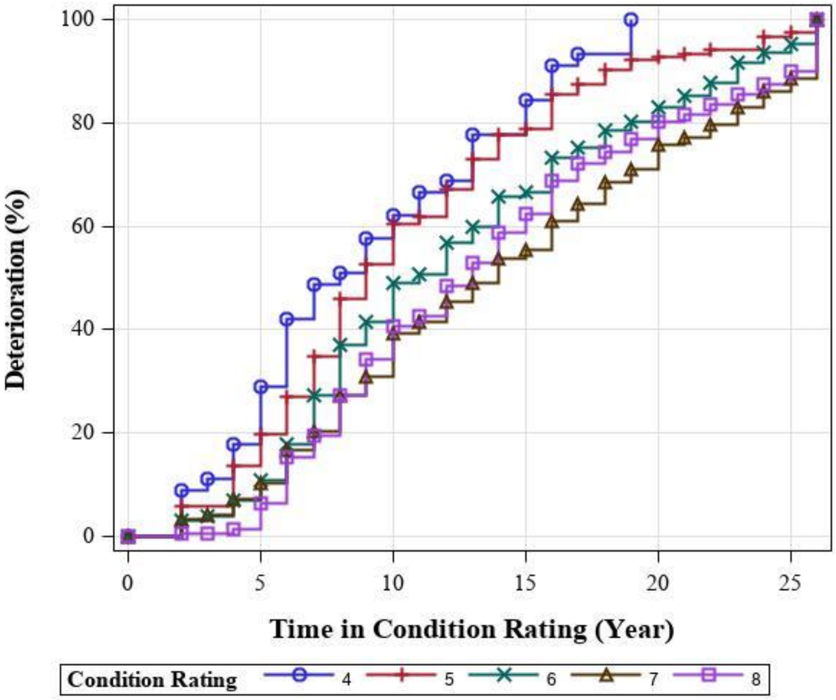

Figure C-12. Deterioration graph for PSC Superstructures in Idaho

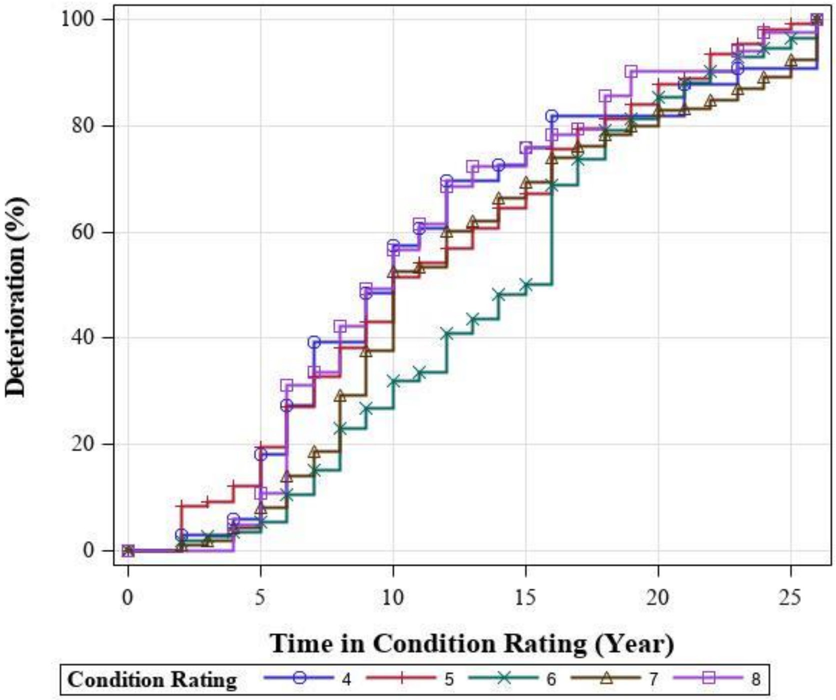

Figure C-13. Deterioration graph for RCC Superstructures in Idaho

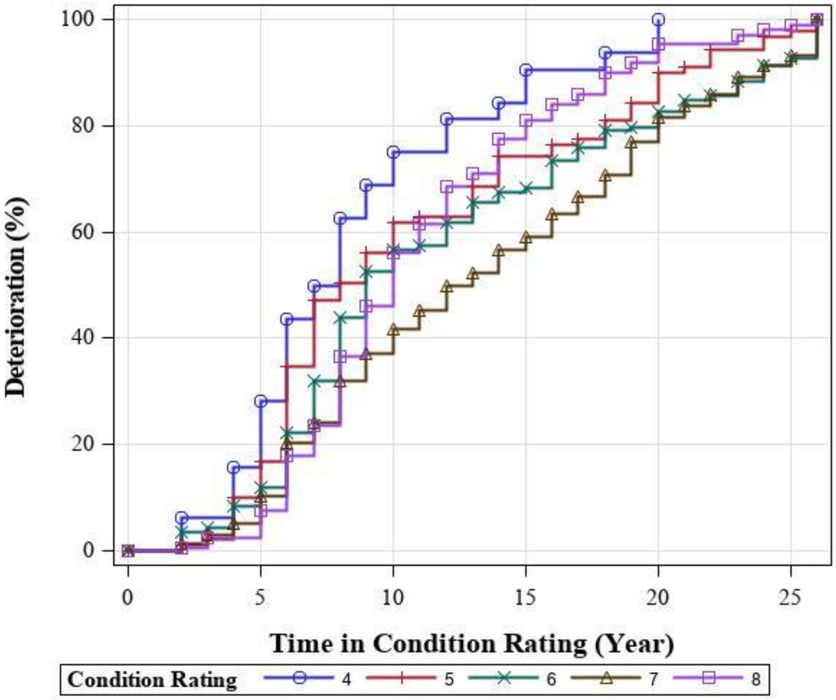

Figure C-14. Deterioration graph for Steel Superstructures in Idaho

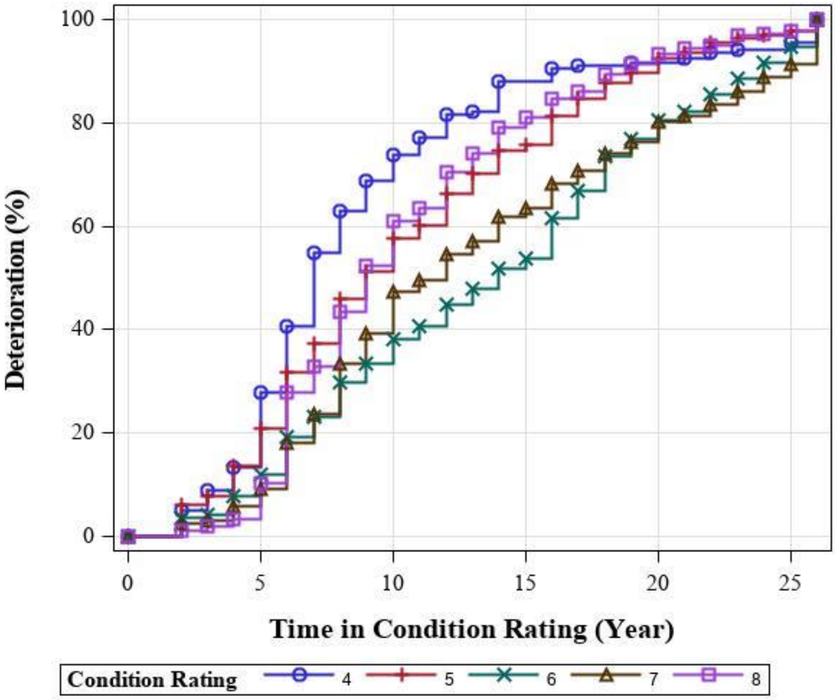

Figure C-15. Deterioration graph for bridge Substructures in Idaho

C.3 Illinois Bridge Components' graphs

This section contains the tables and graphs for Illinois bridge components. First the tables are presented followed by the bar graphs and reliability and deterioration graphs. How to read graphs are presented in the general information section.

Table C-3. Number of bridge components in Illinois for TICR analysis

Bridge Components	# of Bridge Components	# of Bridge Components in each CR				
		CR 4	CR 5	CR 6	CR 7	CR 8
Deck	9628	1090	1976	3340	5201	3674
PSC Superstructure	1477	33	101	360	654	929
RCC Superstructure	1013	181	298	307	360	260
Steel Superstructure	7211	623	1460	3032	3601	1947
Substructure	9581	1148	1911	3318	4726	3216

Table C-4. Kaplan-Meier statistics for Illinois' bridge components

CR	Median TICR	95% CI for Median TICR		Mean TICR	Standard Error of the mean TICR
		Lower CI	Upper CI		
Deck					
4	7			8.03	0.14
5	7	7	8	8.53	0.12
6	8			9.51	0.10
7	11	11	12	11.98	0.09
8	9			10.27	0.10
Prestressed Concrete Superstructure					
4	7	4	8	6.42	0.55
5	6	6	8	7.15	0.42
6	7	7	8	9.00	0.31
7	12	11	12	11.94	0.23
8	11	10	11	11.50	0.18
Reinforced Concrete Superstructure					
4	7	7	8	7.94	0.29
5	8	7	8	9.10	0.30
6	9	8	10	10.23	0.33
7	12	10	13	12.19	0.34
8	13	11	14	13.04	0.39
Steel Superstructure					
4	7	7	8	8.84	0.22
5	8	8	9	9.77	0.15
6	10	10	11	11.17	0.11
7	13	13	14	13.33	0.11
8	9	9	10	10.30	0.12
Substructure					
4	7	6	7	8.04	0.16
5	8	7	8	9.08	0.13
6	9			10.27	0.10
7	13	13	14	13.32	0.09
8	11	10	11	11.56	0.10

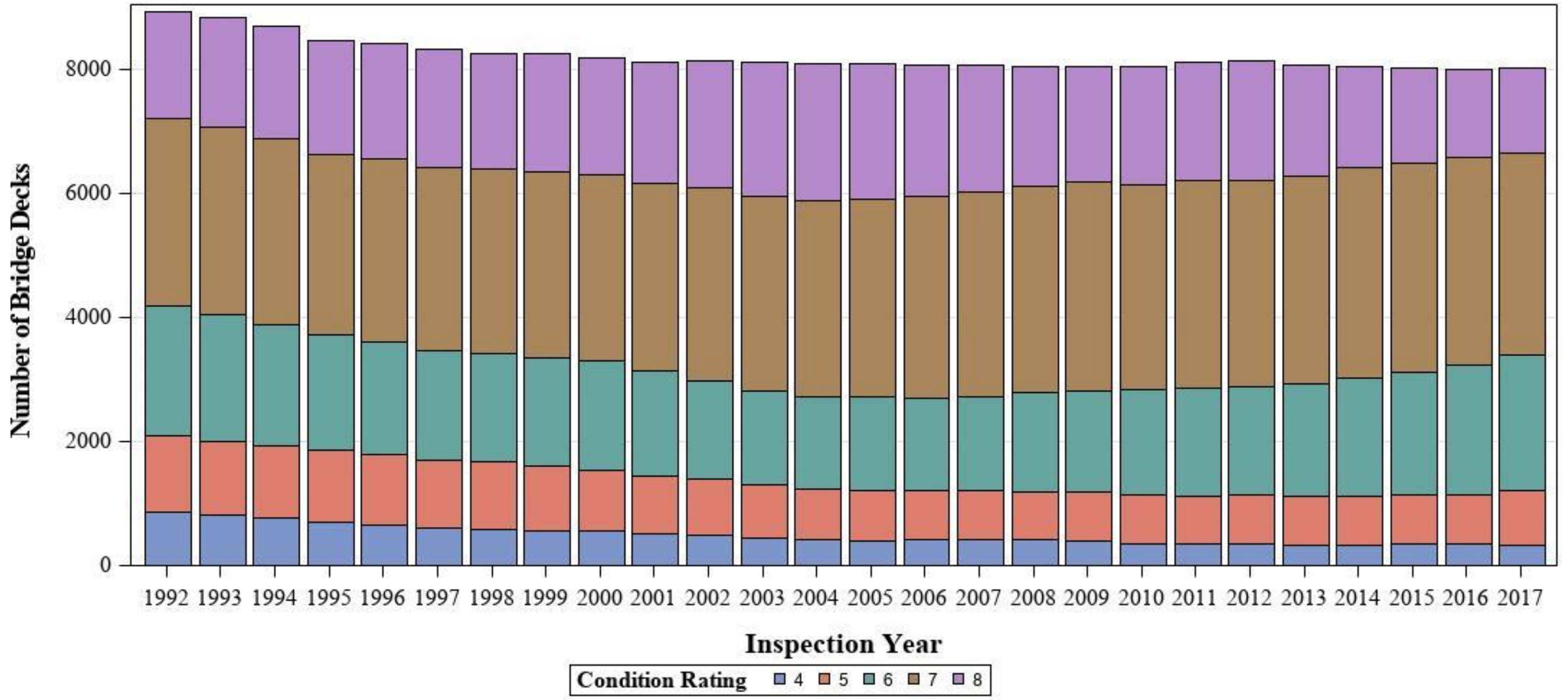

Figure C-16. Bar graph showing the number of bridge Decks in Illinois

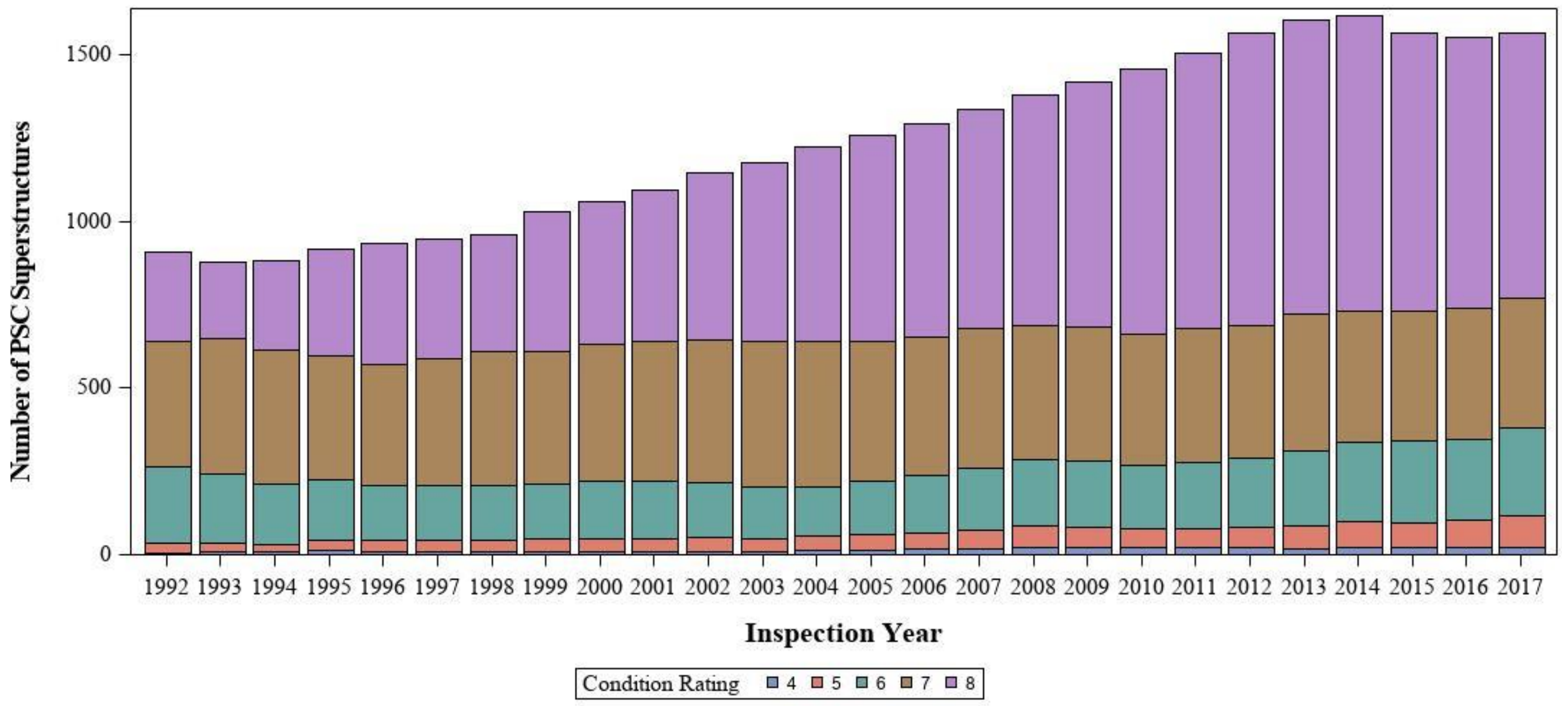

Figure C-17. Bar graph showing the number of PSC Superstructures in Illinois

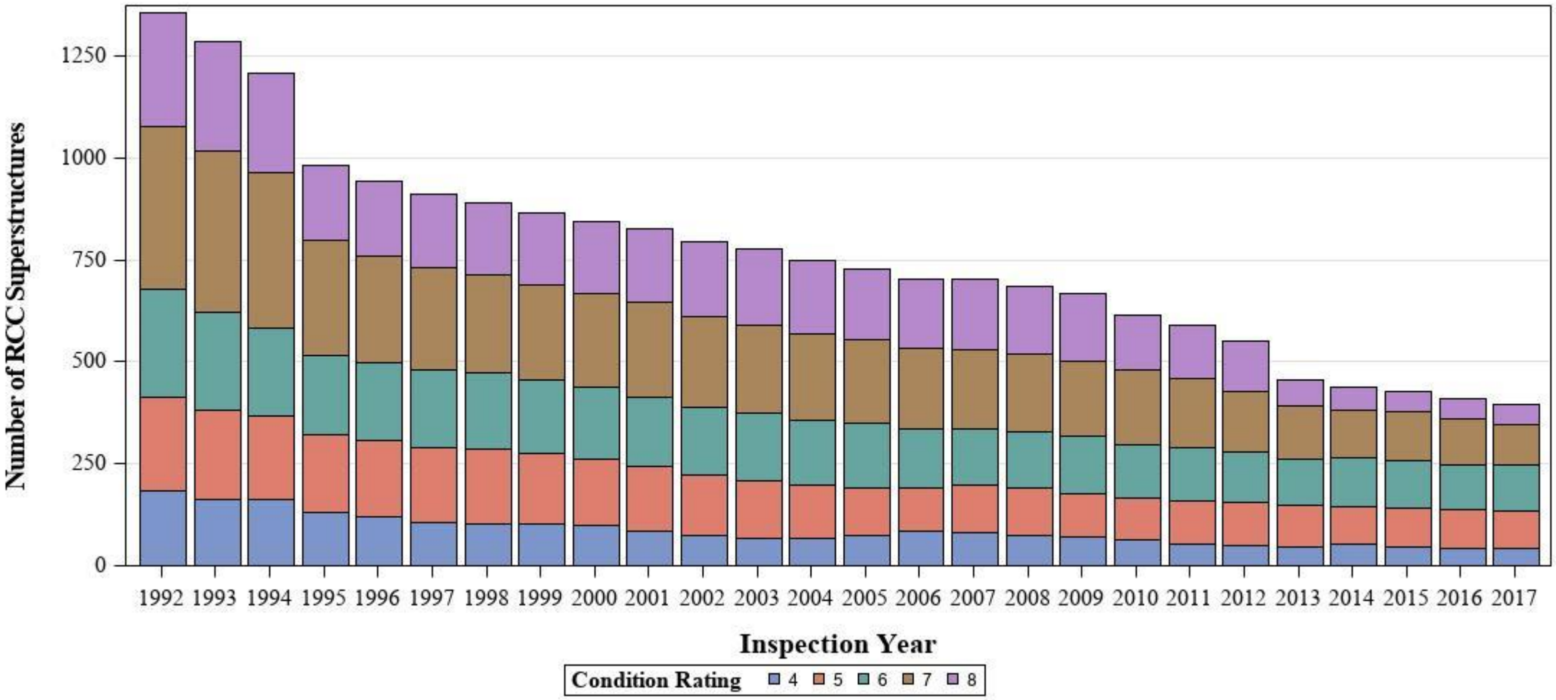

Figure C-18. Bar graph showing the number of RCC Superstructures in Illinois

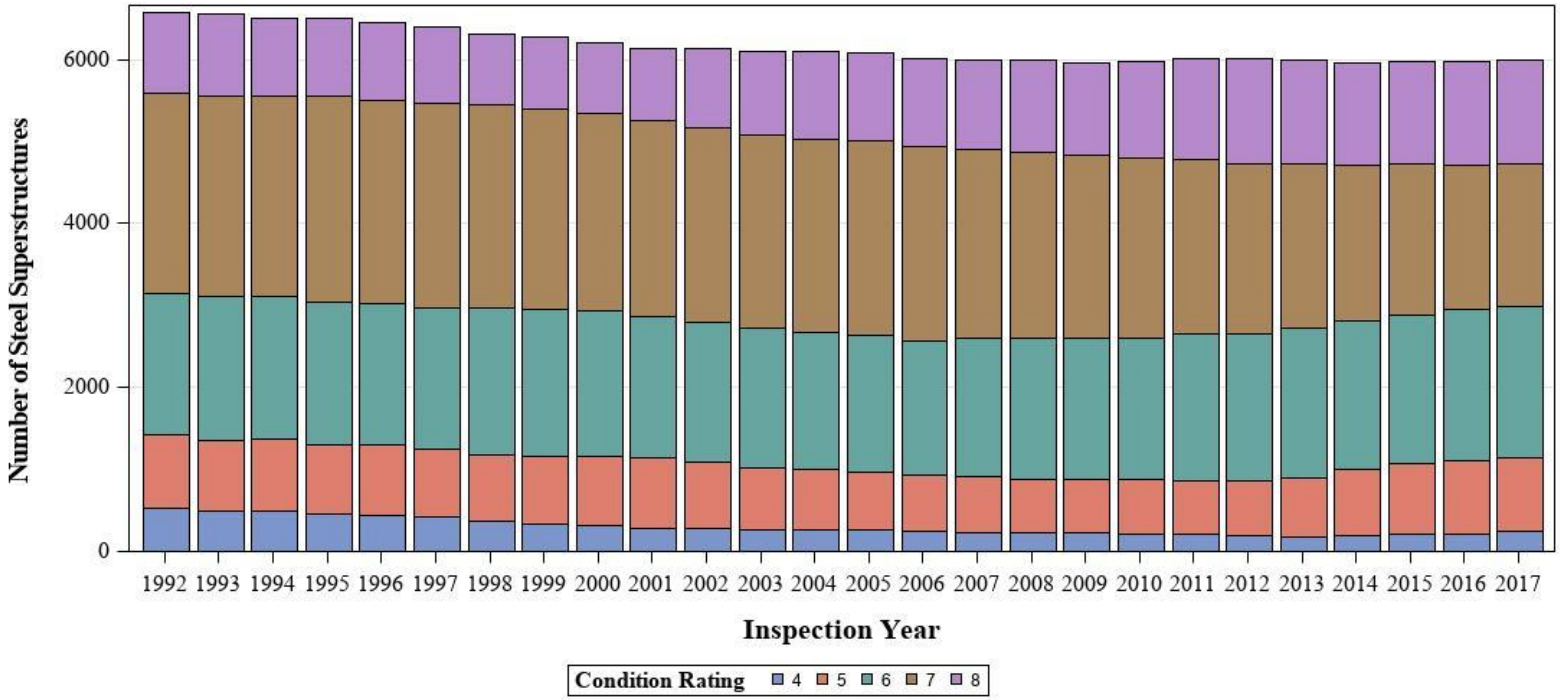

Figure C-19. Bar graph showing the number of Steel Superstructures in Illinois

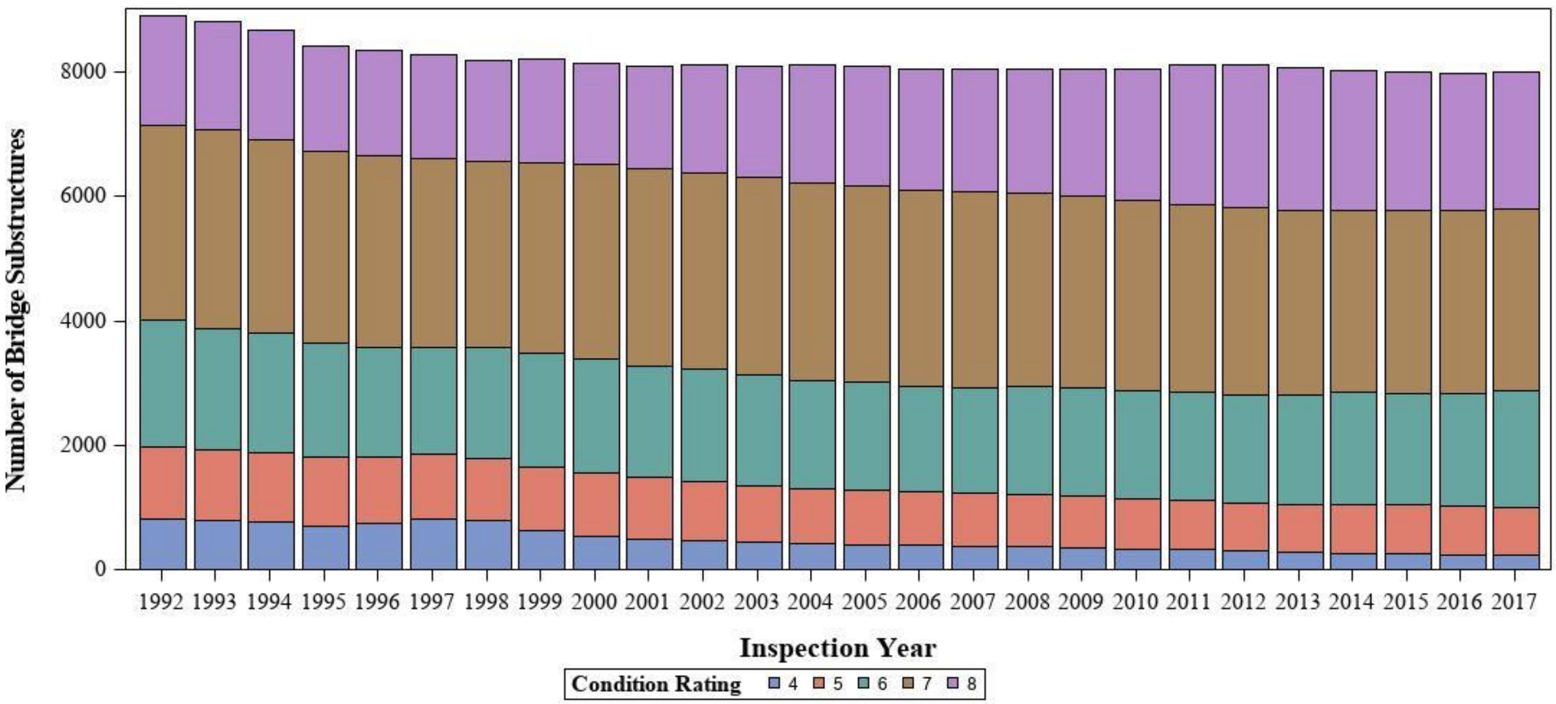

Figure C-20. Bar graph showing the number of Substructures in Illinois

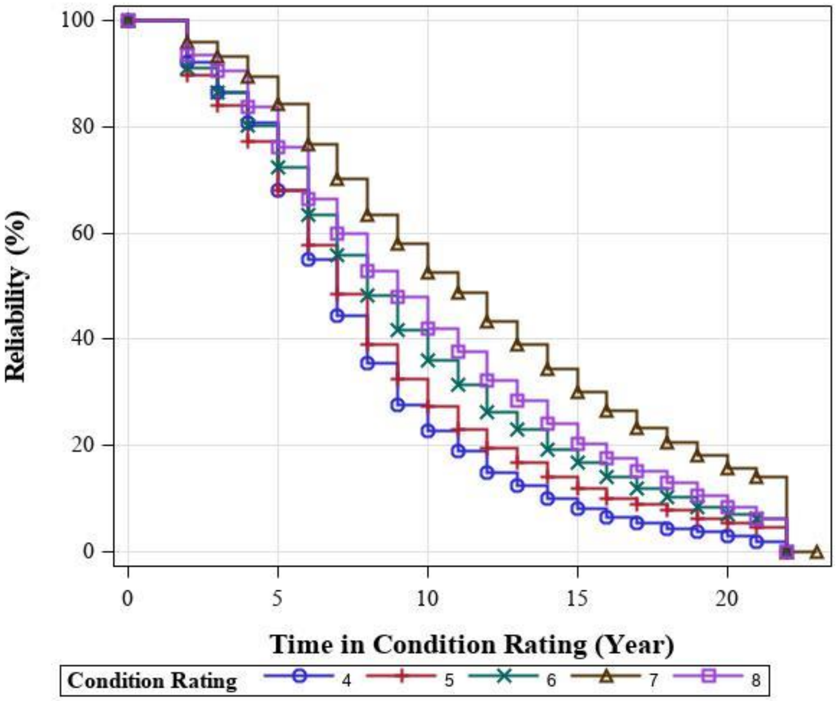

Figure C-21. Reliability graph for bridge Decks in Illinois

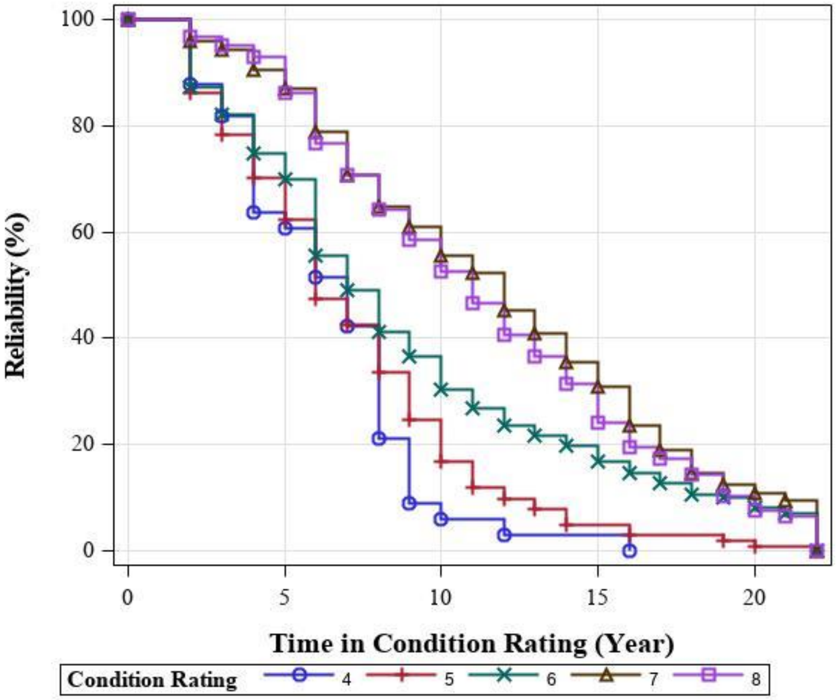

Figure C-22. Reliability graph for PSC Superstructures in Illinois

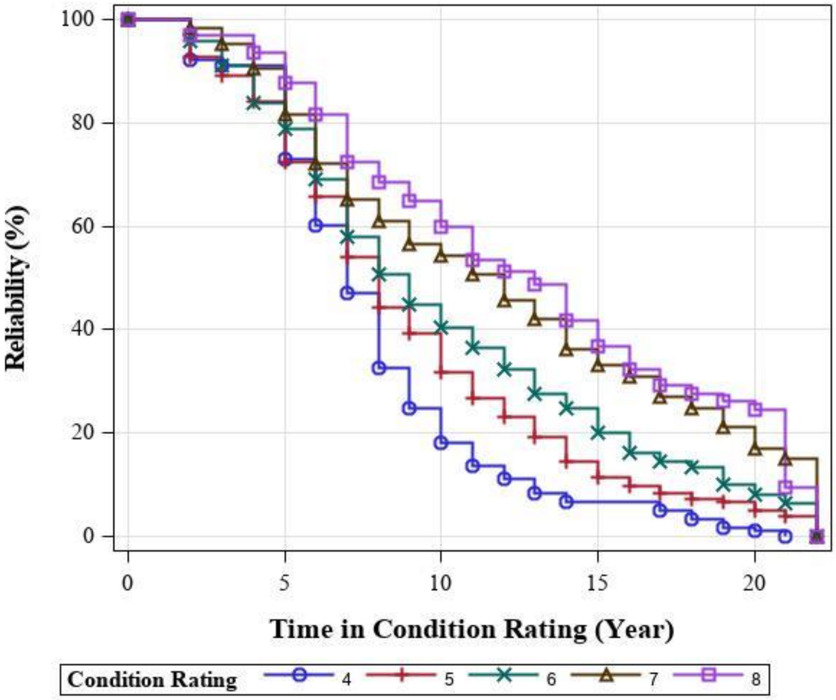

Figure C-23. Reliability graph for RCC Superstructures in Illinois

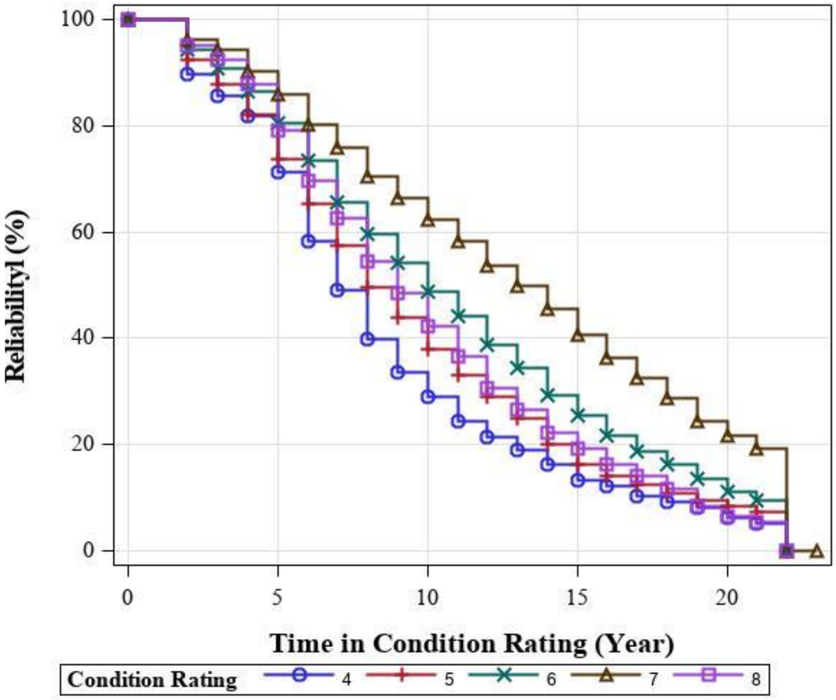

Figure C-24. Reliability graph for Steel Superstructures in Illinois

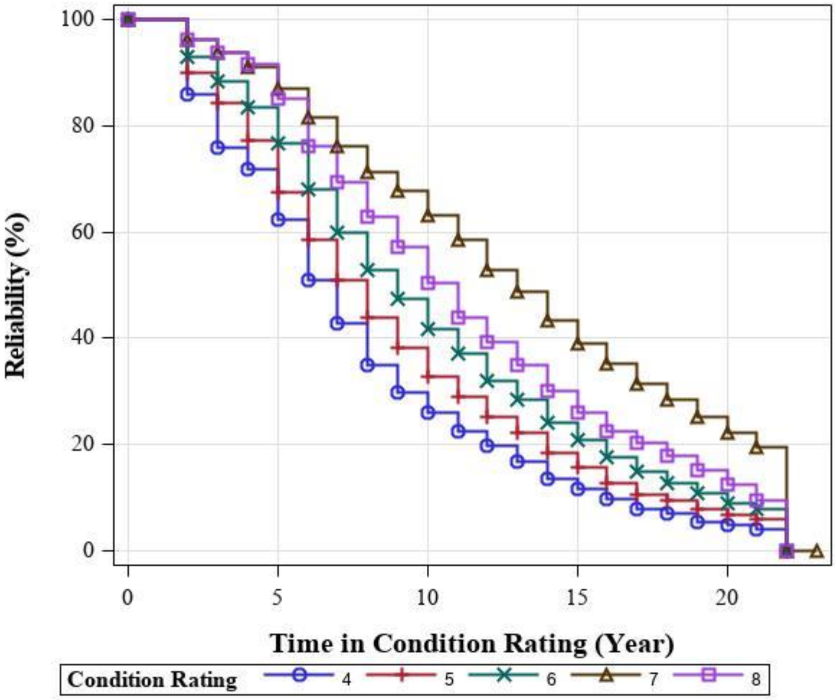

Figure C-25. Reliability graph for bridge Substructures in Illinois

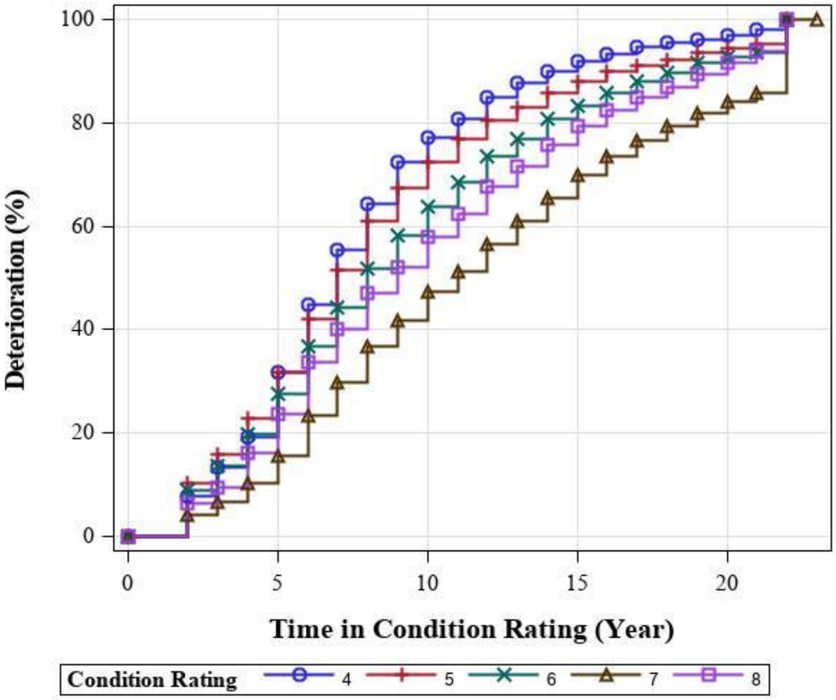

Figure C-26. Deterioration graph for bridge Decks in Illinois

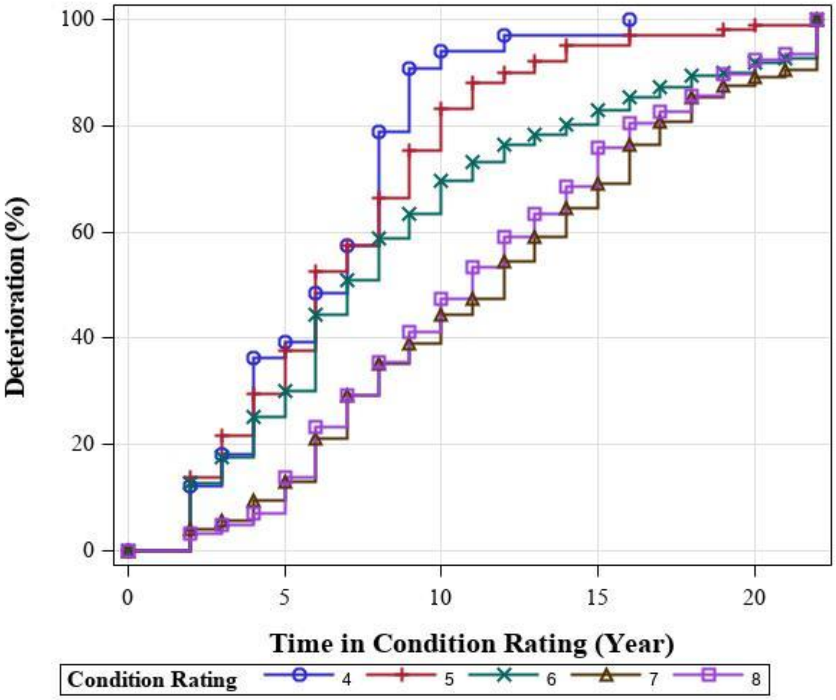

Figure C-27. Deterioration graph for PSC Superstructures in Illinois

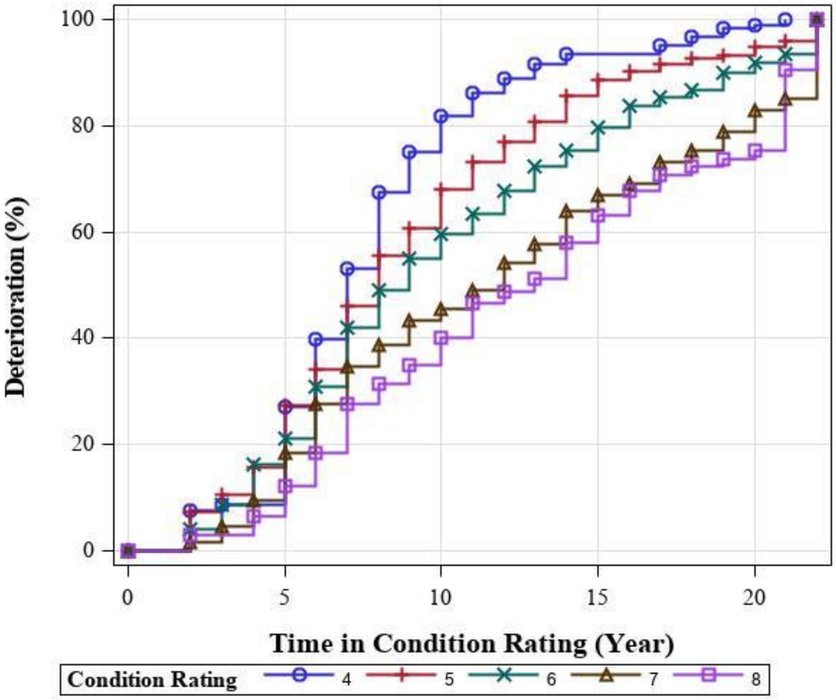

Figure C-28. Deterioration graph for RCC Superstructures in Illinois

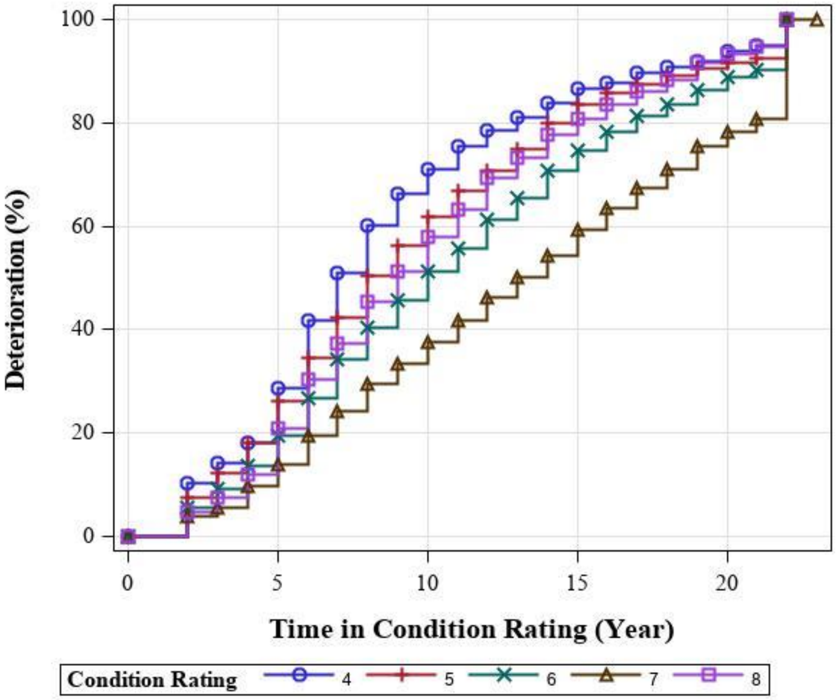

Figure C-29. Deterioration graph for Steel Superstructure in Illinois

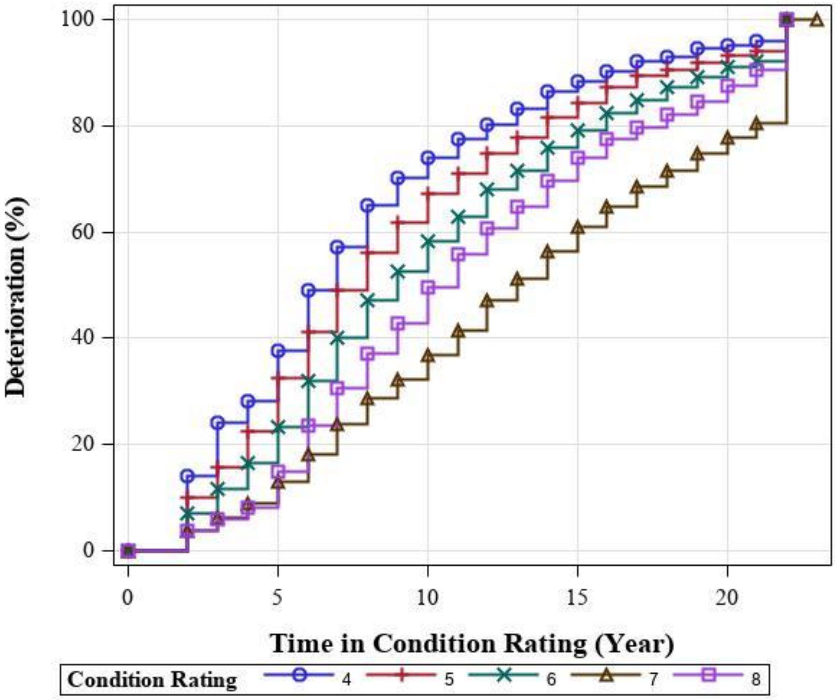

Figure C-30. Deterioration graph for bridge Substructures in Illinois

C.4 Missouri Bridge Components’ graphs

This section contains the graphs for Missouri bridge components. First the tables are presented followed by the bar graphs and reliability and deterioration graphs. How to read graphs are presented in the general information section.

Table C-5. Number of bridge components in Missouri for TICR analysis

Bridge Components	**# of Bridge Components**	**# of Bridge Components in each CR**				
		CR 4	**CR 5**	**CR 6**	**CR 7**	**CR 8**
Deck	16504	1282	3304	5804	8502	6201
PSC Superstructure	2618	13	73	341	1553	1399
RCC Superstructure	1279	239	502	548	383	155
Steel Superstructure	12911	435	2021	5120	7137	4426
Substructure	15809	1201	3406	6286	7391	5388

Table C-6. Kaplan-Meier statistics for Missouri’s bridge components

CR	Median TICR	95% CI for Median TICR		Mean TICR	Standard Error of the mean TICR
		Lower CI	Upper CI		
Deck					
4	6	6	7	7.83	0.13
5	7	7	8	9.28	0.11
6	10	9	10	11.53	0.09
7	10			12.15	0.08
8	9			9.89	0.06
Prestressed Concrete Superstructure					
4	5	3	5	4.92	0.52
5	7	5	8	7.52	0.47
6	11	9	12	11.76	0.36
7	14	13	14	14.15	0.18
8	10			11.10	0.14
Reinforced Concrete Superstructure					
4	9	8	10	10.57	0.35
5	10	10	12	12.39	0.31
6	12	11	13	13.40	0.31
7	10	10	11	12.31	0.34
8	10	9	11	10.84	0.40
Steel Superstructure					
4	6	6	7	7.14	0.19
5	7	7	8	9.25	0.12
6	10			11.59	0.09
7	12	11	12	12.73	0.08
8	11			11.87	0.08
Substructure					
4	6	6	7	7.61	0.13
5	8	8	9	10.10	0.10
6	10			11.49	0.08
7	11			12.41	0.08
8	10	9	10	11.01	0.08

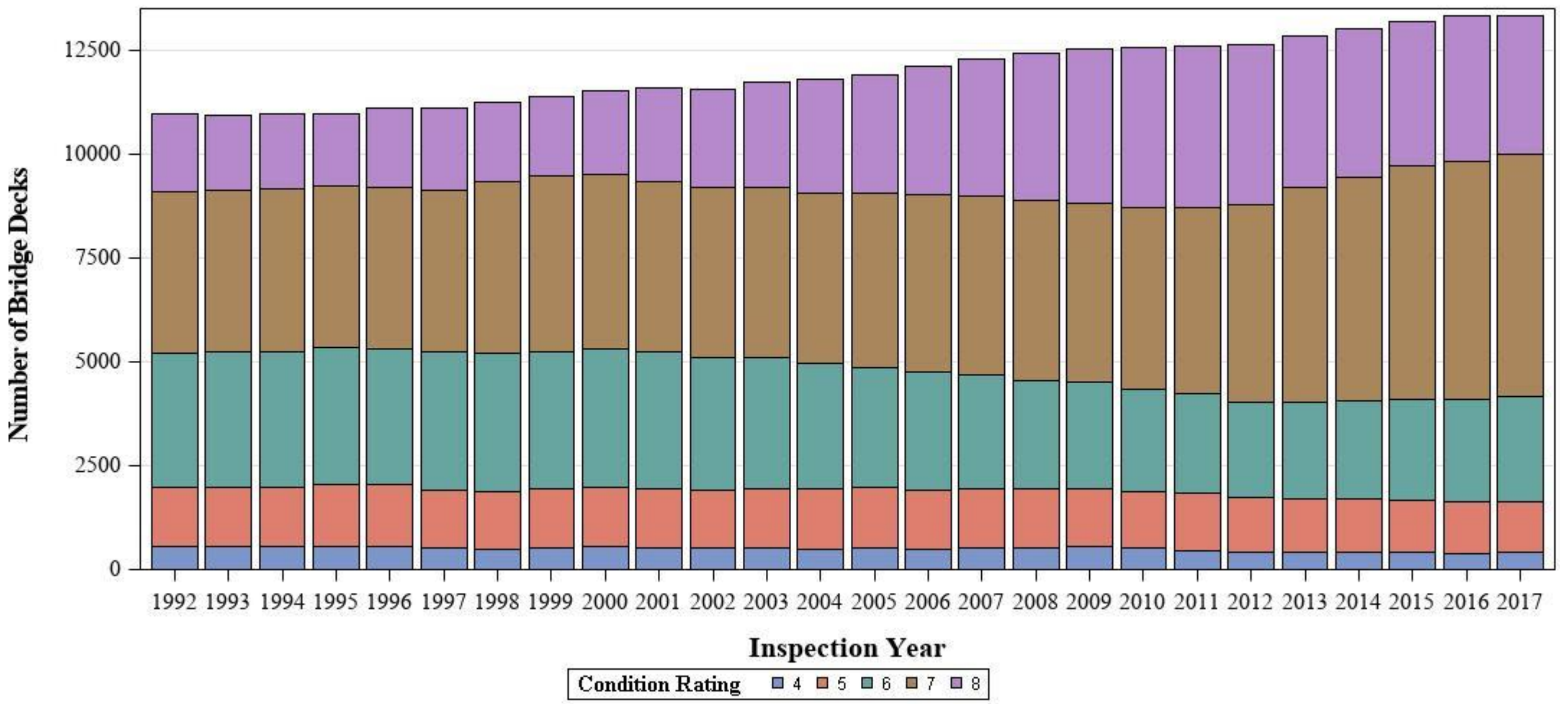

Figure C-31. Bar graph showing the number of bridge Decks in Missouri

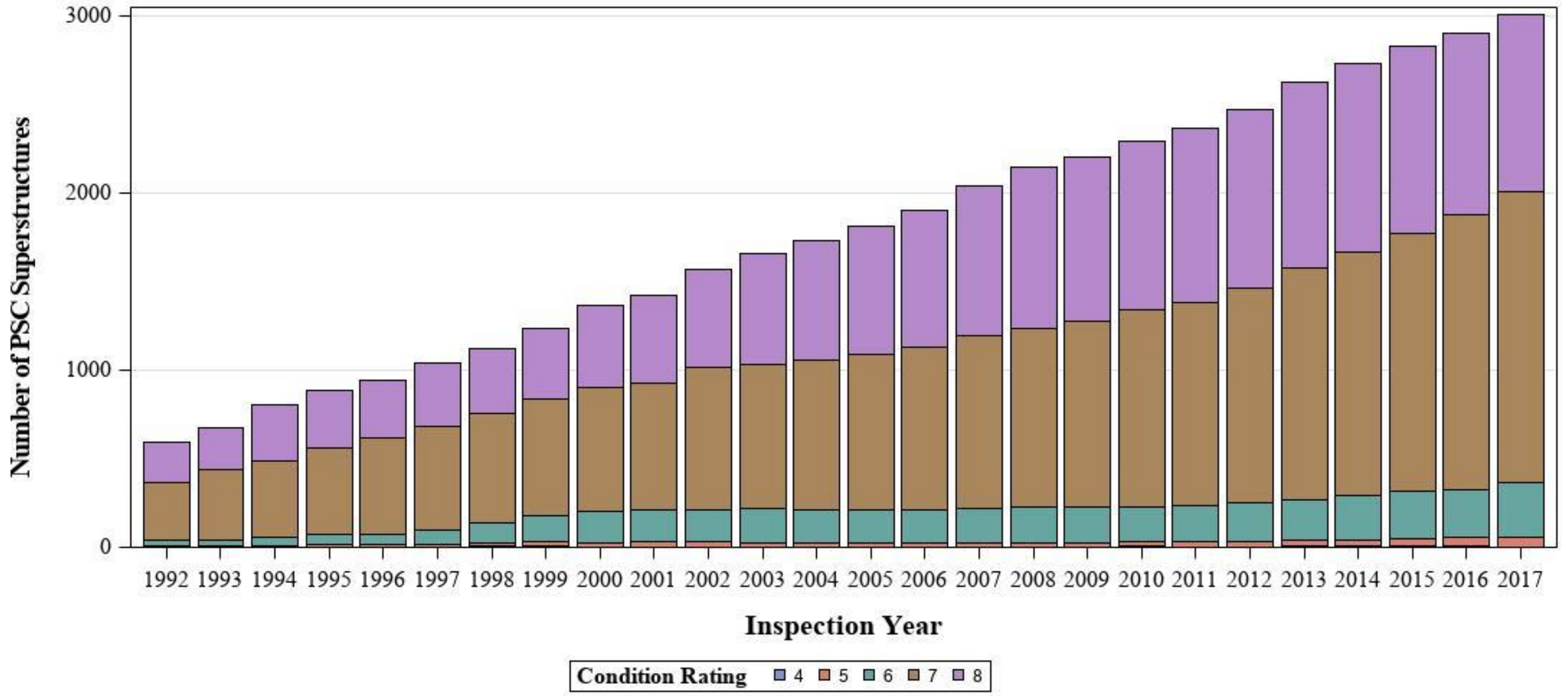

Figure C-32. Bar graph showing the number of PSC Superstructures in Missouri

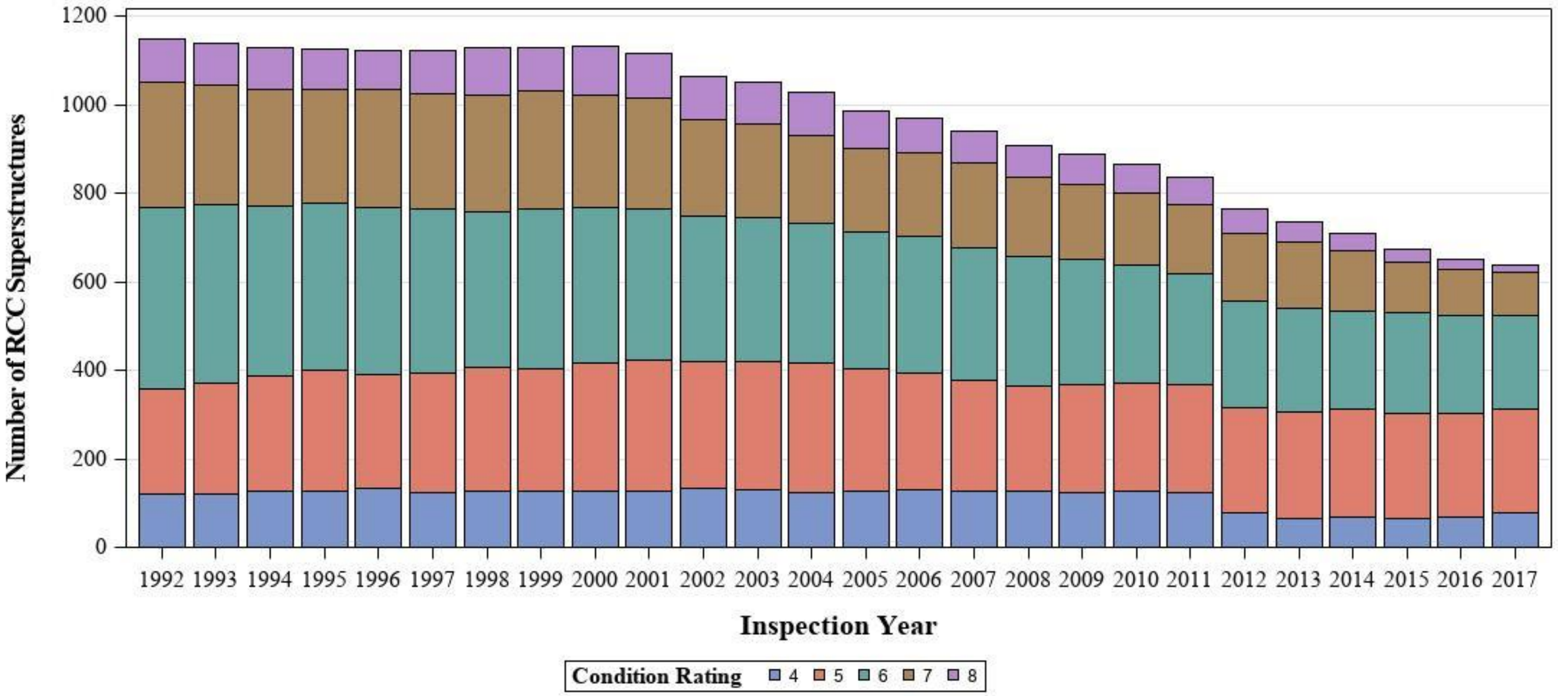

Figure C-33. Bar graph showing the number of RCC Superstructures in Missouri

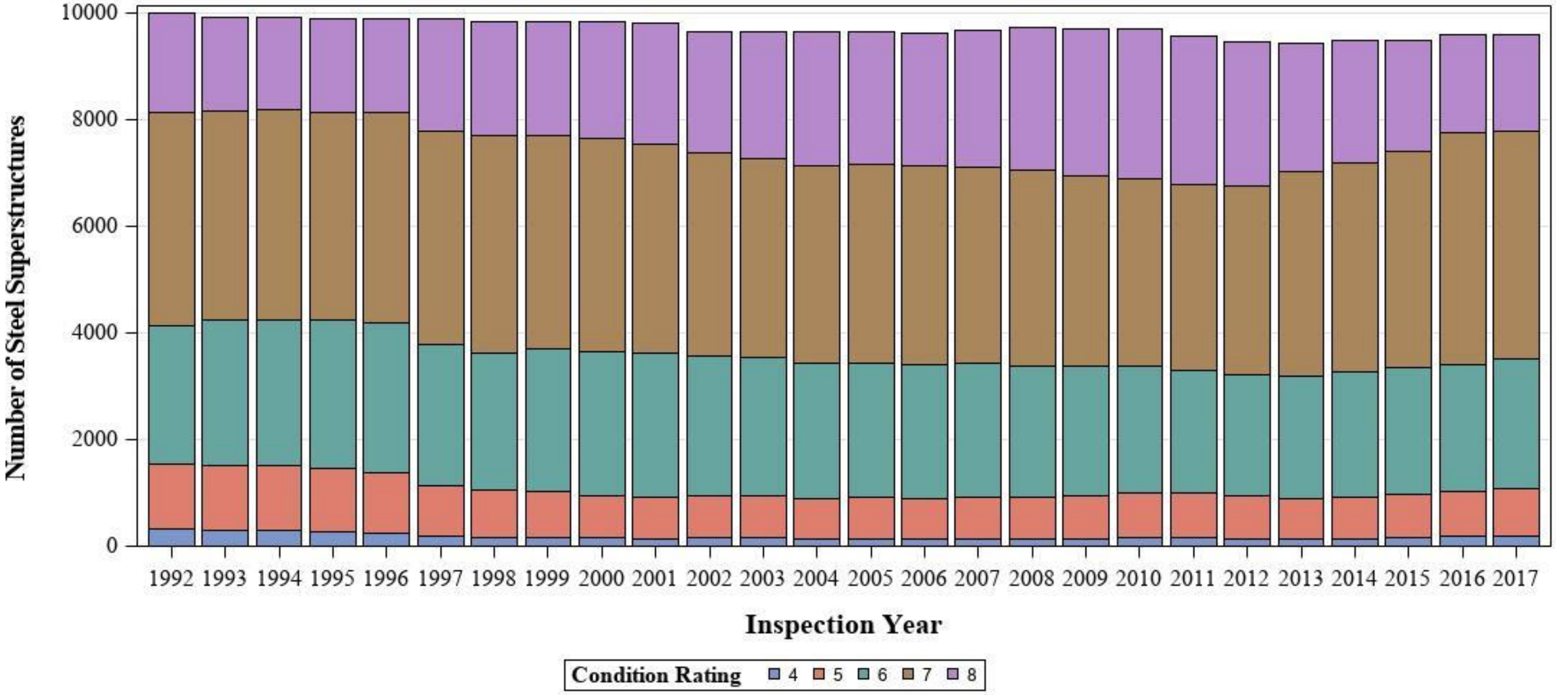

Figure C-34. Bar graph showing the number of Steel Superstructures in Missouri

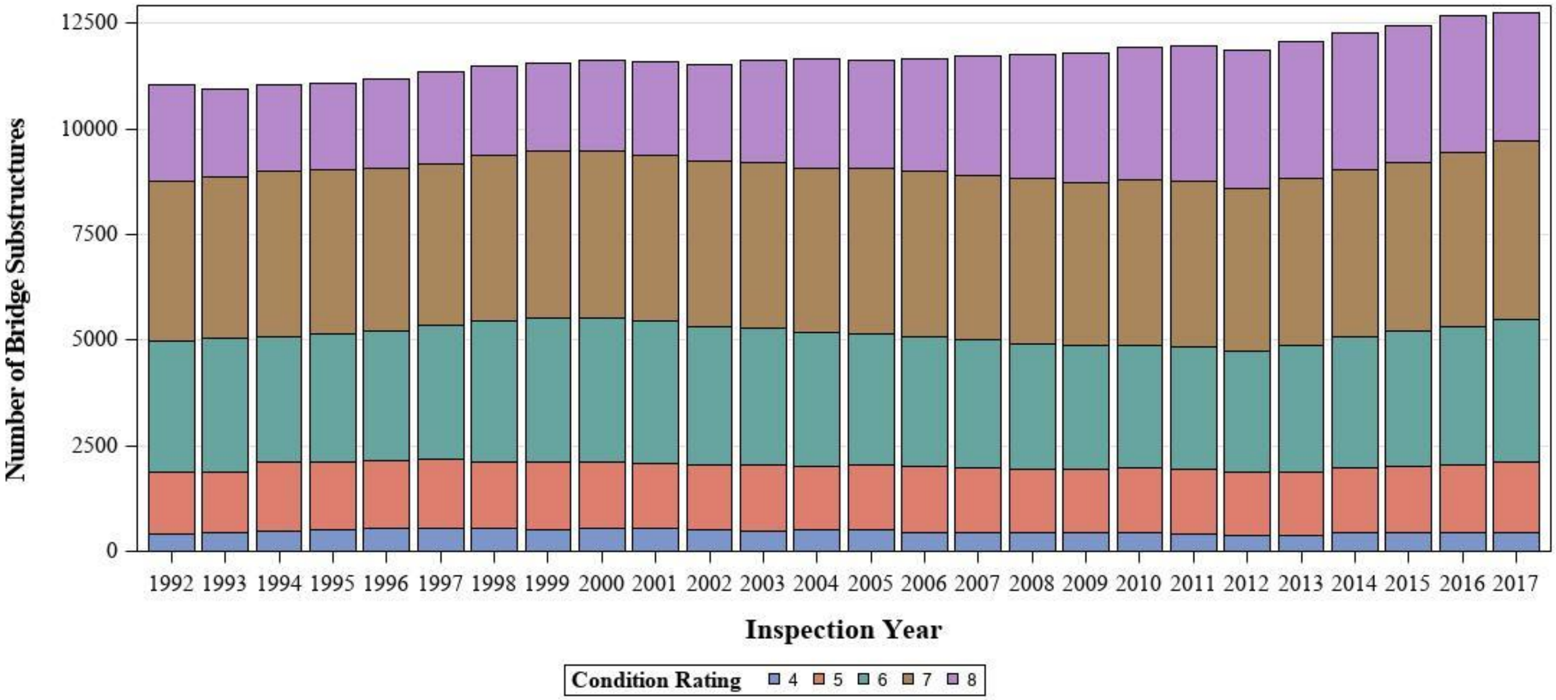

Figure C-35. Bar graph showing the number of bridge Substructures in Missouri

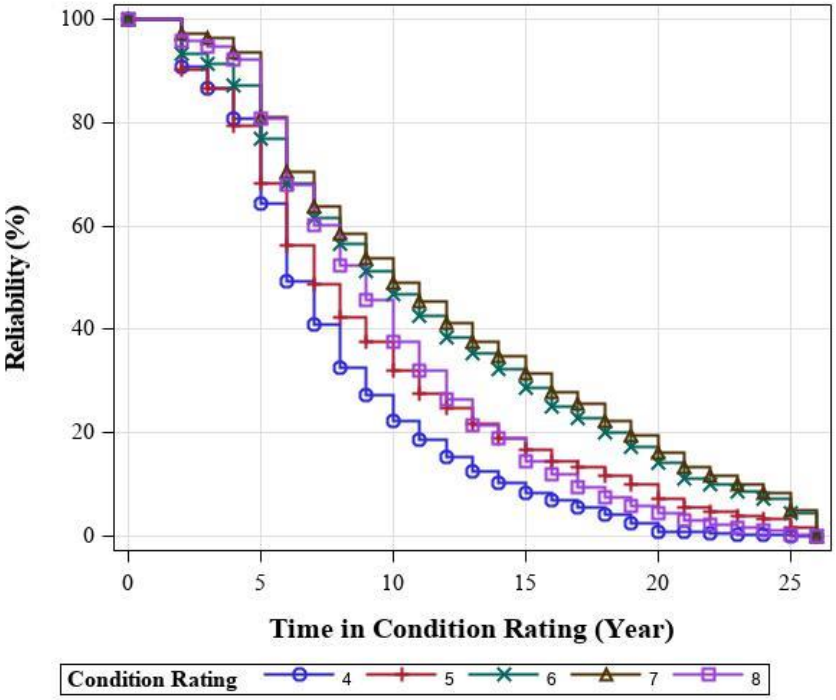

Figure C-36. Reliability graph for bridge Decks in Missouri

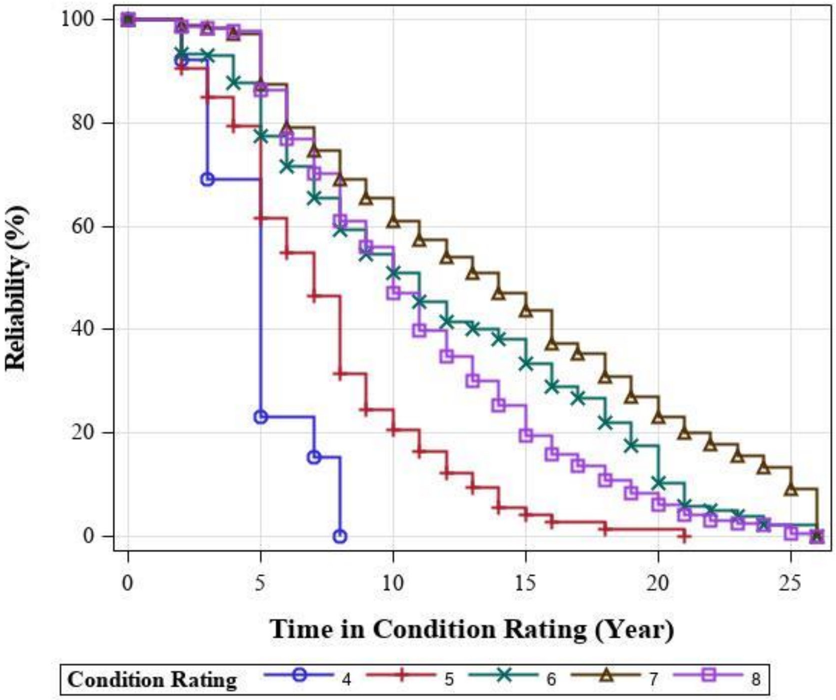

Figure C-37. Reliability graph for PSC Superstructures in Missouri

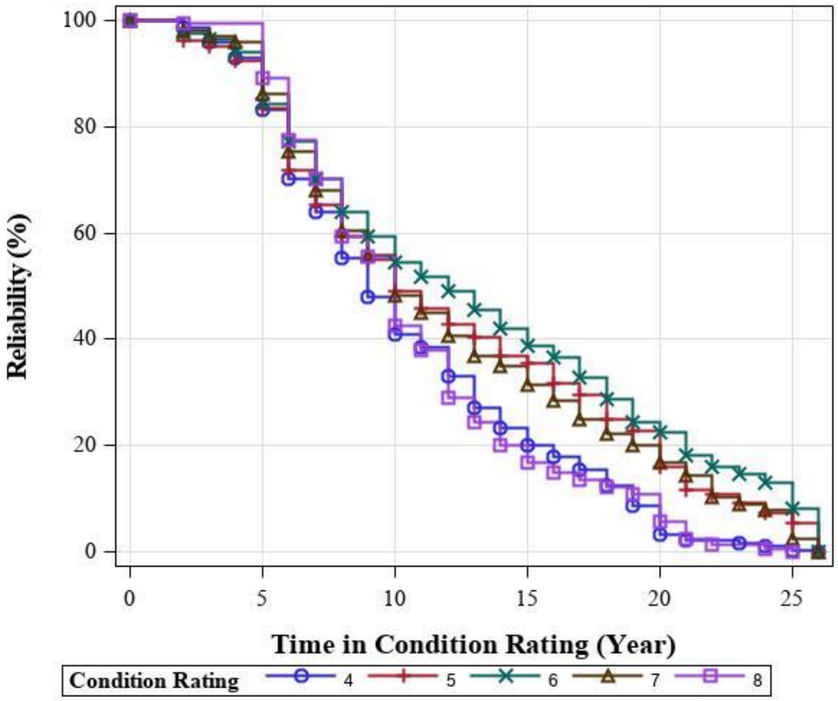

Figure C-38. Reliability graph for RCC Superstructures in Missouri

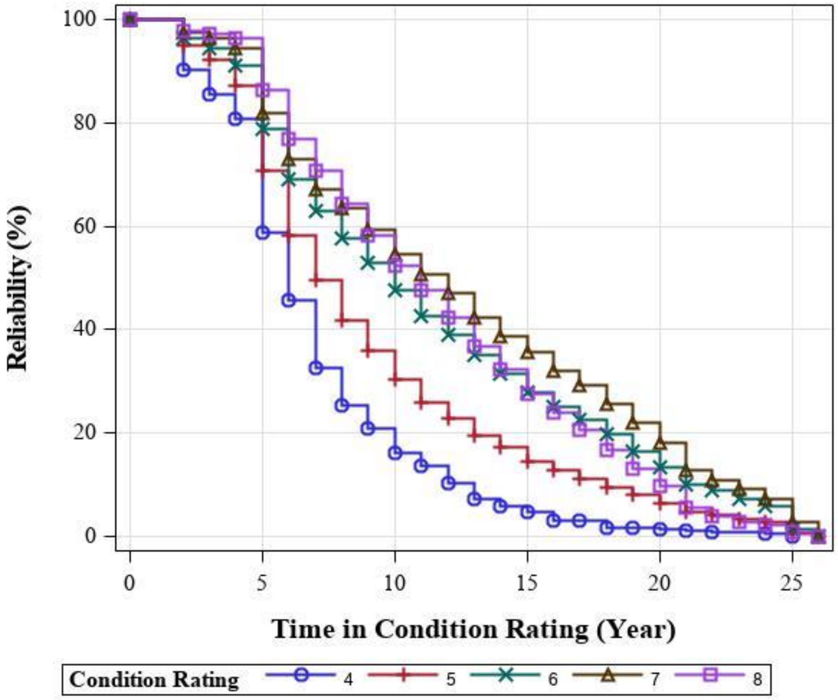

Figure C-39. Reliability graph for Steel Superstructures in Missouri

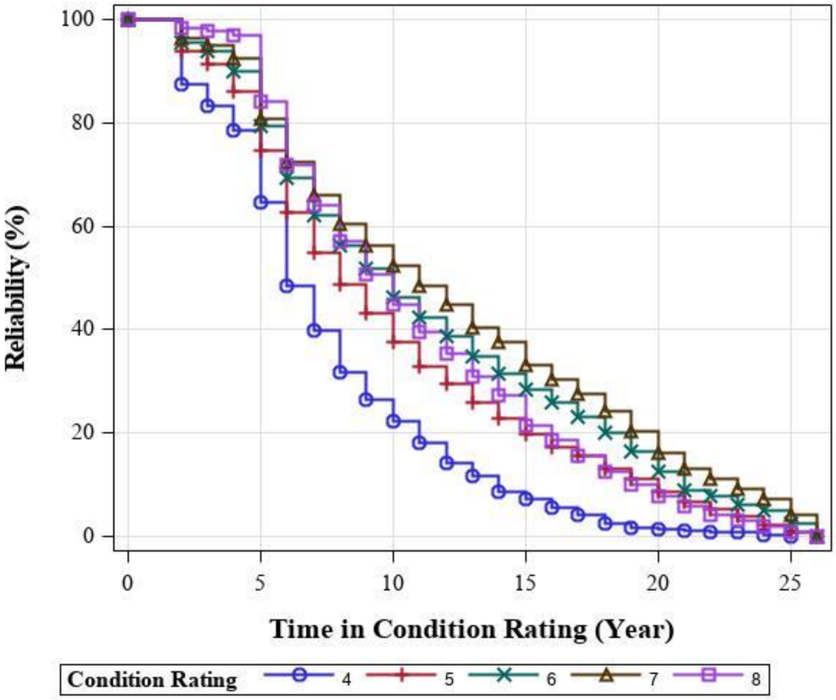

Figure C-40. Reliability graph for bridge Substructures in Missouri

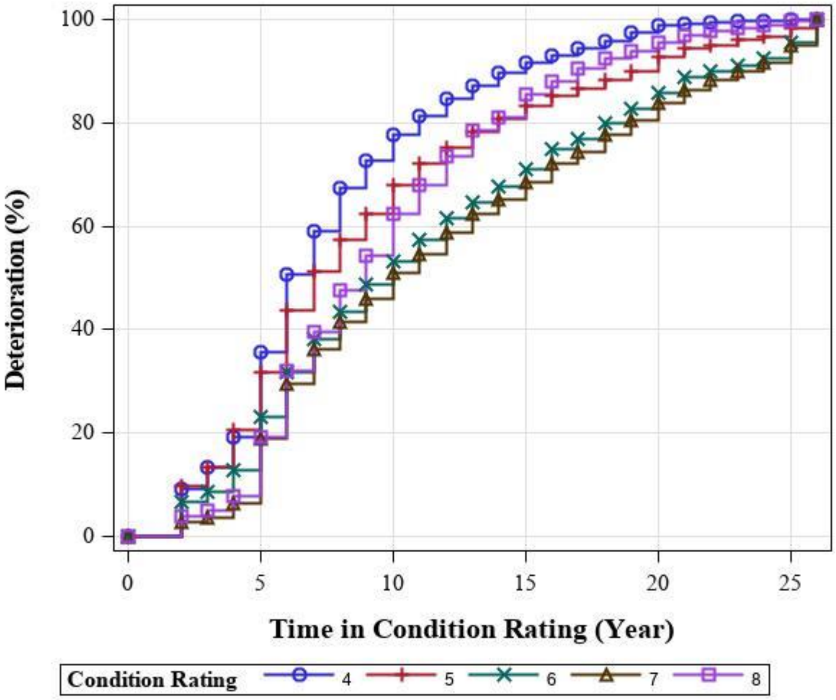

Figure C-41. Deterioration graph for bridge Decks in Missouri

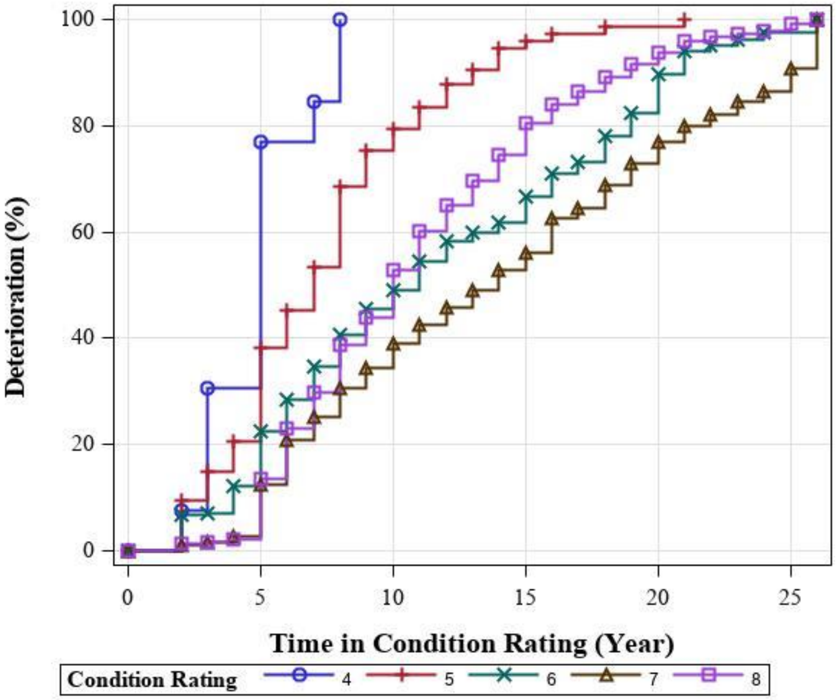

Figure C-42. Deterioration graph for PCS Superstructure in Missouri

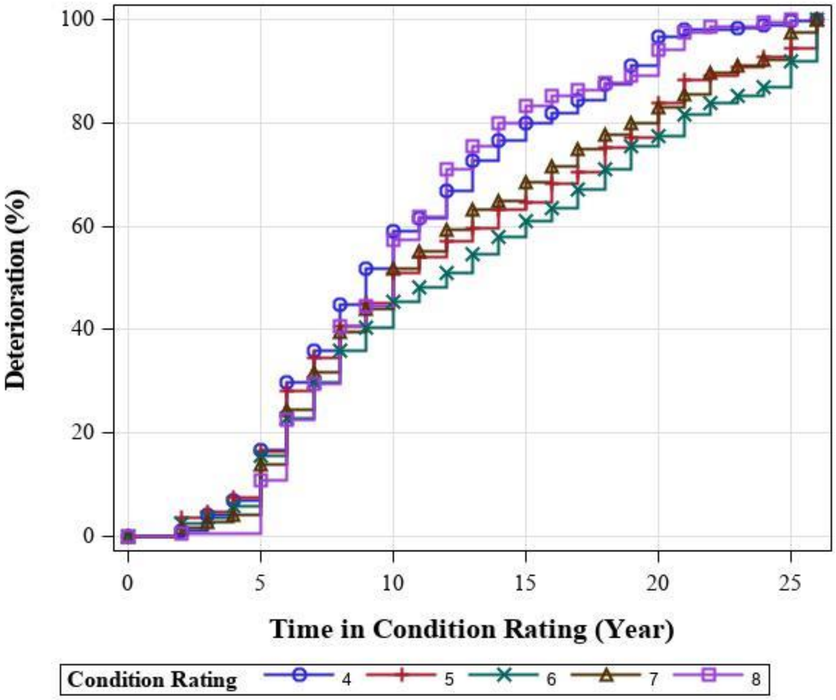

Figure C-43. Deterioration graph for RCC Superstructure in Missouri

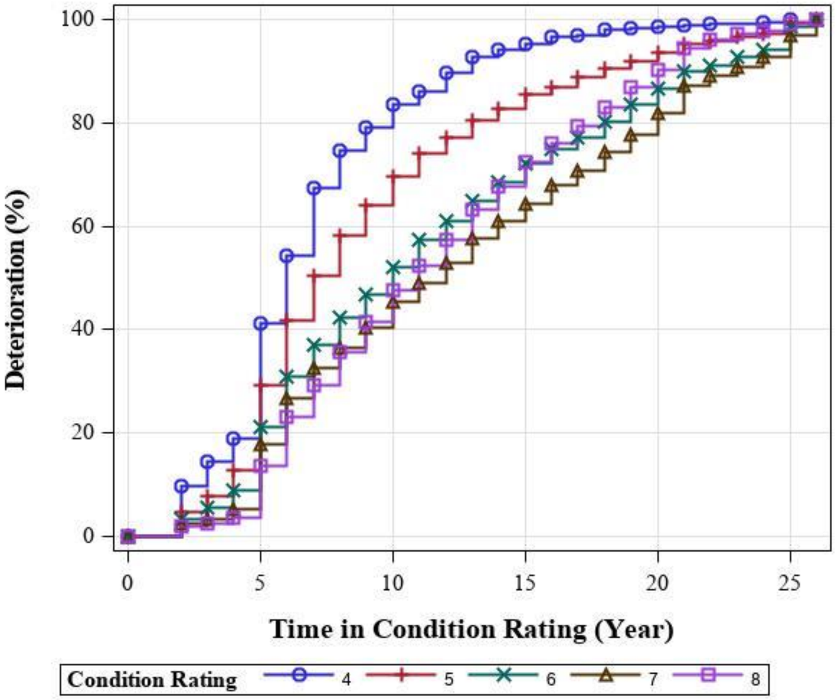

Figure C-44. Deterioration graph for Steel Superstructure in Missouri

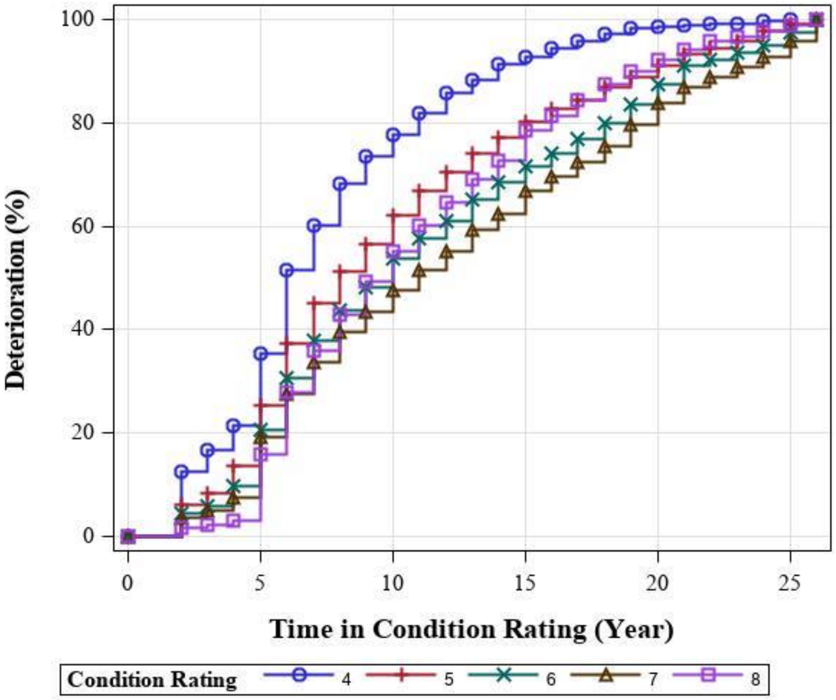

Figure C-45. Deterioration graph for bridge Substructures in Missouri

C.5 New York Bridge Components' graphs

This section contains the graphs for New York bridge components. First the tables are presented followed by the bar graphs and reliability and deterioration graphs. How to read graphs are presented in the general information section.

Table C-7. Number of bridge components in New York for TICR analysis

Bridge Components	**# of Bridge Components**	**# of Bridge Components in each CR**				
		CR 4	**CR 5**	**CR 6**	**CR 7**	**CR 8**
Deck	11089	4136	5742	5889	4848	4048
PSC Superstructure	572	63	134	196	266	333
RCC Superstructure	212	120	130	89	33	23
Steel Superstructure	10126	2305	5055	6277	5188	4177
Substructure	11005	4824	6960	6905	5245	3174

Table C-8. Kaplan-Meier statistics for New York's bridge components

CR	Median TICR	95% CI for Median TICR		Mean TICR	Standard Error of the mean TICR
		Lower CI	Upper CI		
Deck					
4	7			8.51	0.08
5	7			9.07	0.08
6	8	7	8	9.20	0.08
7	8			8.80	0.08
8	8	8	9	9.97	0.10
Prestressed Concrete Superstructure					
4	6	5	6	5.90	0.48
5	7	6	8	7.82	0.43
6	6	6	8	8.10	0.35
7	8	8	10	8.74	0.30
8	9	8	10	10.01	0.28
Reinforced Concrete Superstructure					
4	7	7	8	8.94	0.45
5	9	8	10	10.14	0.47
6	8	7	10	9.46	0.63
7	8	6	12	9.33	0.96
8	6	2	10	7.78	1.21
Steel Superstructure					
4	6			6.73	0.08
5	6	6	7	7.87	0.07
6	7			8.73	0.07
7	8	8	9	9.20	0.08
8	10			11.02	0.10
Substructure					
4	6			7.11	0.06
5	7			8.22	0.06
6	7	7	8	8.55	0.07
7	8			8.90	0.07
8	8			8.56	0.094

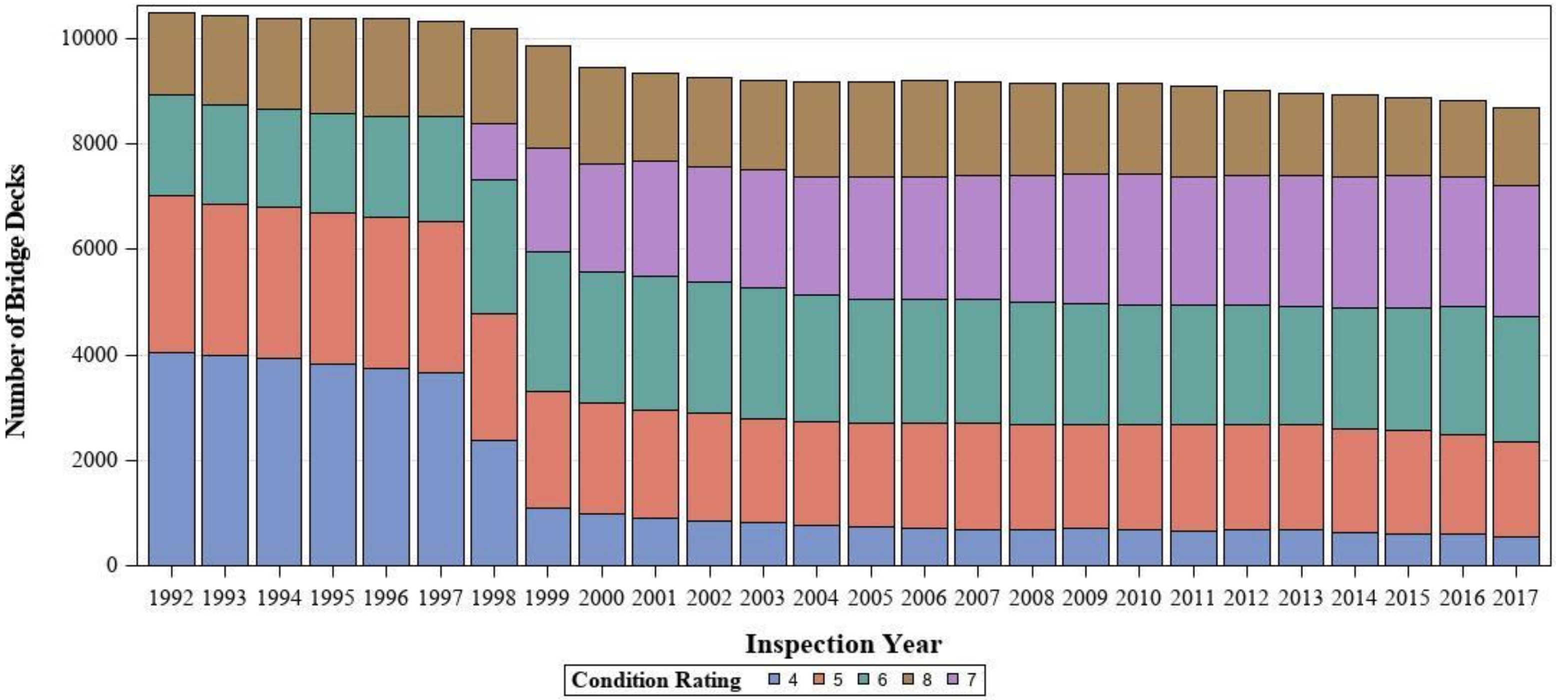

Figure C-46. Bar graph showing the number of bridge Decks in New York

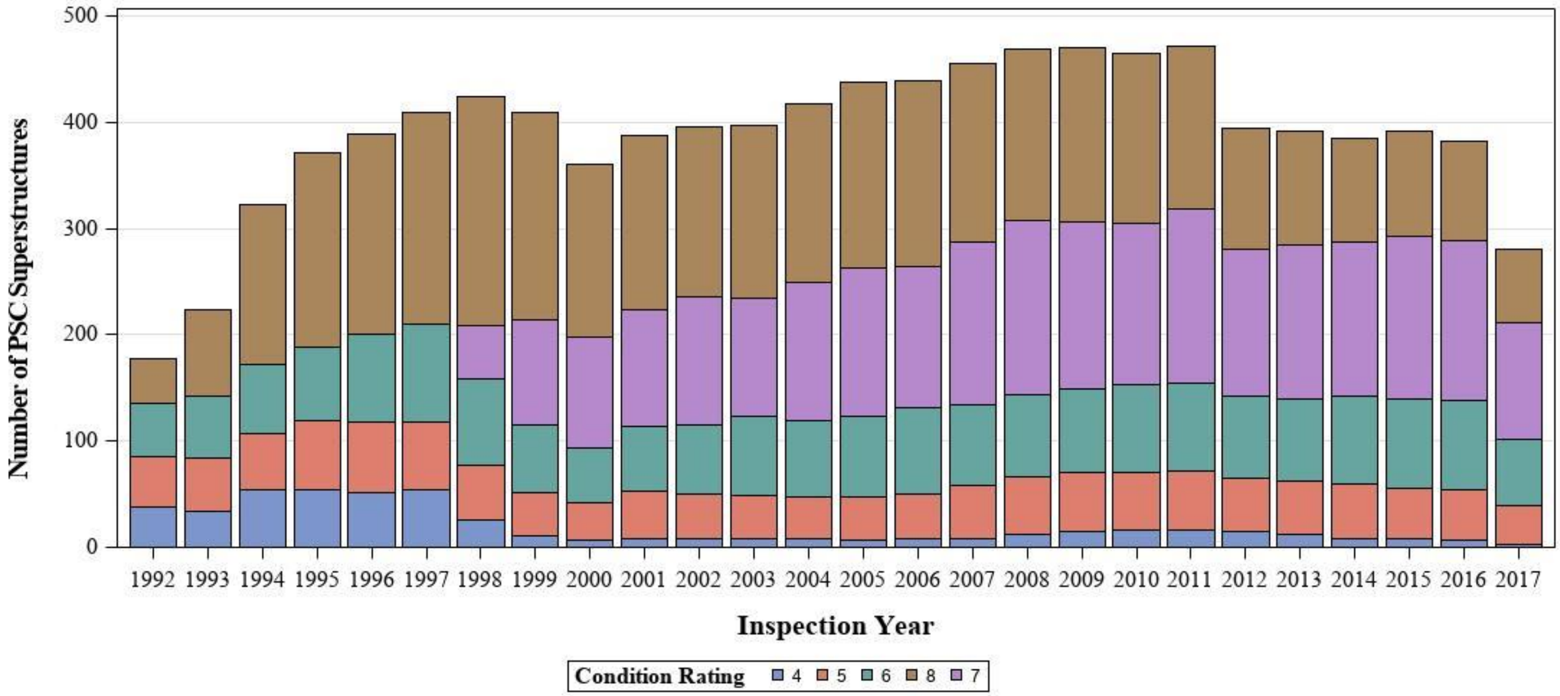

Figure C-47. Bar graph showing the number of PSC Superstructures in New York

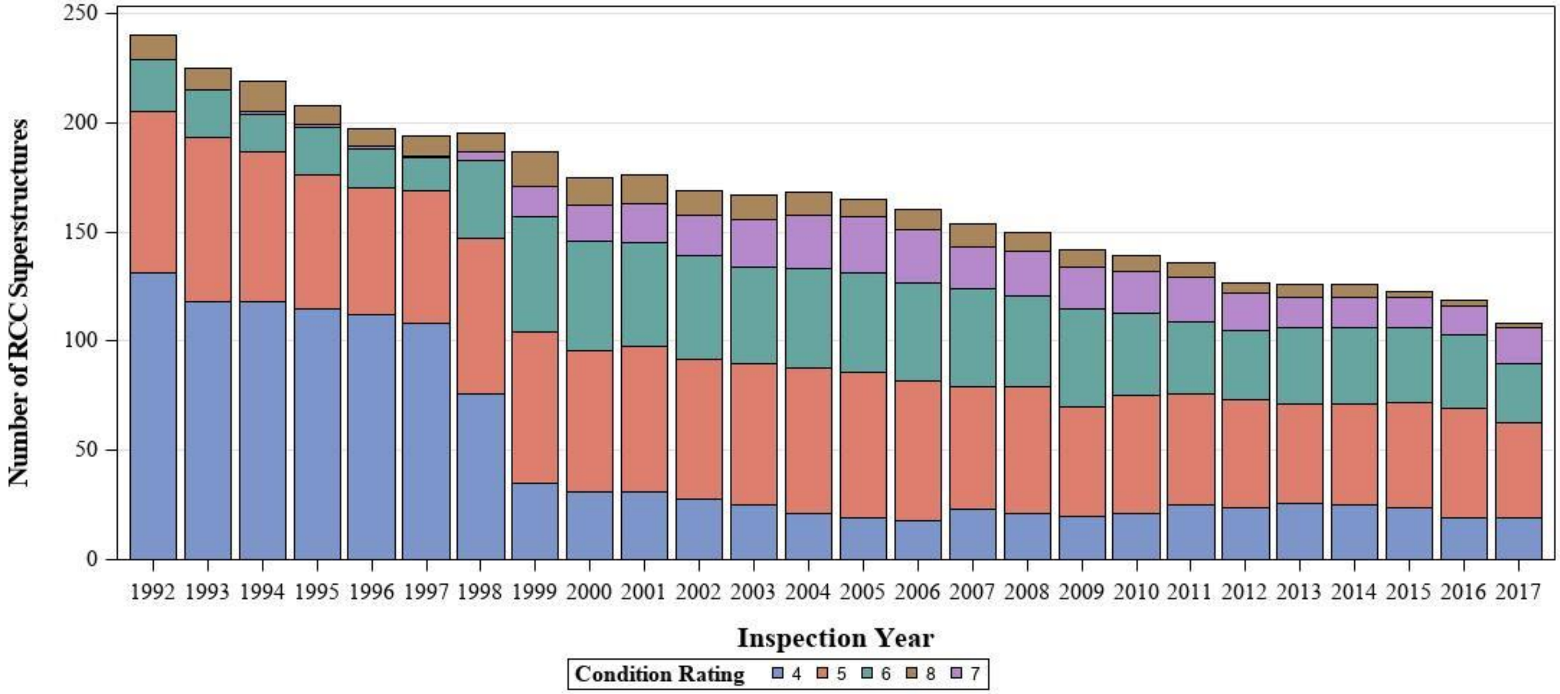

Figure C-48. Bar graph showing the number of RCC Superstructures in New York

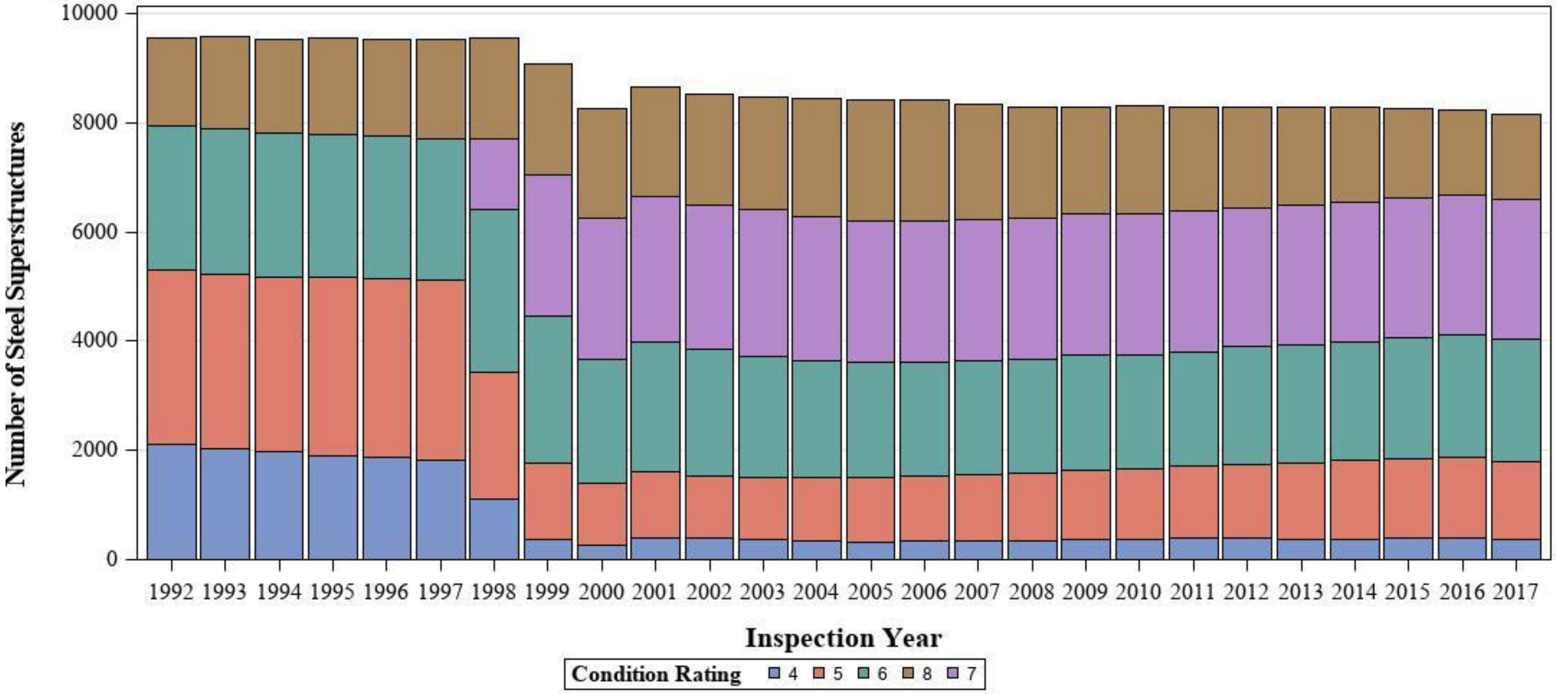

Figure C-49. Bar graph showing the number of Steel Superstructures in New York

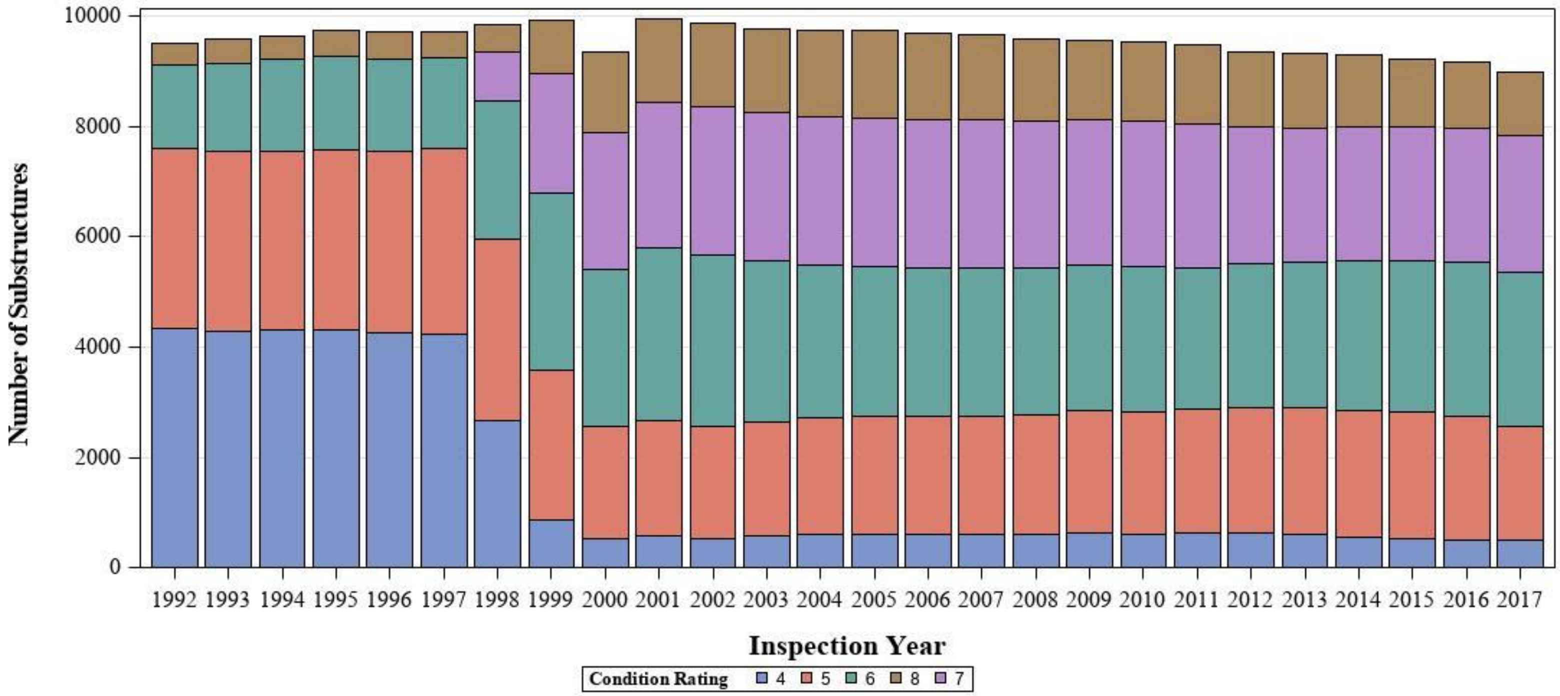

Figure C-50. Bar graph showing the number of Substructures in New York

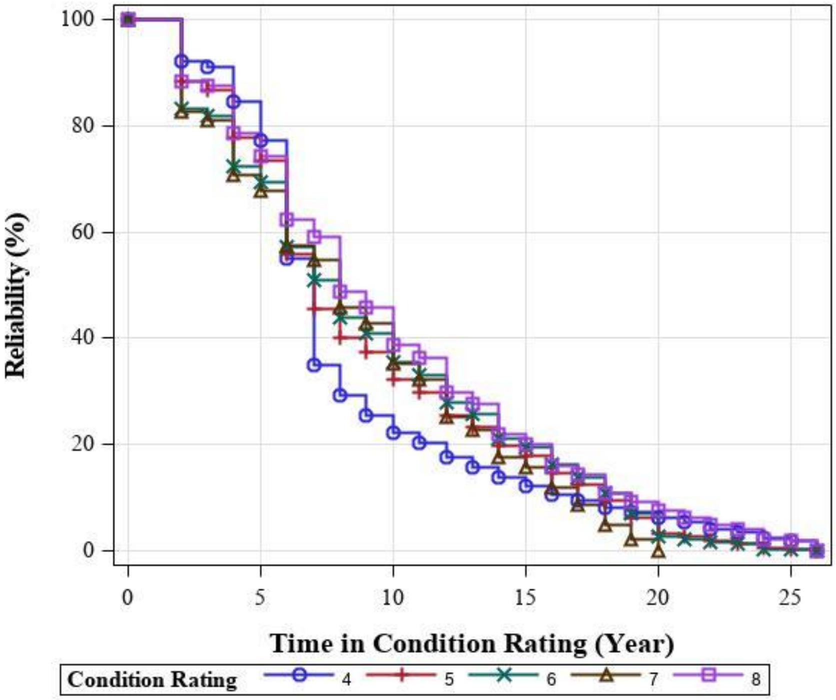

Figure C-51. Reliability graph for bridge Decks in New York

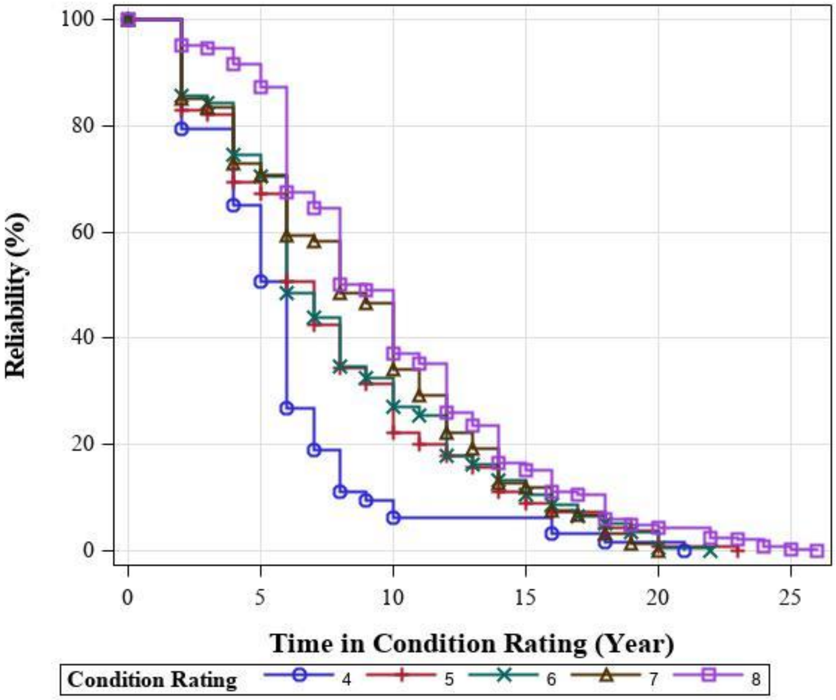

Figure C-52. Reliability graph for PSC Superstructures in New York

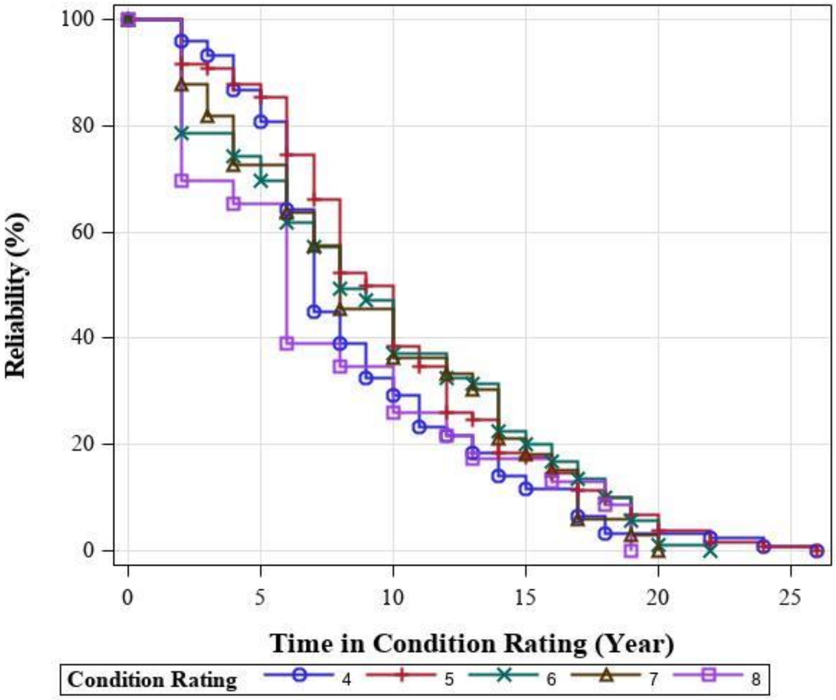

Figure C-53. Reliability graph for RCC Superstructures in New York

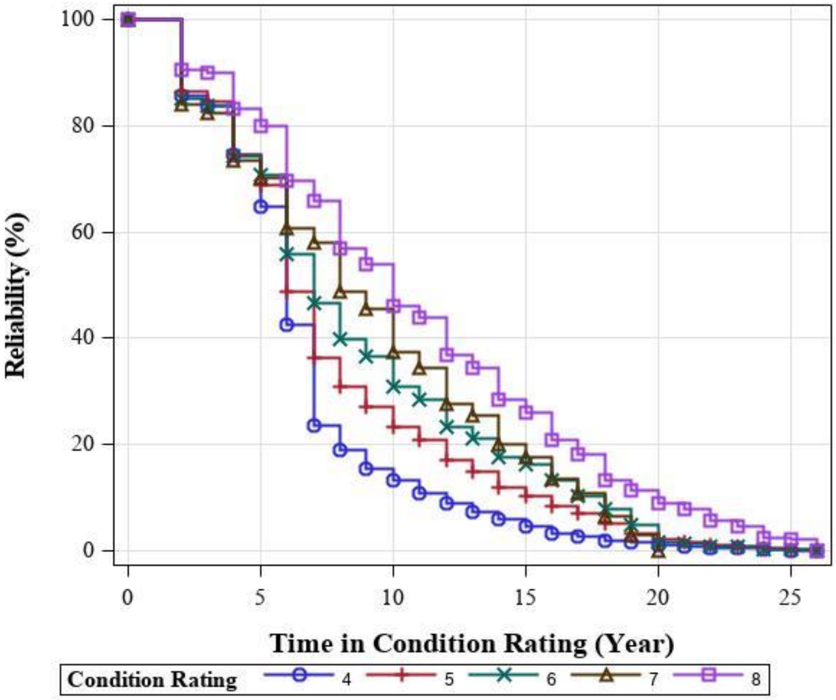

Figure C-54. Reliability graph for Steel Superstructures in New York

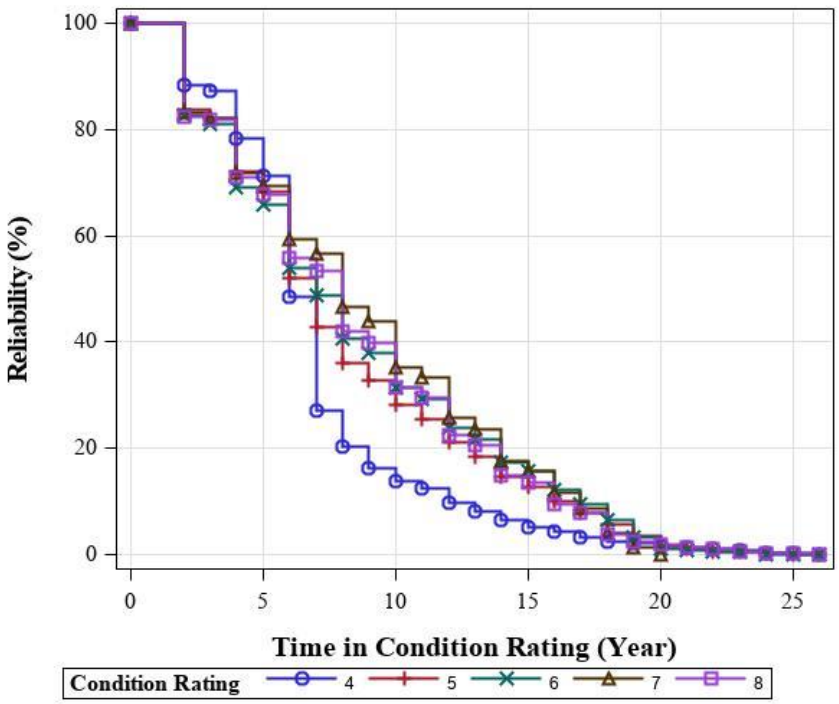

Figure C-55. Reliability graph for bridge Substructures in New York

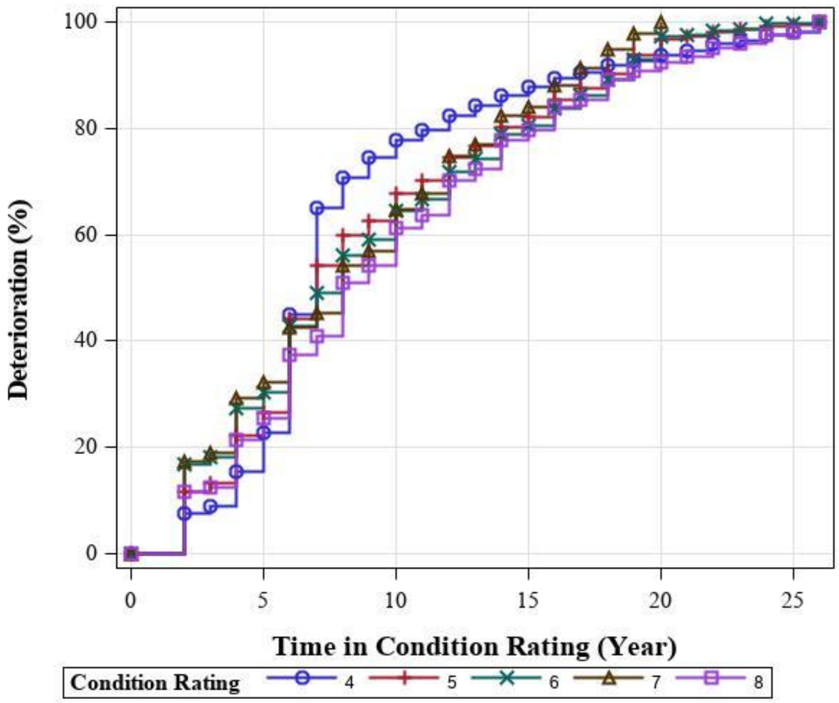

Figure C-56. Deterioration graph for bridge Decks in New York

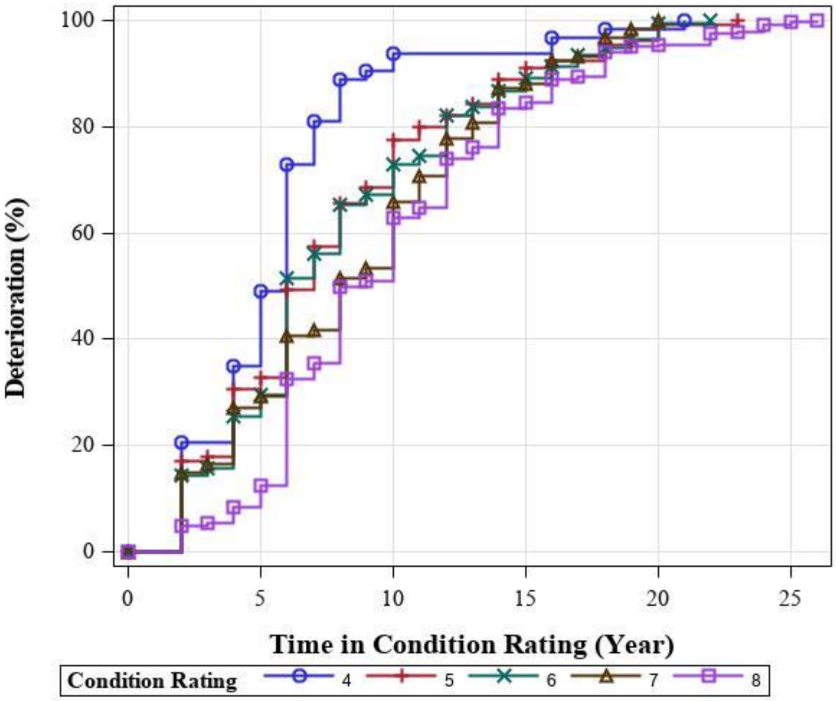

Figure C-57. Deterioration graph for PSC Superstructures in New York

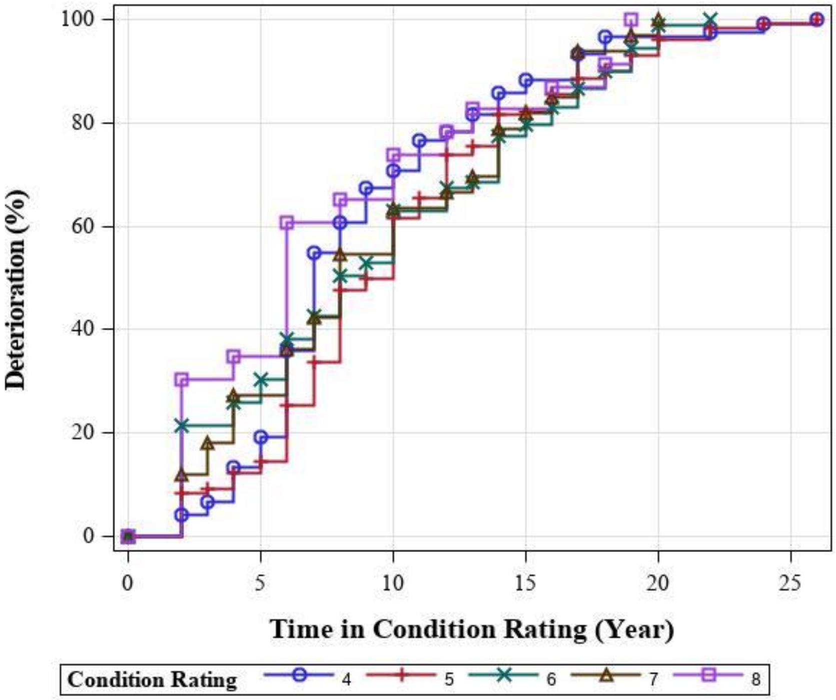

Figure C-58. Deterioration graph for RCC Superstructures in New York

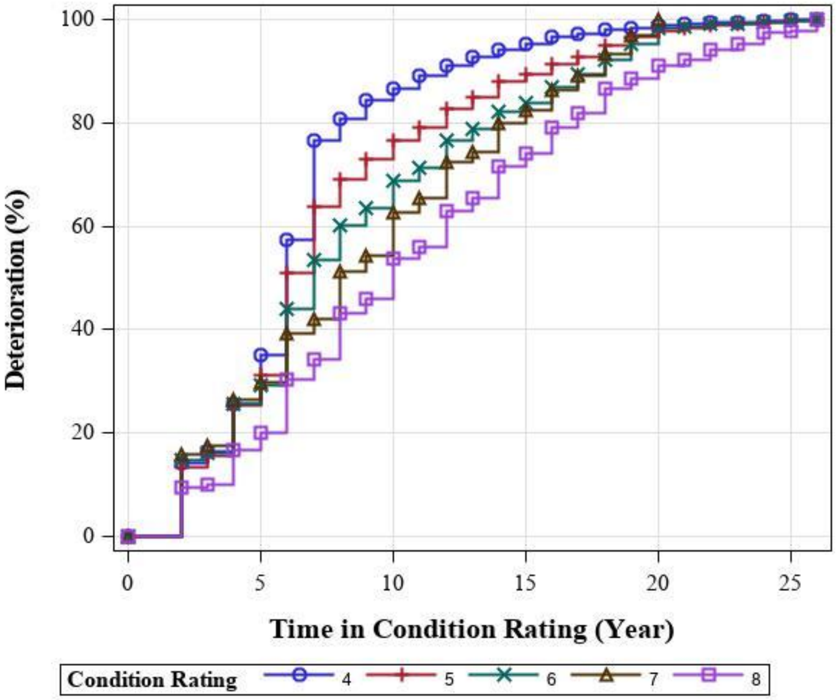

Figure C-59. Deterioration graph for Steel Superstructures in New York

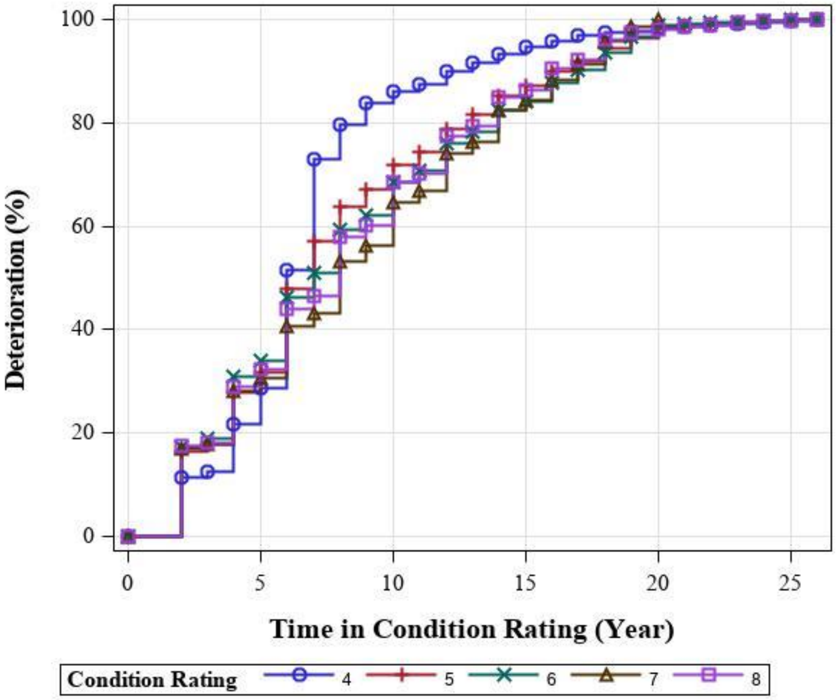

Figure C-60. Deterioration graph for gridge Substructures in New York

C.6 Pennsylvania Bridge Components' graphs

This section contains the graphs for Pennsylvania bridge components. First the tables are presented followed by the bar graphs and reliability and deterioration graphs. How to read graphs are presented in the general information section.

Table C-9. Number of bridge components in Pennsylvania for TICR analysis

Bridge Components	# of Bridge Components	# of Bridge Components in each CR				
		CR 4	CR 5	CR 6	CR 7	CR 8
Deck	21417	3132	7046	7795	6804	2036
PSC Superstructure	2814	45	335	845	1289	793
RCC Superstructure	6083	1677	2965	1658	777	67
Steel Superstructure	12465	1907	4632	4309	3234	1550
Substructure	21569	3617	8281	7784	6065	1181

Table C-10. Kaplan-Meier statistics for Pennsylvania's bridge components

CR	Median TICR	95% CI for Median TICR		Mean TICR	Standard Error of the mean TICR
		Lower CI	Upper CI		
Deck					
4	7			8.76	0.08
5	7			9.14	0.05
6	7			8.66	0.05
7	7			8.48	0.05
8	6	6	7	7.00	0.08
Prestressed Concrete Superstructure					
4	7	6	7	7.56	0.50
5	7			8.37	0.21
6	7			8.50	0.14
7	7			8.74	0.11
8	7			8.39	0.14
Reinforced Concrete Superstructure					
4	7	7	8	9.92	0.12
5	7			10.00	0.09
6	7			9.14	0.11
7	7	7	8	9.56	0.17
8	6	5	6	7.22	0.51
Steel Superstructure					
4	7			8.32	0.09
5	7			9.01	0.06
6	7			8.43	0.06
7	7			8.64	0.07
8	7			7.94	0.10
Substructure					
4	7			8.81	0.07
5	7			8.93	0.05
6	7			8.60	0.05
7	7			8.67	0.05
8	7			7.36	0.11

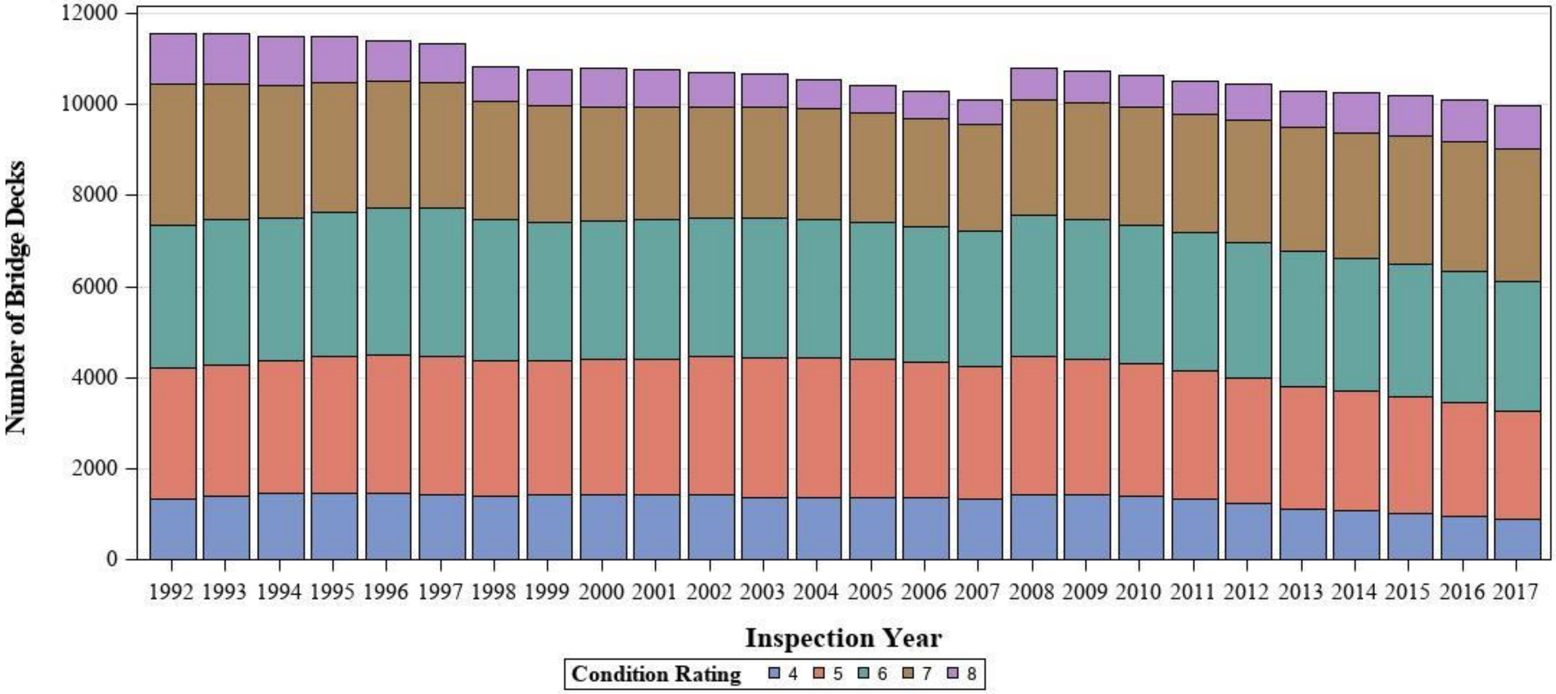

Figure C-61. Bar graph showing the number of bridge Decks in Pennsylvania

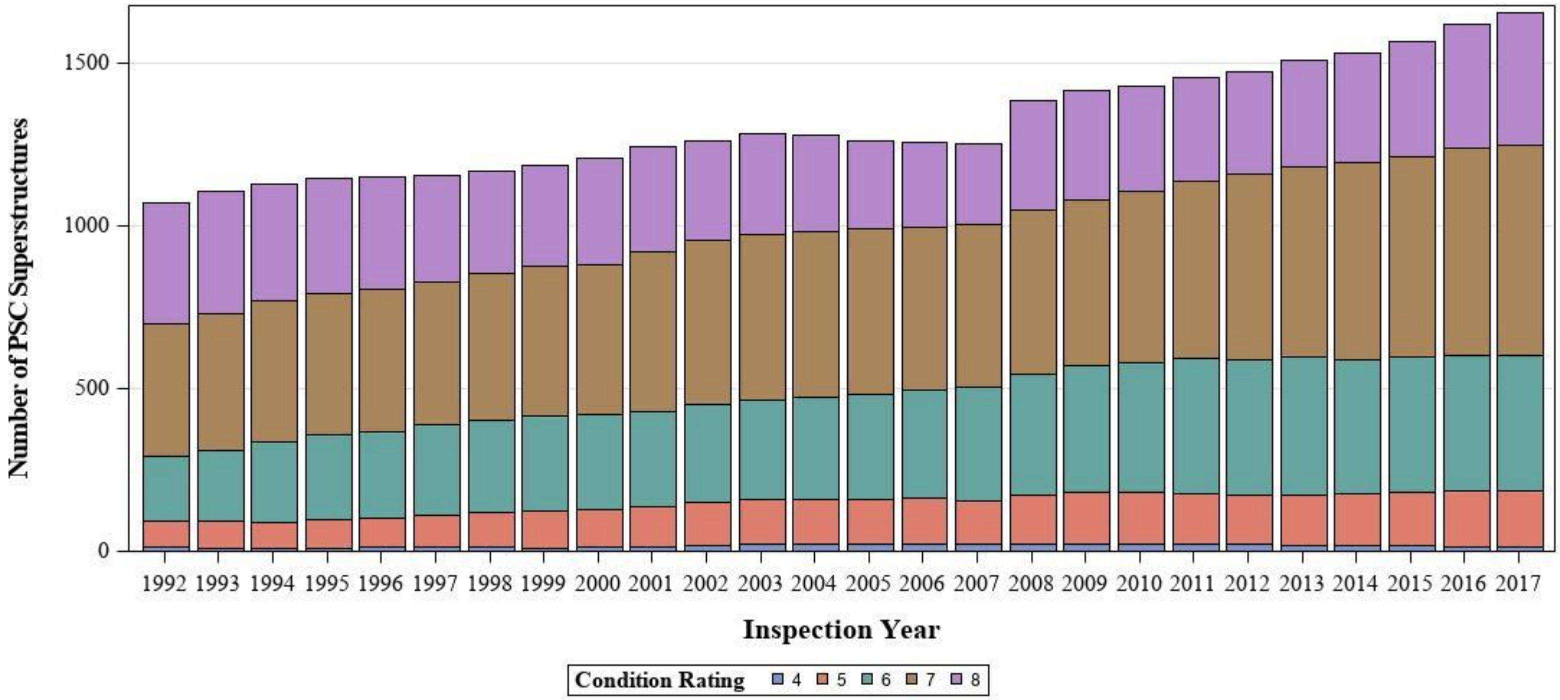

Figure C-62. Bar graph showing the number of PSC Superstructures in Pennsylvania

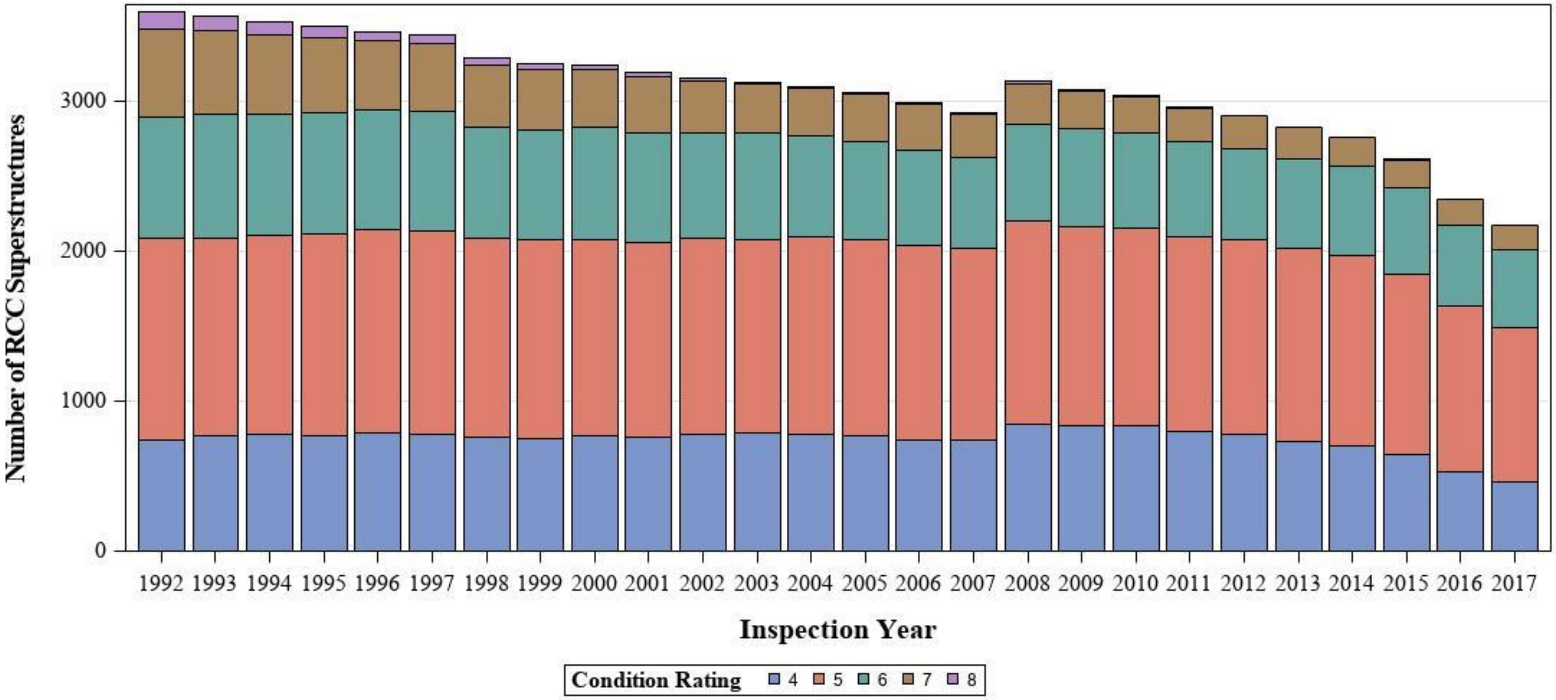

Figure C-63. Bar graph showing the number of RCC Superstructures in Pennsylvania

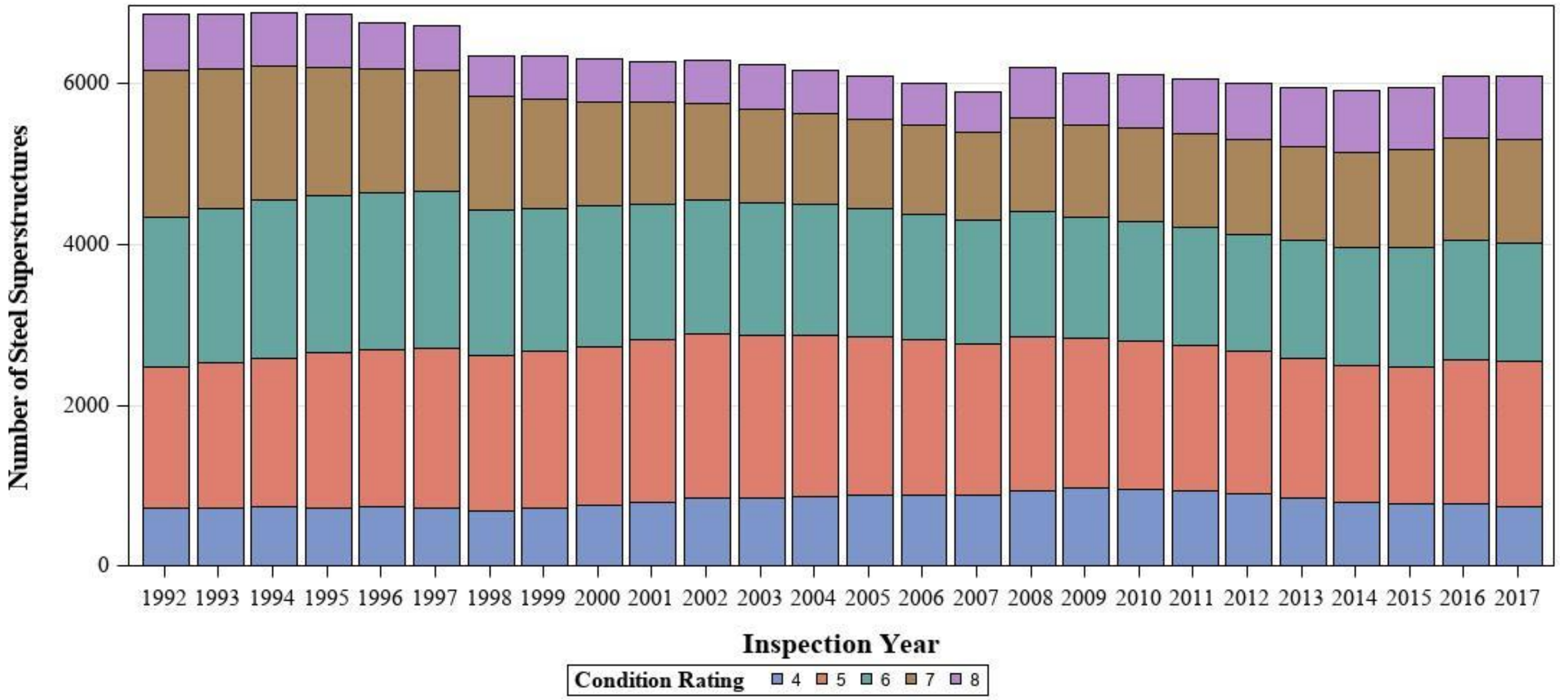

Figure C-64. Bar graph showing the number of Steel Superstructures in Pennsylvania

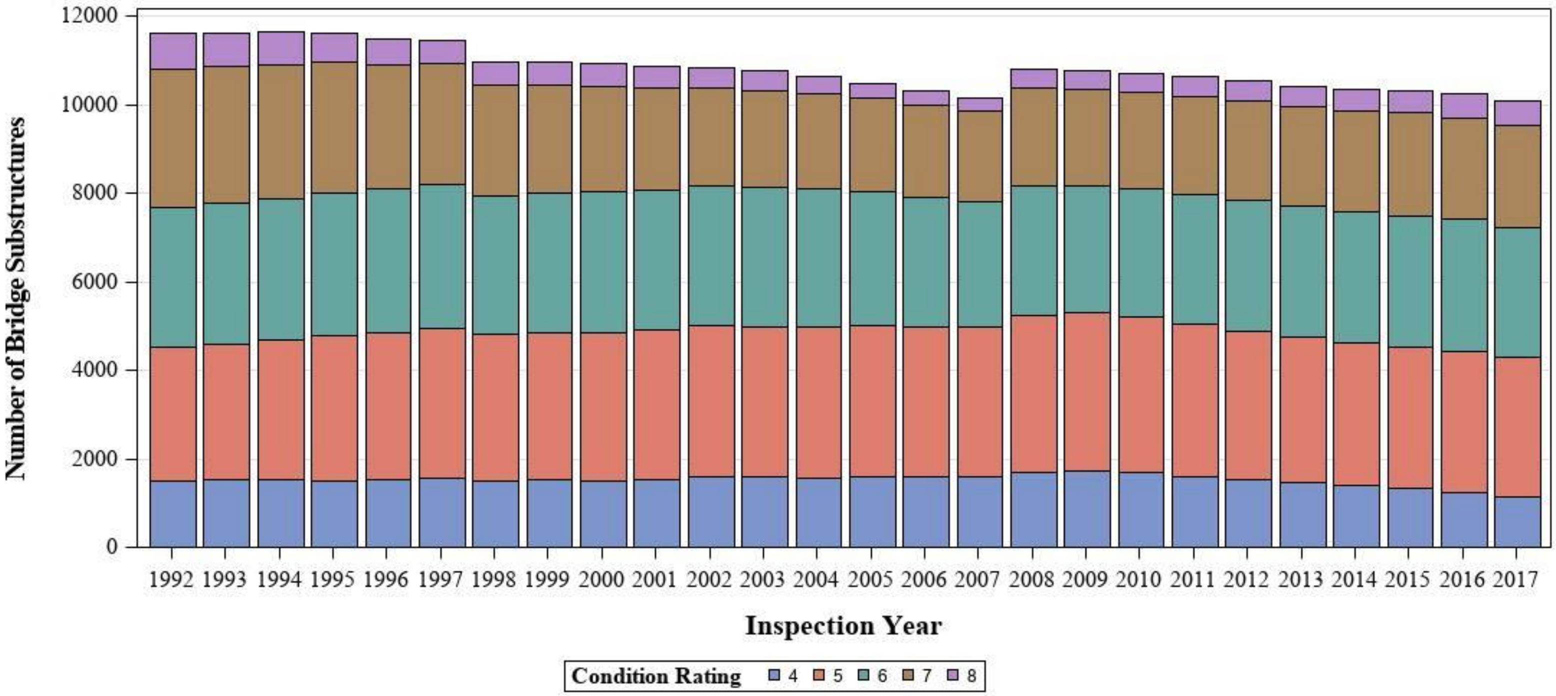

Figure C-65. Bar graph showing the number of bridge Substructures in Pennsylvania

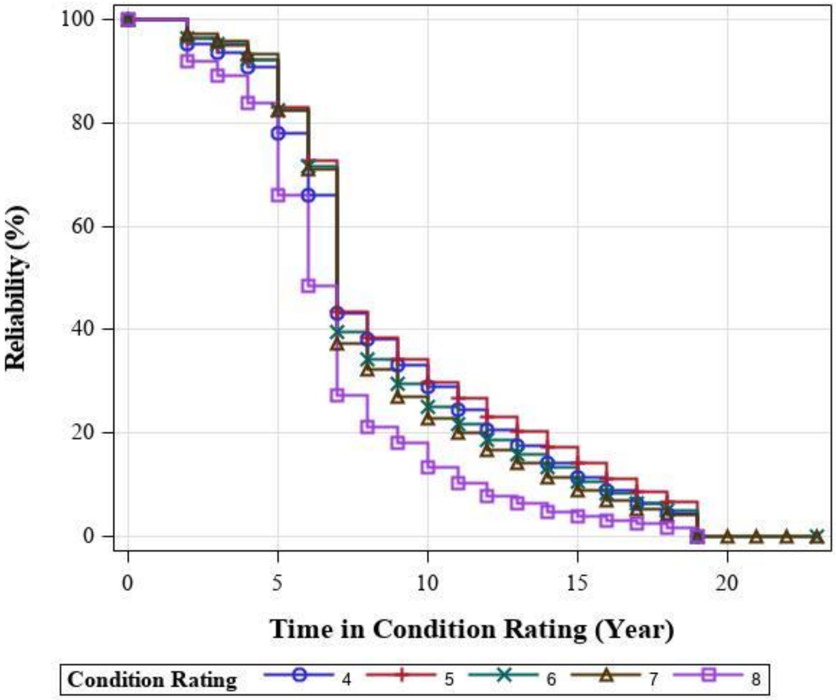

Figure C-66. Reliability graph for bridge Decks in Pennsylvania

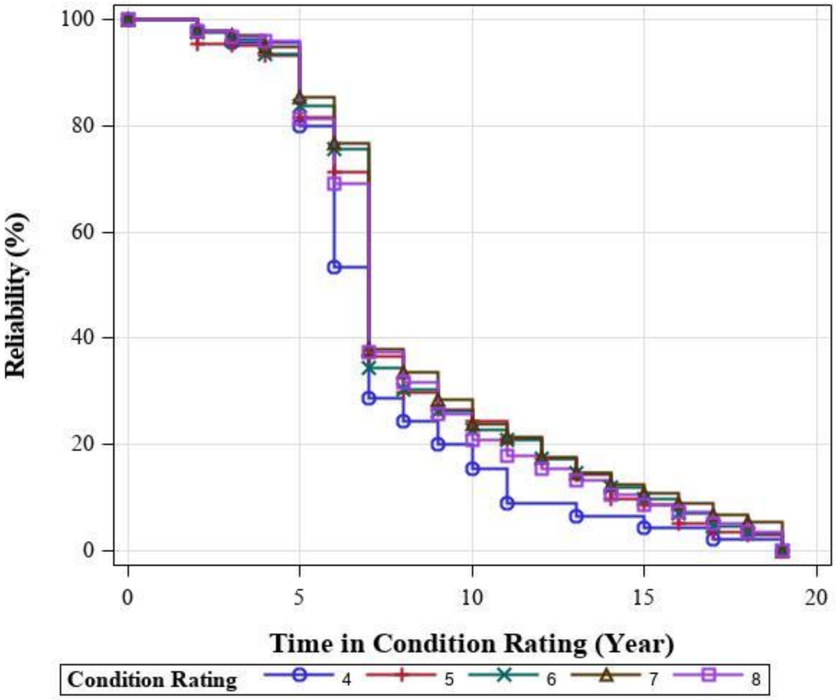

Figure C-67. Reliability graph for PSC Superstructures in Pennsylvania

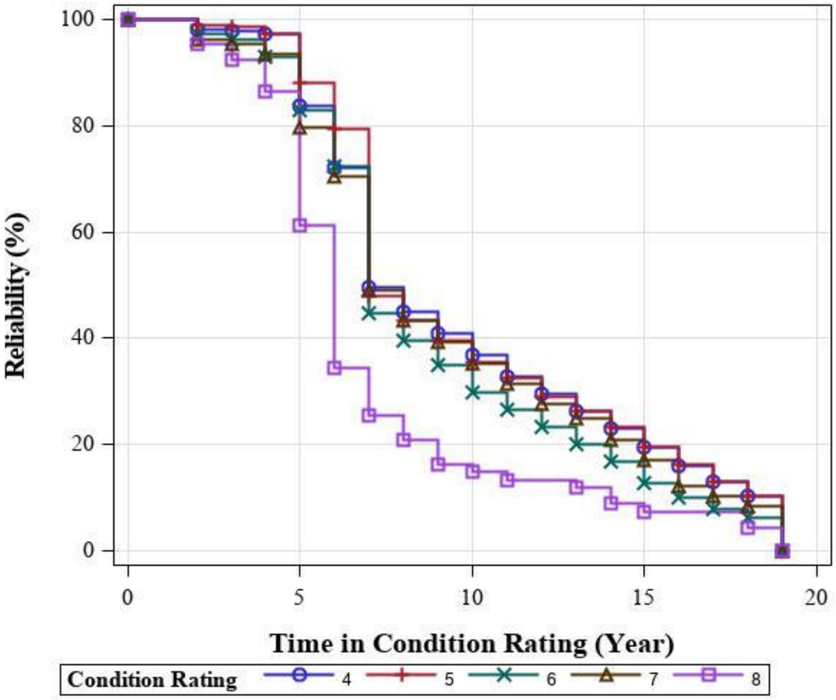

Figure C-68. Reliability graph for RCC Superstructures in Pennsylvania

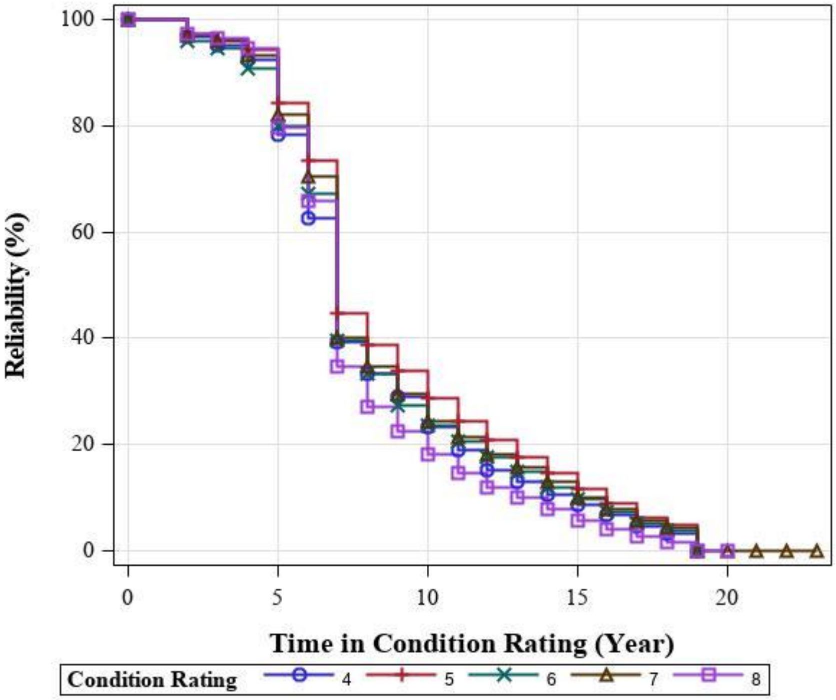

Figure C-69. Reliability graph for Steel Superstructures in Pennsylvania

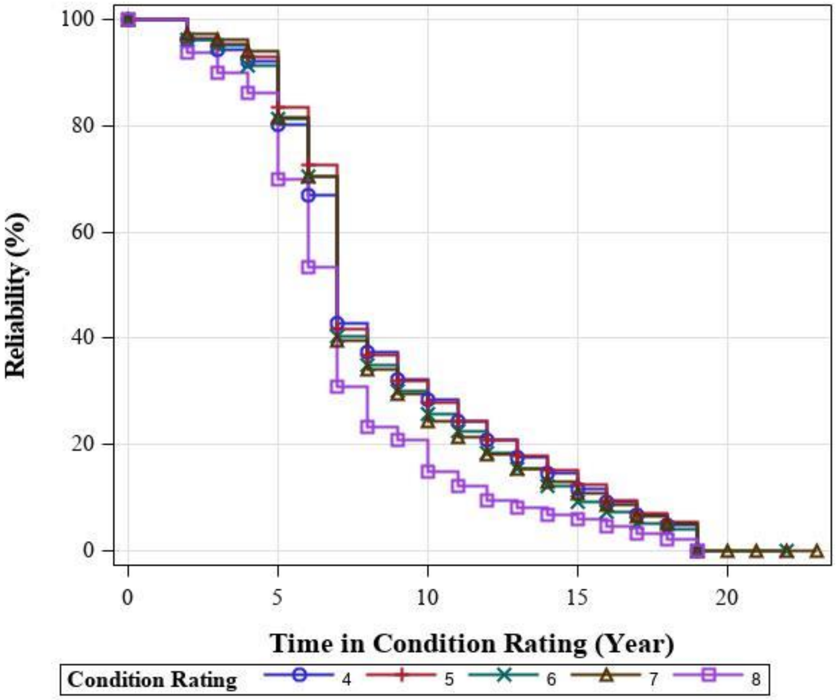

Figure C-70. Reliability graph for bridge Substructures in Pennsylvania

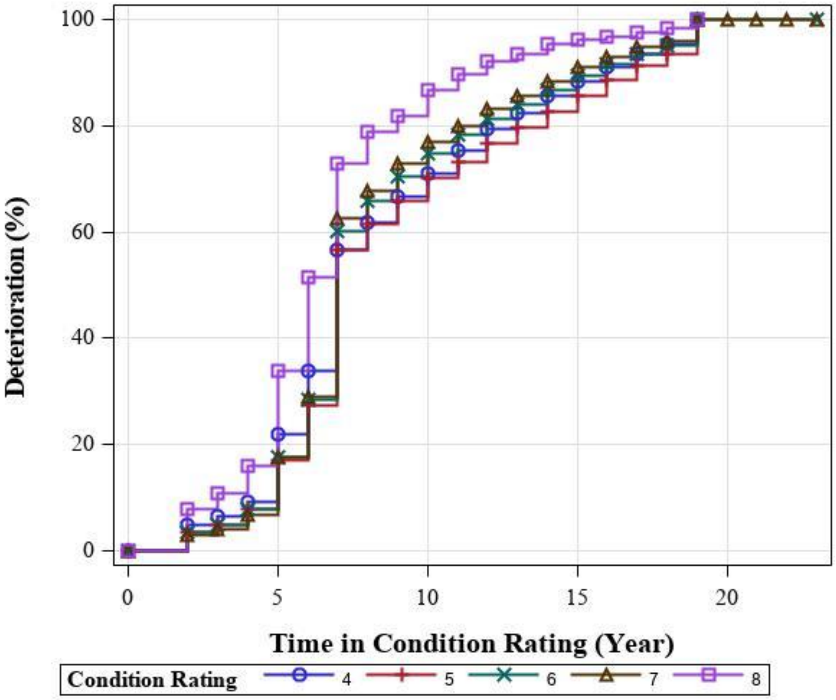

Figure C-71. Deterioration graph for bridge Decks in Pennsylvania

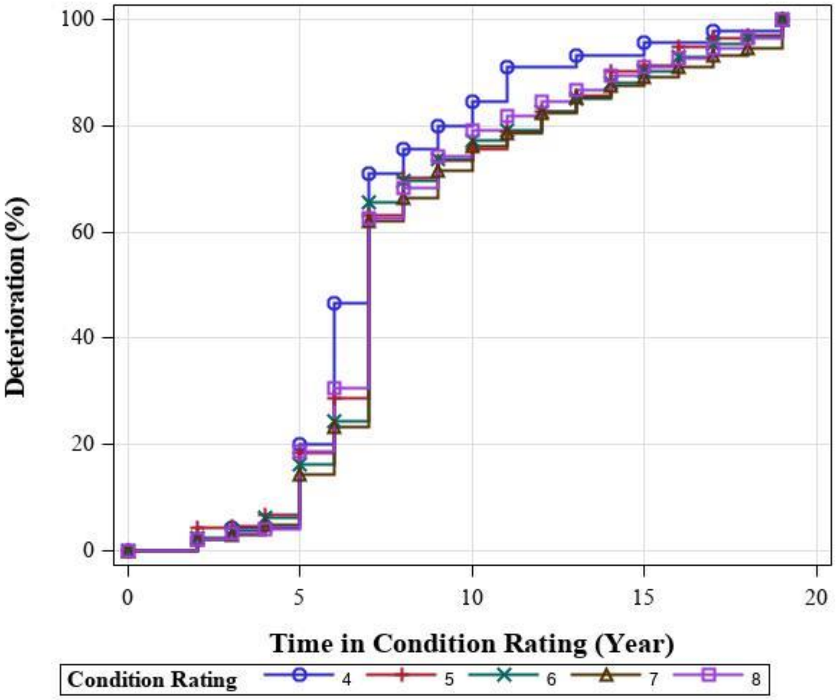

Figure C-72. Deterioration graph for PSC Superstructures in Pennsylvania

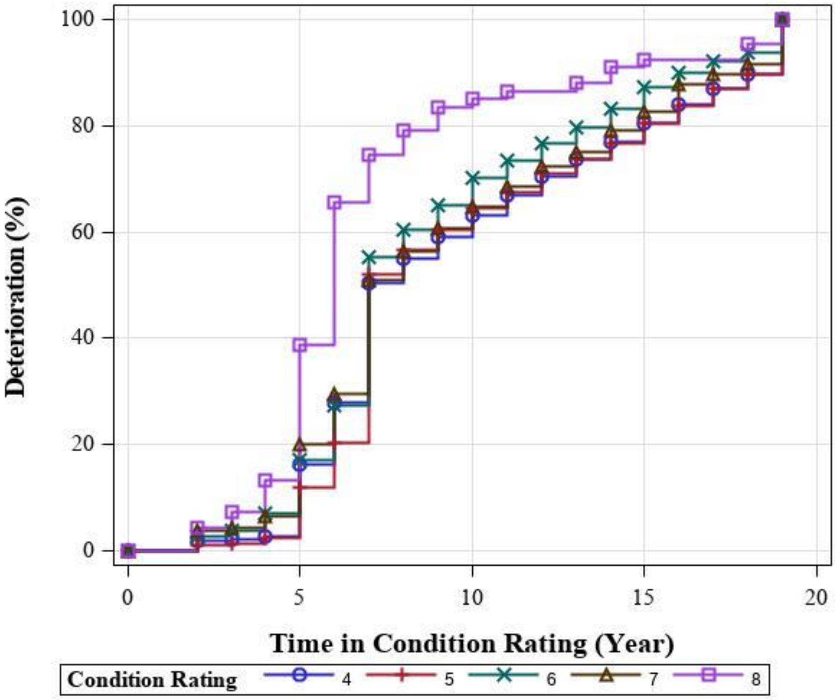

Figure C-73. Deterioration graph for RCC Superstructures in Pennsylvania

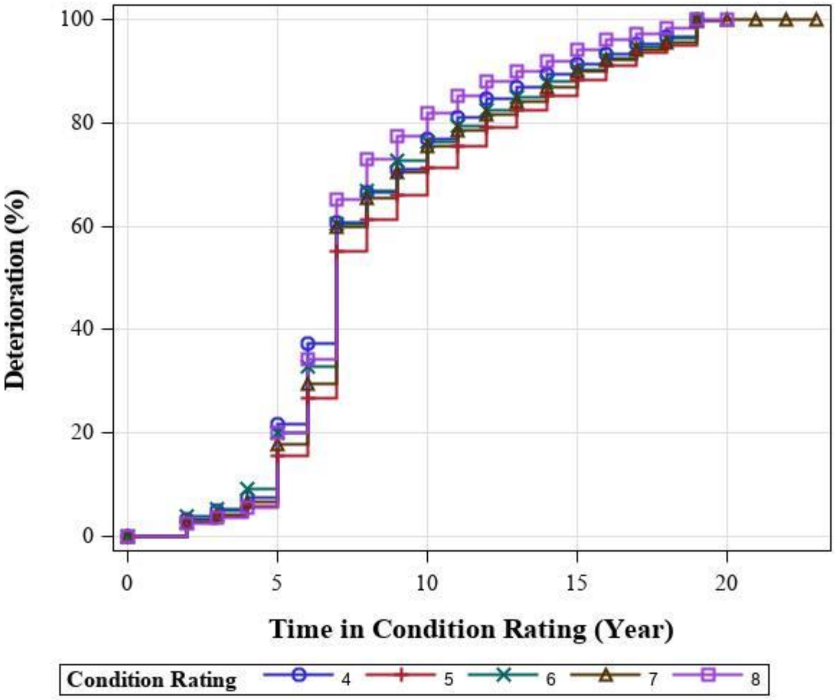

Figure C-74. Deterioration graph for Steel Superstructures in Pennsylvania

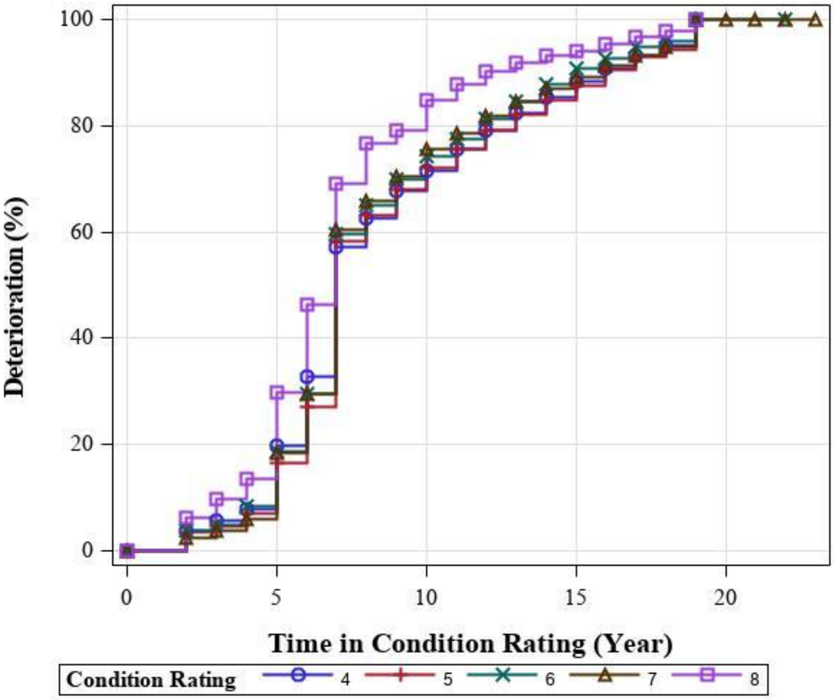

Figure C-75. Deterioration graph for bridge Substructures in Pennsylvania

C.7 Washington Bridge Components' graphs

This section contains the graphs for Washington bridge components. The tables are presented first, followed by the bar graphs and reliability and deterioration graphs. How to read graphs are presented in the general information section.

Table C-11. Number of bridge components in Washington for TICR analysis

Bridge Components	**# of Bridge Components**	**# of Bridge Components in each CR**				
		CR 4	**CR 5**	**CR 6**	**CR 7**	**CR 8**
Deck	4491	169	329	1569	3018	1584
PSC Superstructure	2786	25	105	600	1924	1248
RCC Superstructure	1104	50	135	437	636	281
Steel Superstructure	652	31	107	310	447	178
Substructure	4487	139	478	1176	2968	1546

Table C-12. Kaplan-Meier statistics for Washington's bridge components

CR	Median TICR	95% CI for Median TICR		Mean TICR	Standard Error of the mean TICR
		Lower CI	Upper CI		
Deck					
4	6	6	7	6.64	0.24
5	7	6	8	8.26	0.29
6	12	11	12	12.60	0.17
7	16	15	16	15.94	0.13
8	10	10	11	12.43	0.17
Prestressed Concrete Superstructure					
4	3	2	5	4.76	0.80
5	7	6	9	7.88	0.47
6	10	10	11	11.27	0.25
7	18	17	18	17.72	0.16
8	11	10	11	12.85	0.19
Reinforced Concrete Superstructure					
4	6	6	7	6.88	0.54
5	10	8	10	9.92	0.46
6	13	12	14	13.56	0.35
7	16	14	16	15.92	0.30
8	10	9	12	12.79	0.43
Steel Superstructure					
4	5	5	6	6.03	0.65
5	6	6	8	8.02	0.51
6	12	11	13	12.42	0.34
7	11	11	12	13.17	0.32
8	9	8	9	9.35	0.29
Substructure					
4	6	5	7	7.24	0.37
5	8	8	9	9.49	0.25
6	11	11	12	12.35	0.20
7	18	18	19	17.88	0.14
8	10	10	11	12.40	0.17

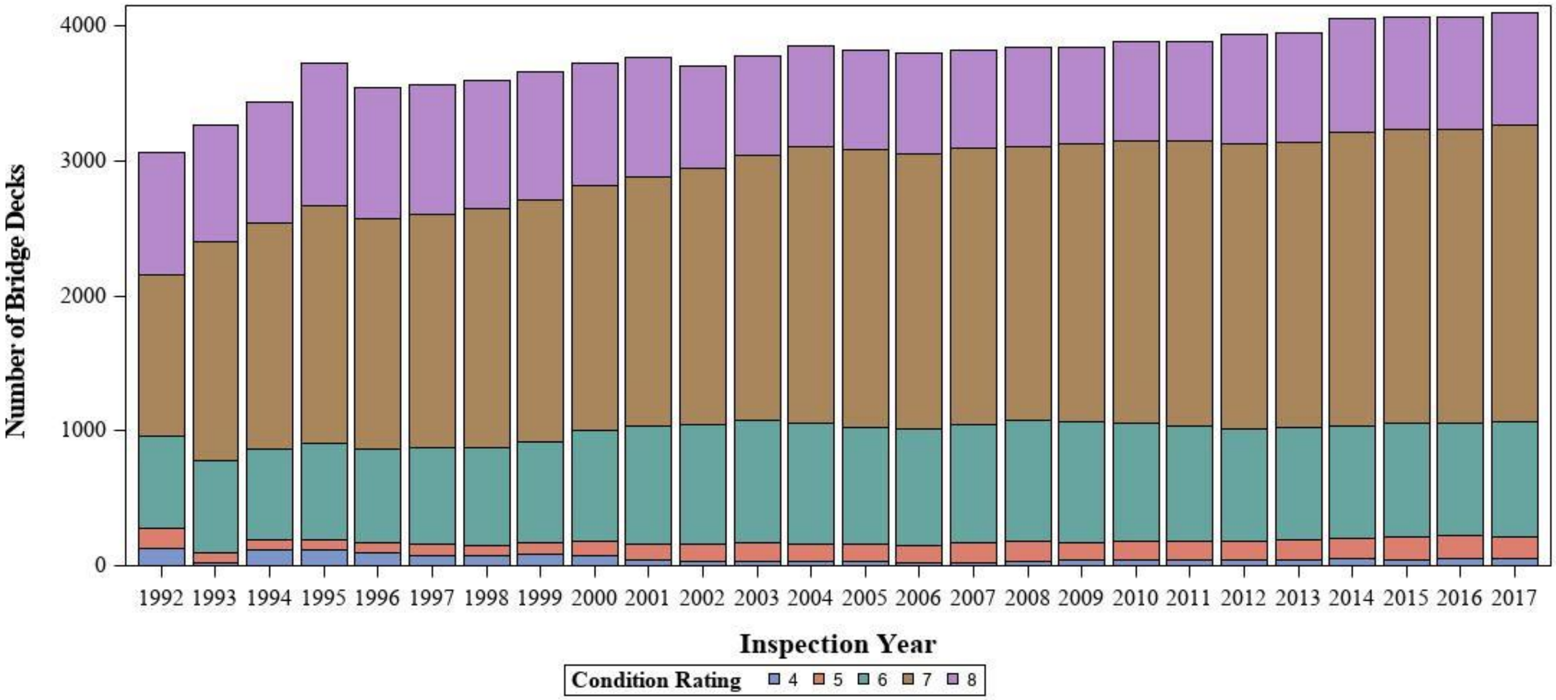

Figure C-76. Bar graph showing the number of bridge Decks in Washington

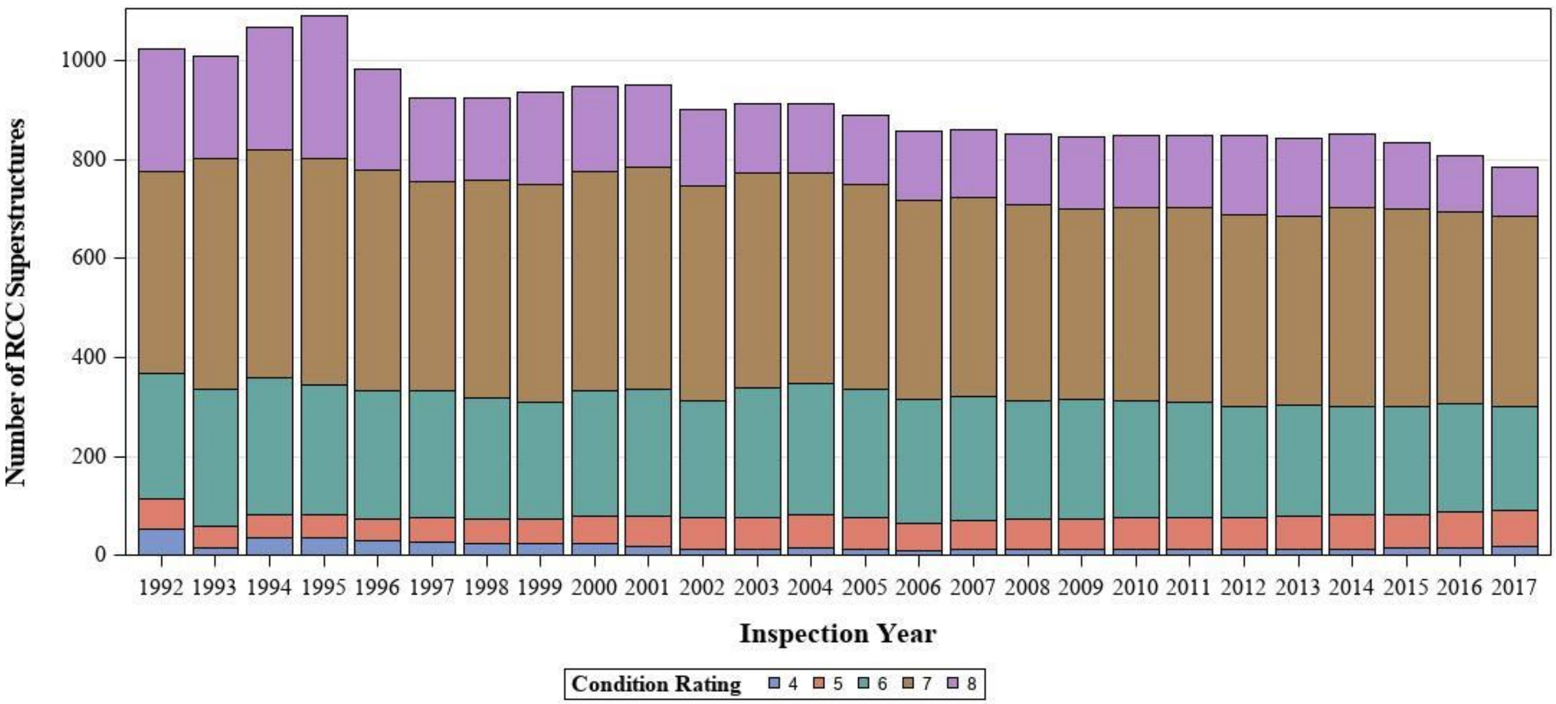

Figure C-77. Bar graph showing the number of PSC Superstructures in Washington

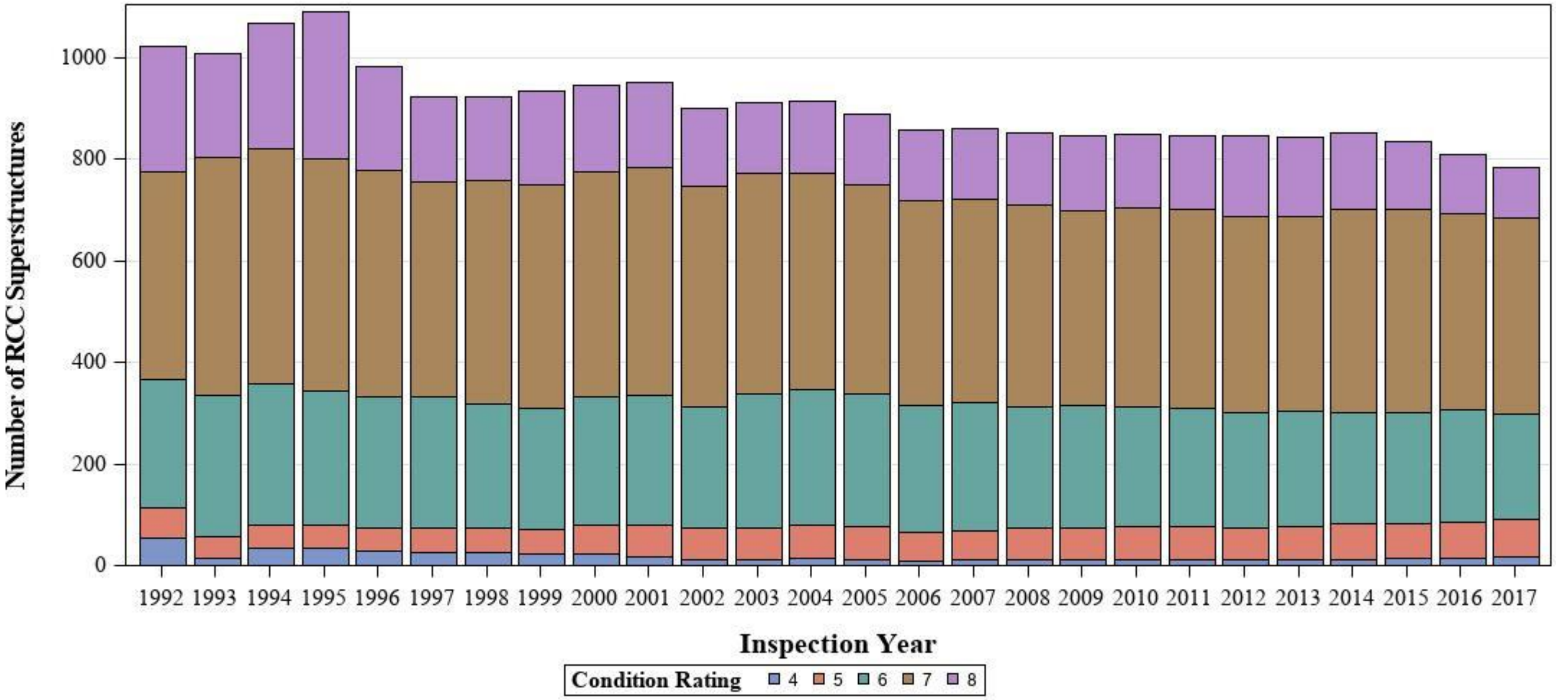

Figure C-78. Bar graph showing the number of RCC Superstructures in Washington

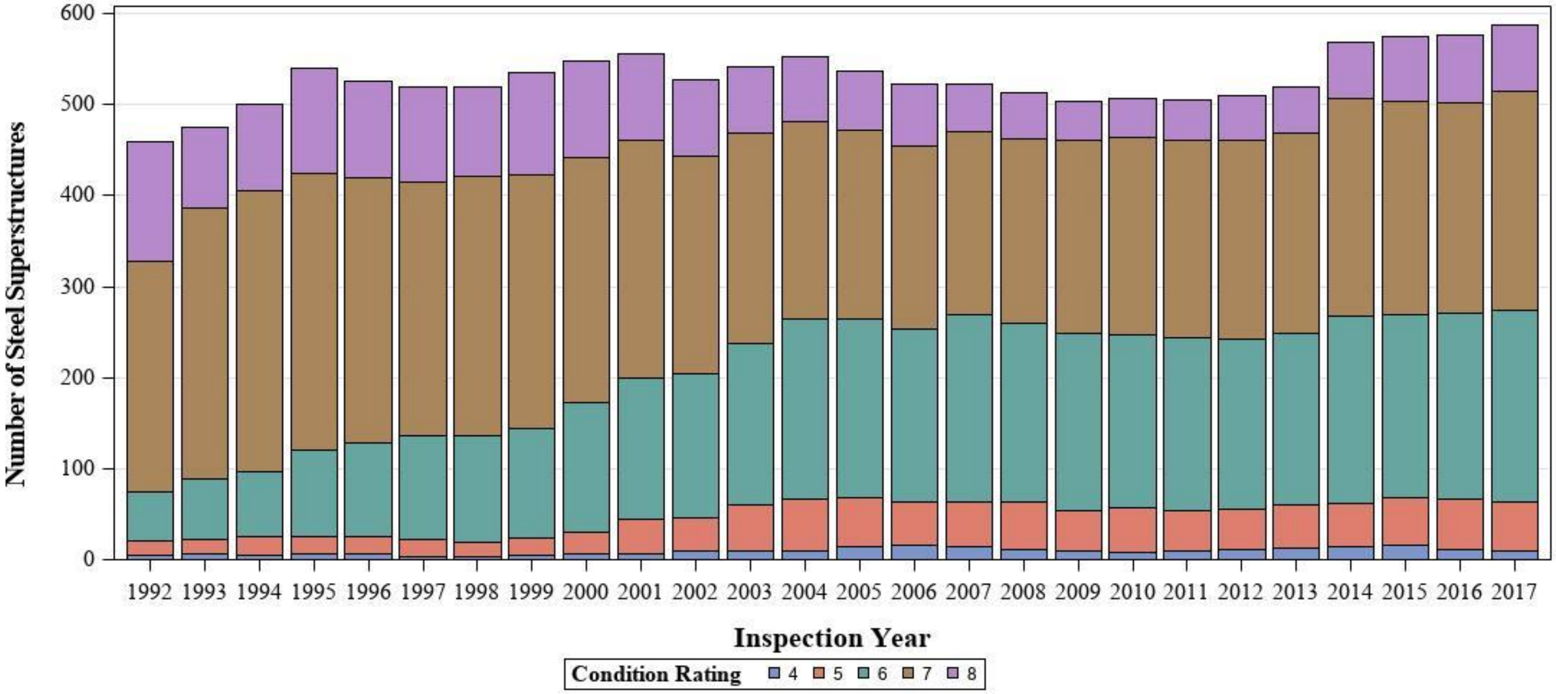

Figure C-79. Bar graph showing the number of Steel Superstructures in Washington

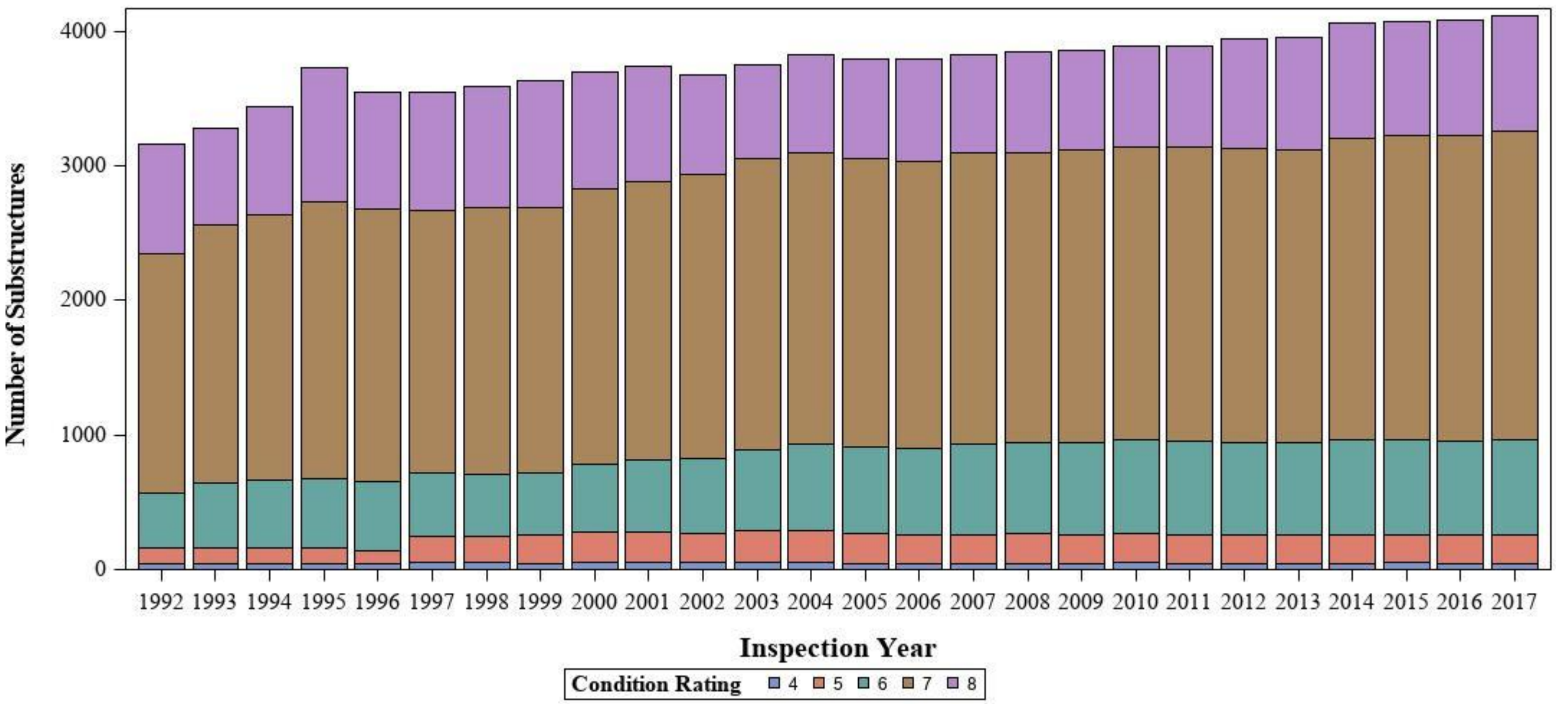

Figure C-80. Bar graph showing the number of bridge Substructures in Washington

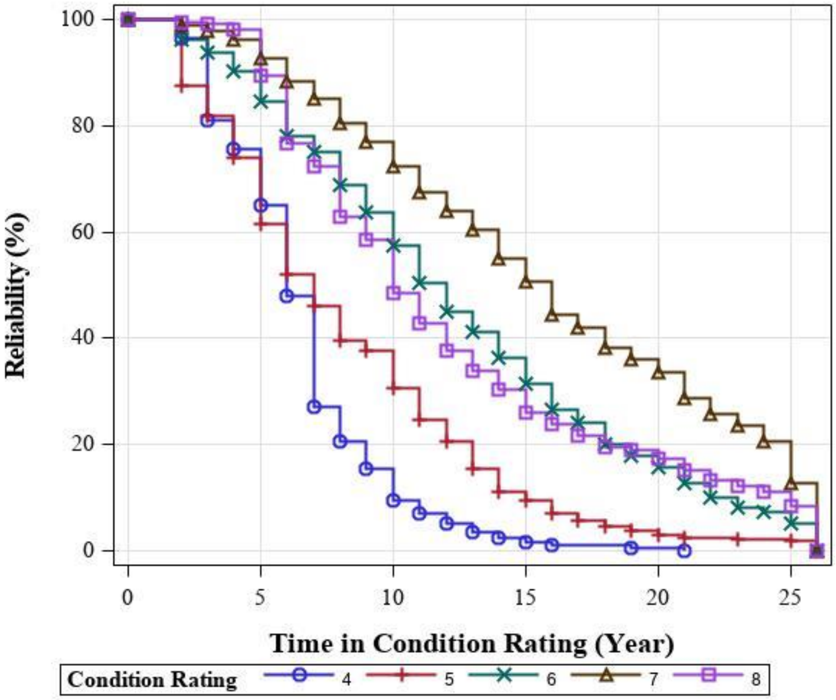

Figure C-81. Reliability graph for bridge Decks in Washington

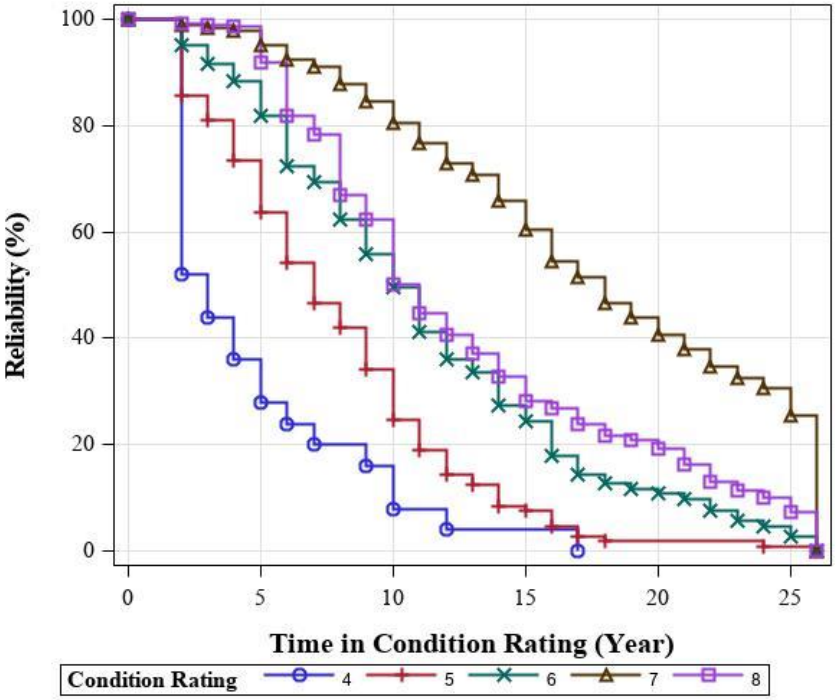

Figure C-82. Reliability graph for PSC Superstructures in Washington

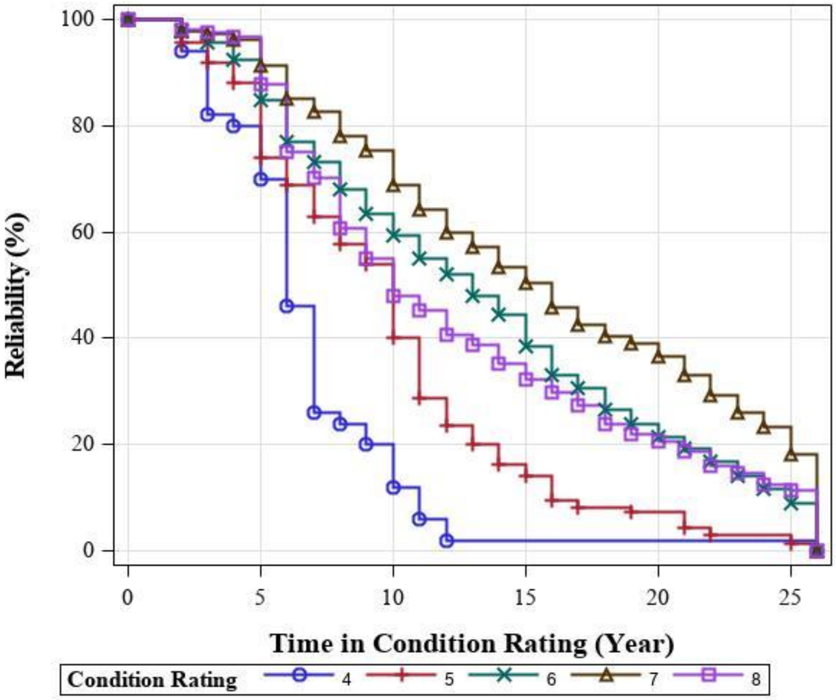

Figure C-83. Reliability graph for RCC Superstructures in Washington

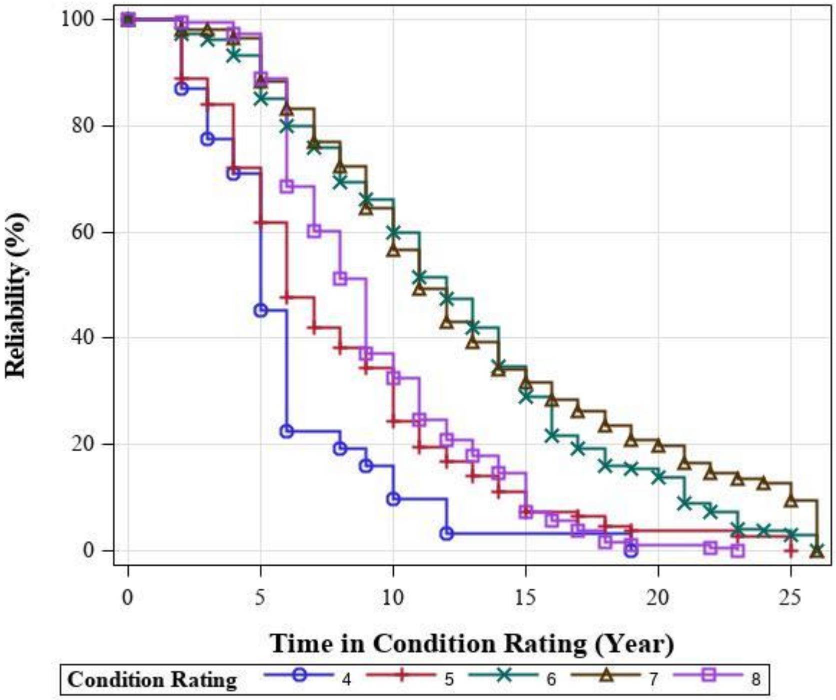

Figure C-84. Reliability graph for Steel Superstructures in Washington

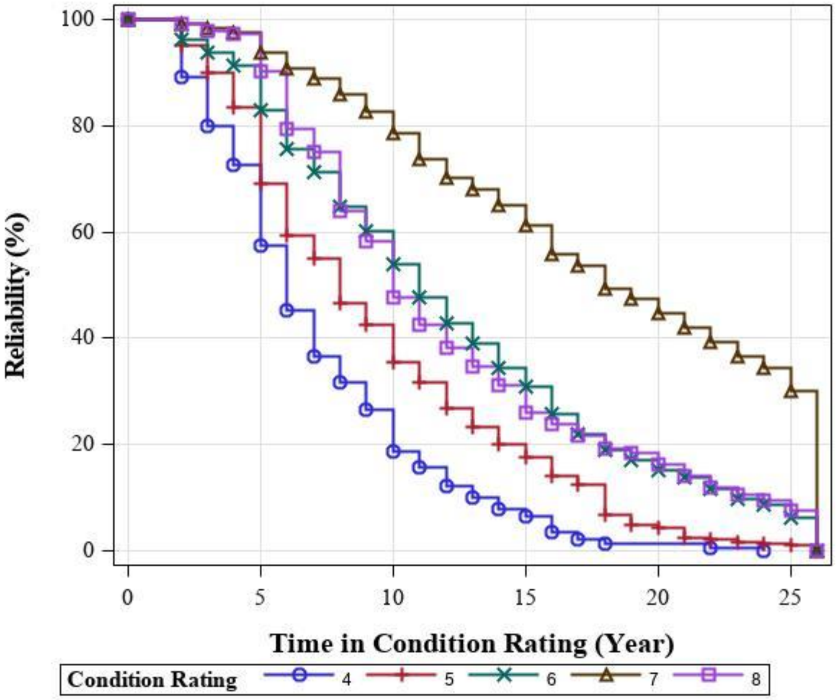

Figure C-85. Reliability graph for bridge Substructures in Washington

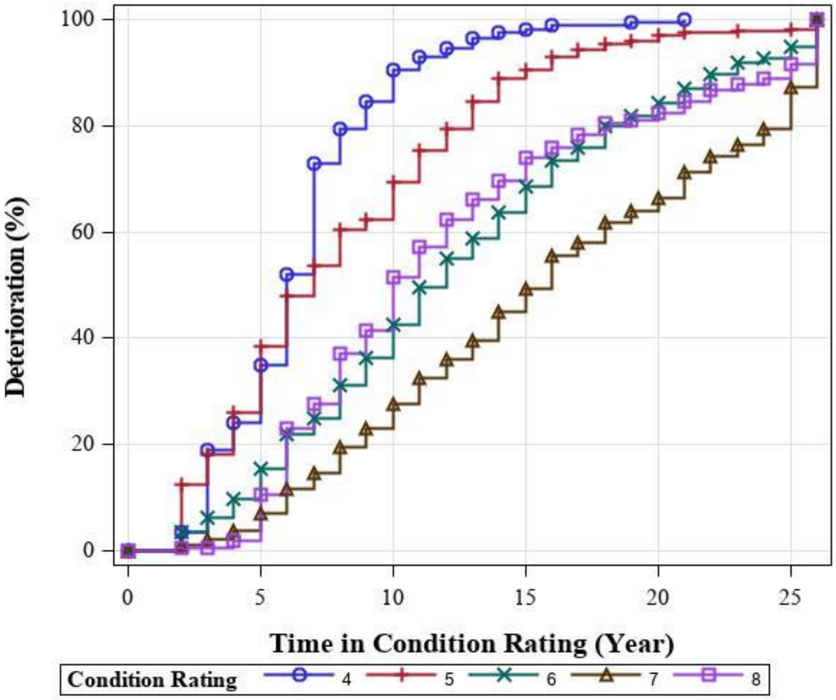

Figure C-86. Deterioration graph for bridge Decks in Washington

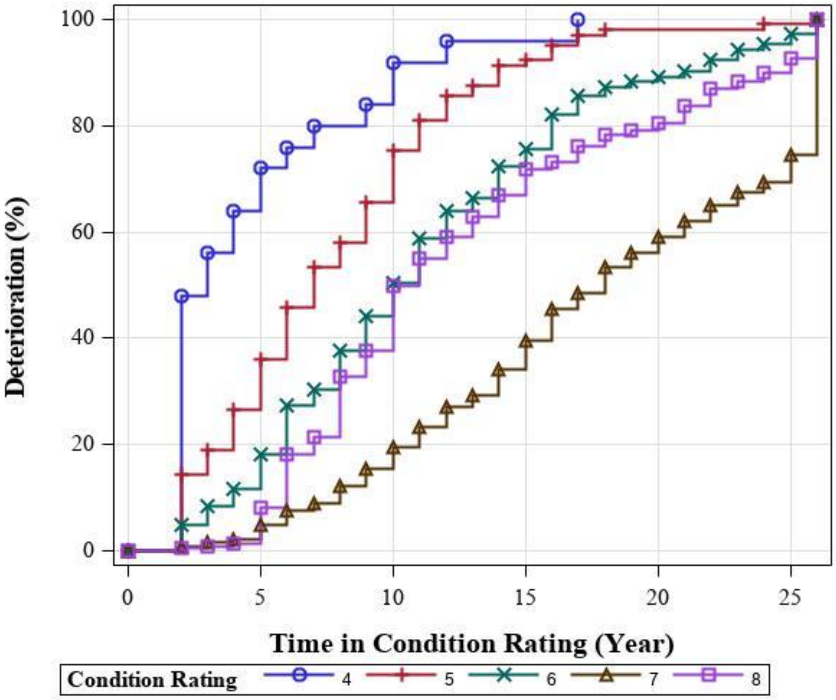

Figure C-87. Deterioration graph for PSC Superstructures in Washington

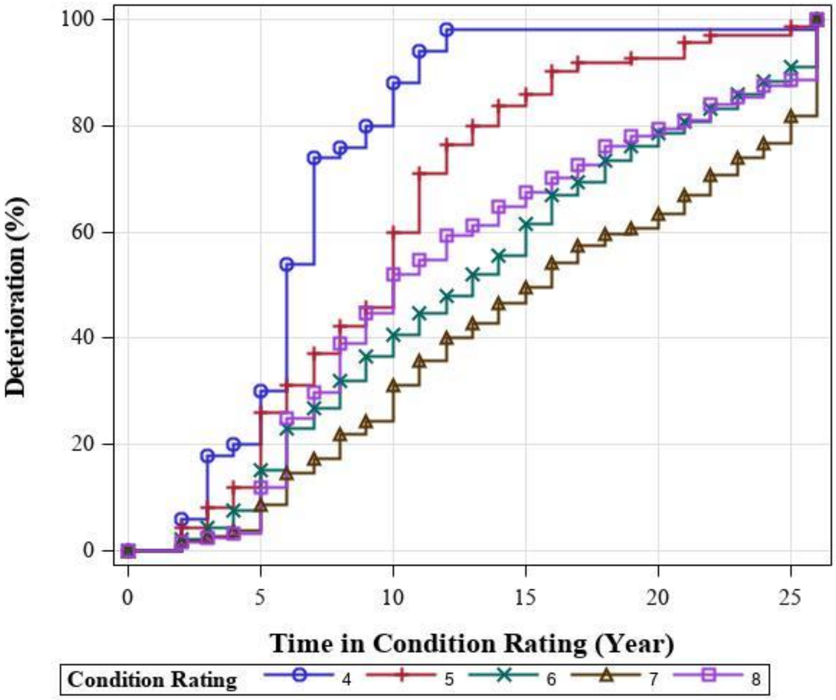

Figure C-88. Deterioration graph for RCC Superstructures in Washington

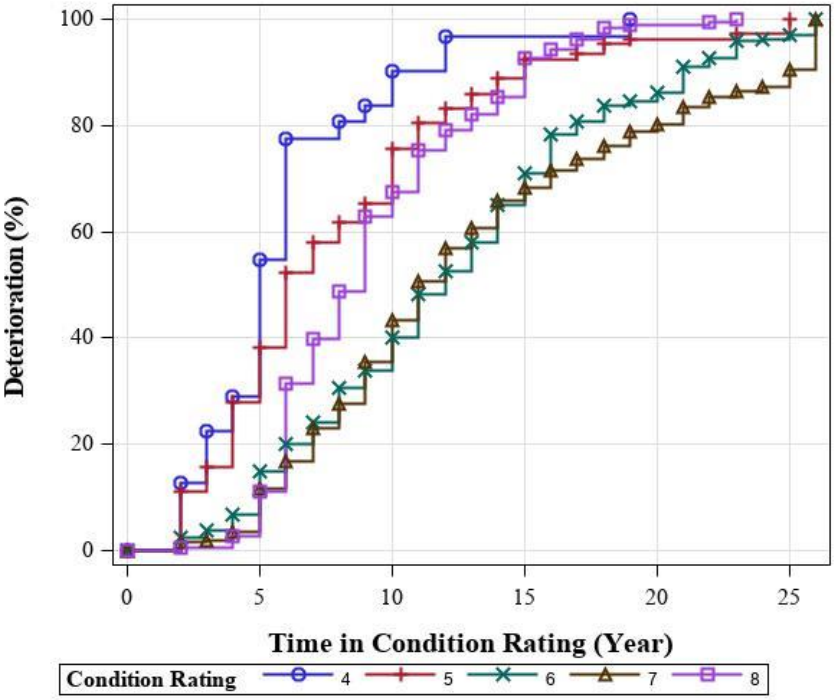

Figure C-89. Deterioration graph for Steel Superstructures in Washington

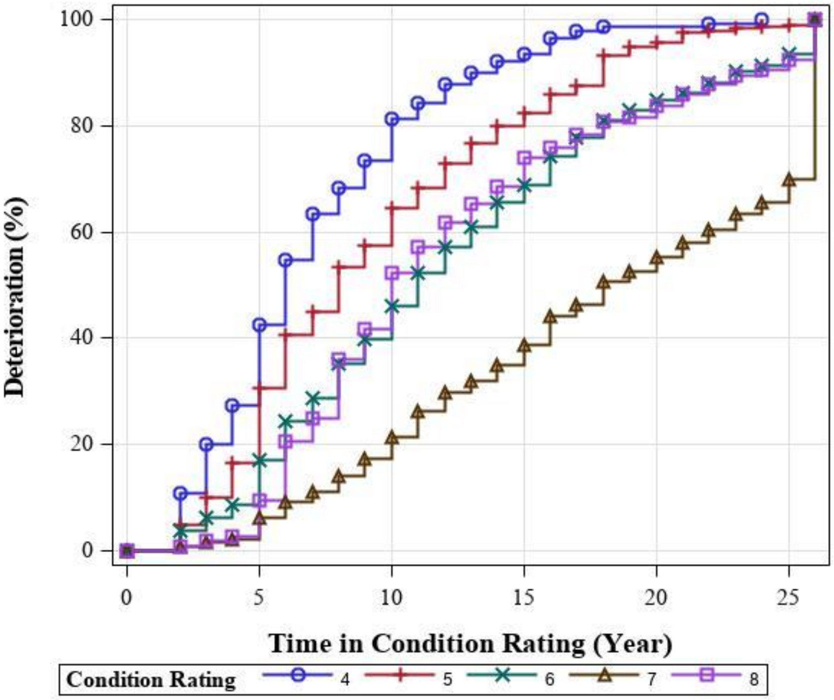

Figure C-90. Deterioration graph for bridge Substructures in Washington

C.8 Wisconsin Bridge Components’ graphs

This section contains the graphs for Wisconsin bridge components. The tables are presented first, followed by the bar graphs and reliability and deterioration graphs. How to read graphs are presented in the general information section.

Table C-13. Number of bridge components in Wisconsin for TICR analysis

Bridge Components	# of Bridge Components	# of Bridge Components in each CR				
		CR 4	CR 5	CR 6	CR 7	CR 8
Deck	7776	1048	2147	3959	4497	3621
PSC Superstructure	3067	29	179	357	1228	2682
RCC Superstructure	623	136	219	350	194	210
Steel Superstructure	4145	491	1401	2719	2074	1771
Substructure	7730	936	1755	3561	3659	3362

Table C-14. Kaplan-Meier statistics for Wisconsin's bridge components

CR	Median TICR	95% CI for Median TICR		Mean TICR	Standard Error of the mean TICR
		Lower CI	Upper CI		
Deck					
4	7			8.02	0.14
5	7			8.10	0.11
6	8	8	9	9.93	0.10
7	9	9	10	10.46	0.09
8	8	7	8	9.06	0.09
Prestressed Concrete Superstructure					
4	6	5	7	6.86	0.77
5	7	6	7	7.77	0.35
6	9	8	10	10.21	0.31
7	10	10	11	10.84	0.16
8	15	14	15	15.06	0.14
Reinforced Concrete Superstructure					
4	7	7	8	8.82	0.40
5	8	6	8	8.87	0.38
6	9	8	9	10.44	0.33
7	6	6	7	8.01	0.40
8	7	7	8	9.38	0.36
Steel Superstructure					
4	6	6	7	7.29	0.17
5	8			9.03	0.14
6	8	8	9	10.26	0.12
7	9	8	9	9.74	0.13
8	7			9.10	0.12
Substructure					
4	7			8.58	0.15
5	8	7	8	9.04	0.13
6	10			11.79	0.12
7	11	10	11	11.54	0.11
8	10			11.72	0.11

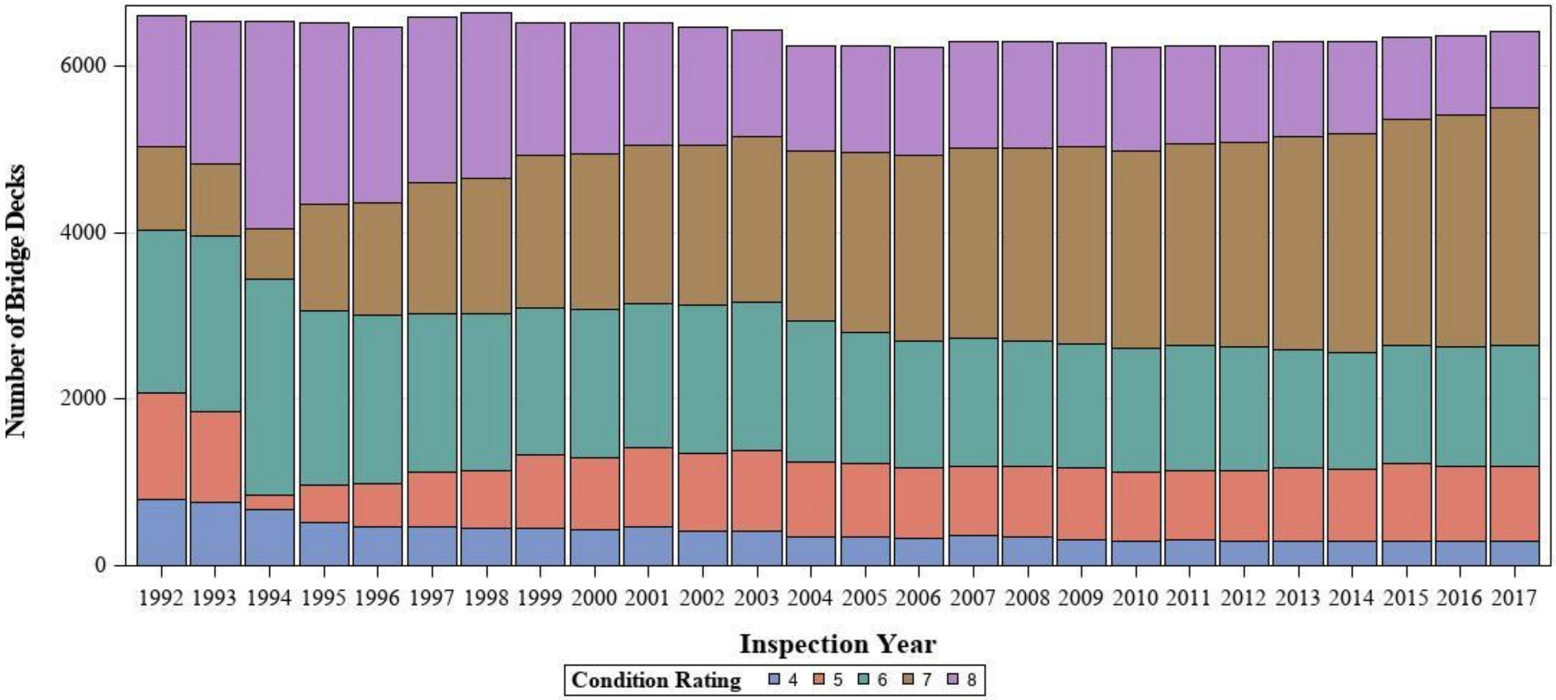

Figure C-91. Bar graph showing the number of bridge Decks in Wisconsin

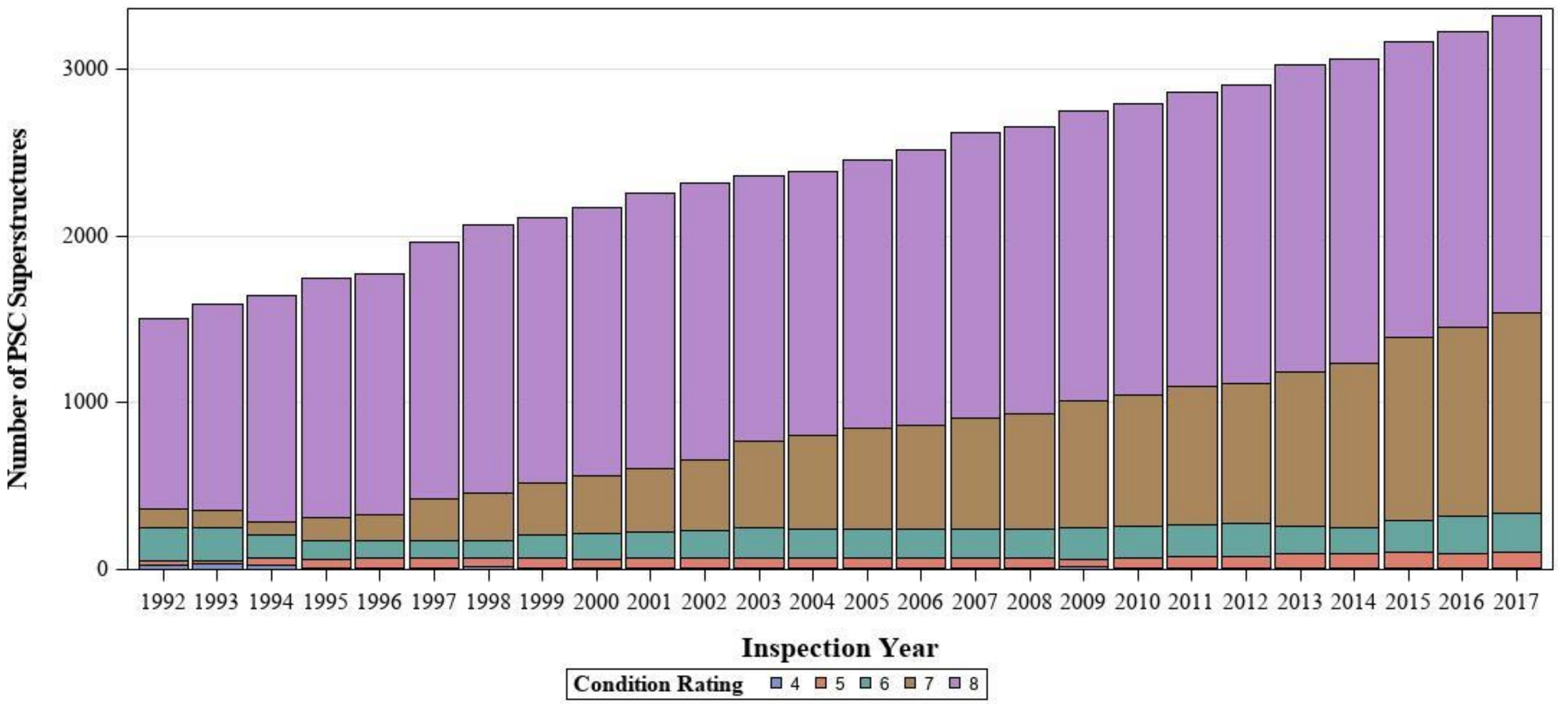

Figure C-92. Bar graph showing the number of PSC Superstructures in Wisconsin

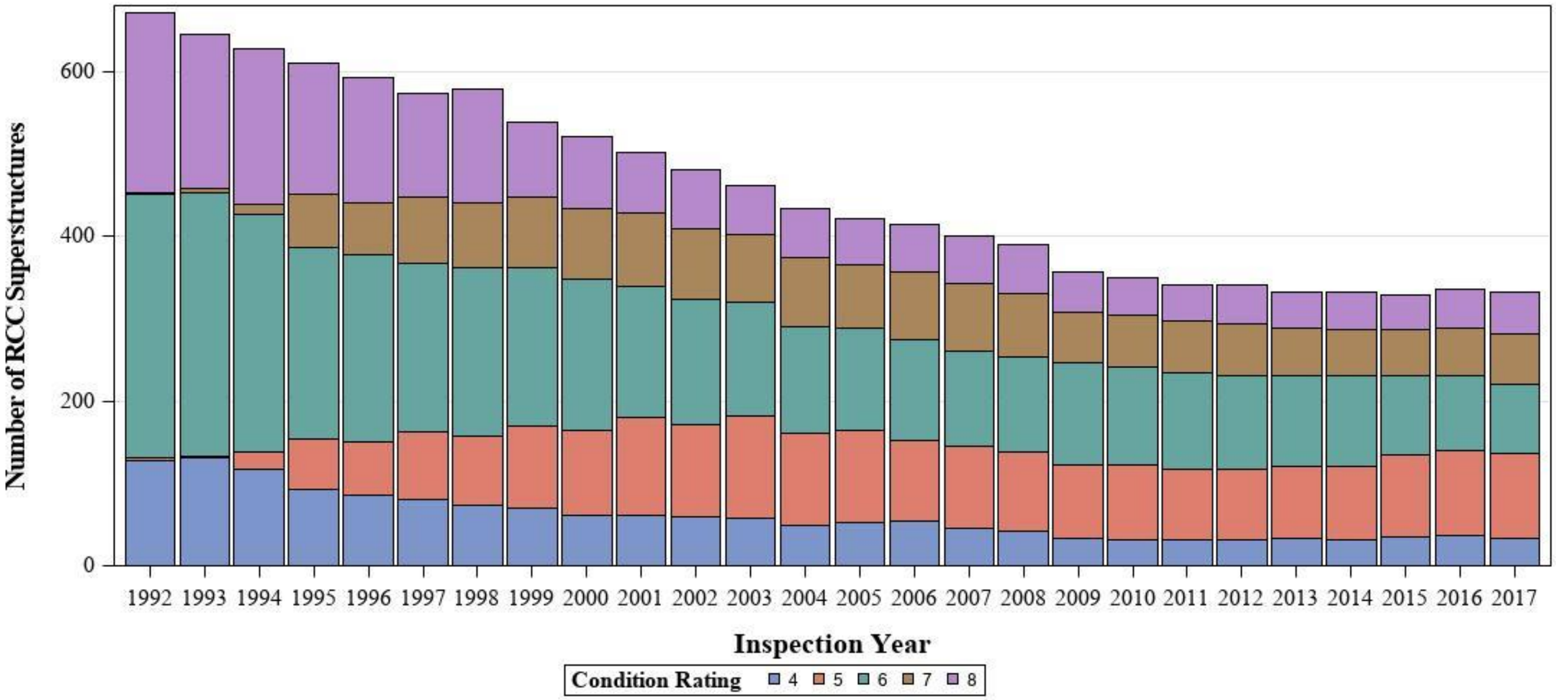

Figure C-93. Bar graph showing the number of RCC Superstructures in Wisconsin

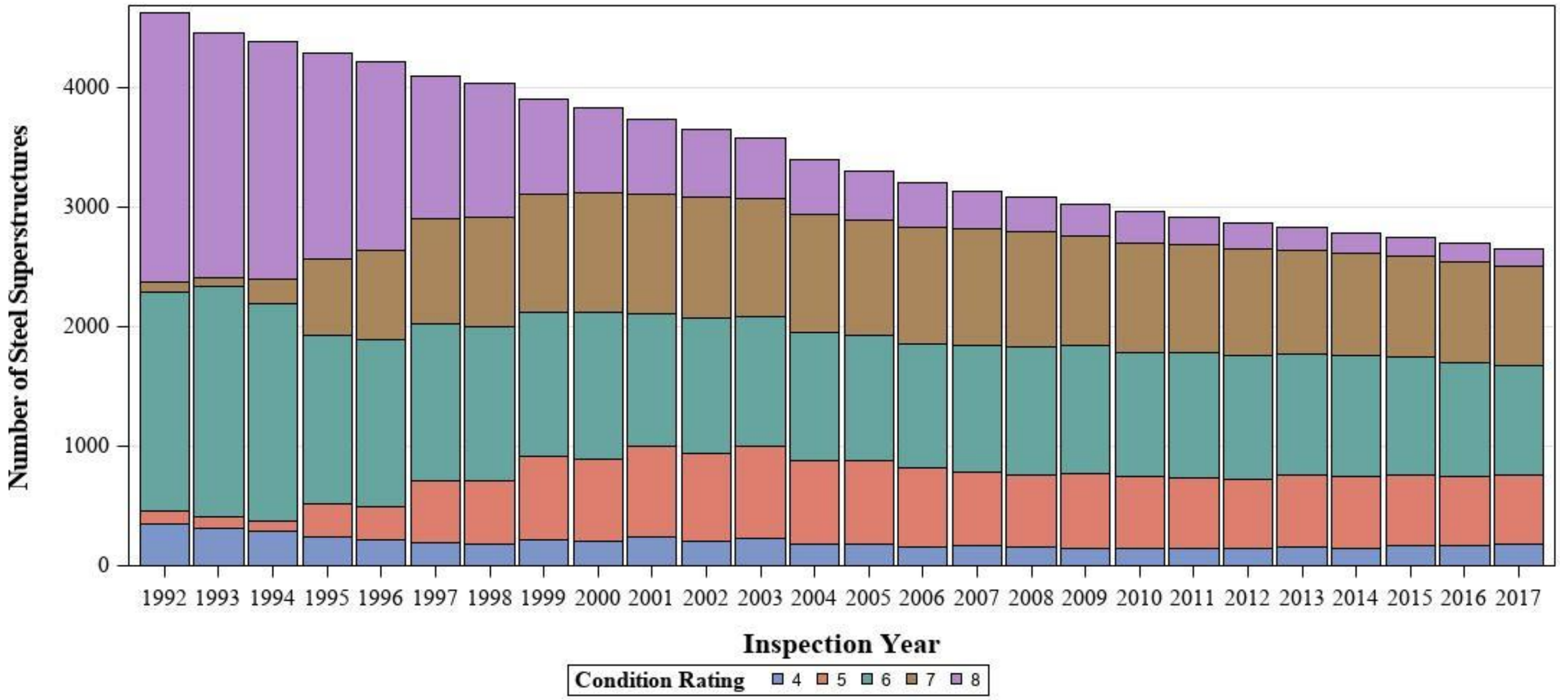

Figure C-94. Bar graph showing the number of Steel Superstructures in Wisconsin

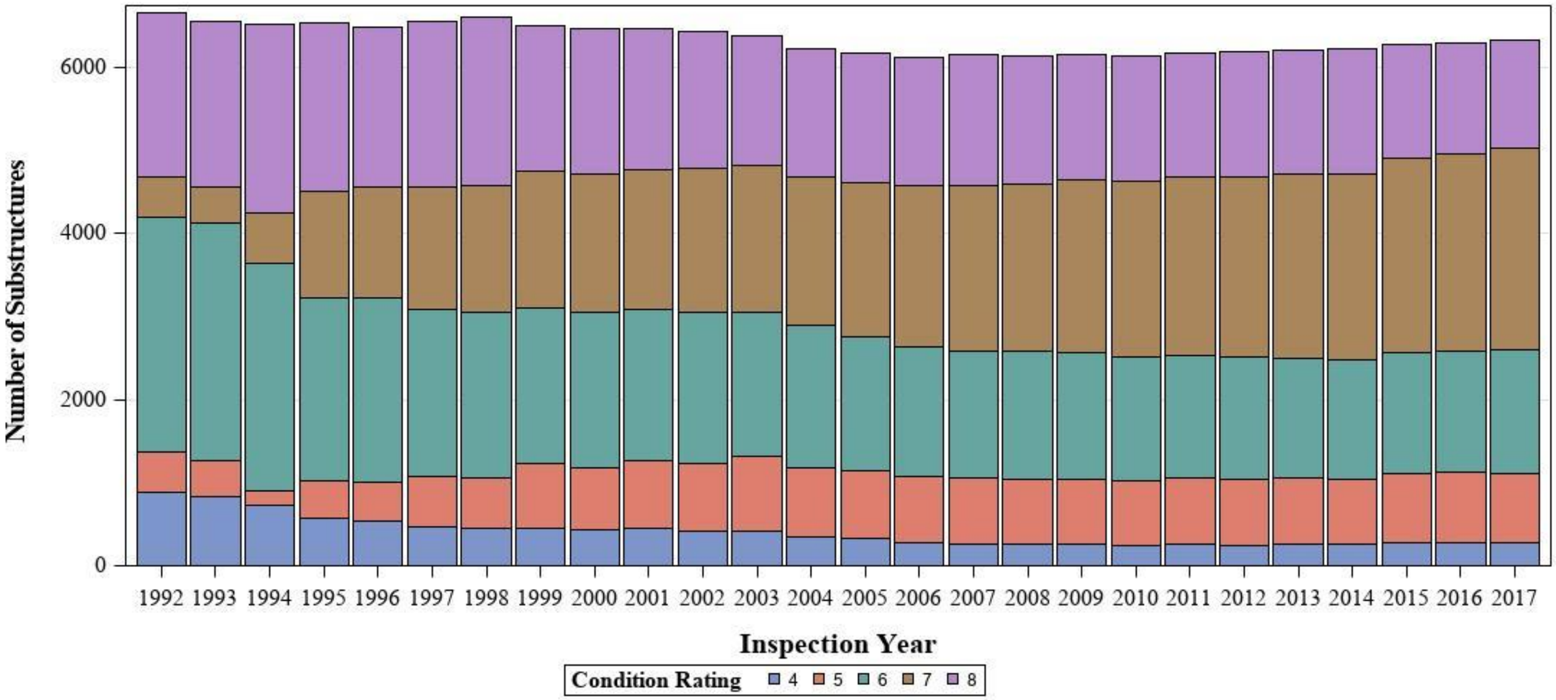

Figure C-95. Bar graph showing the number of bridge Substructures in Wisconsin

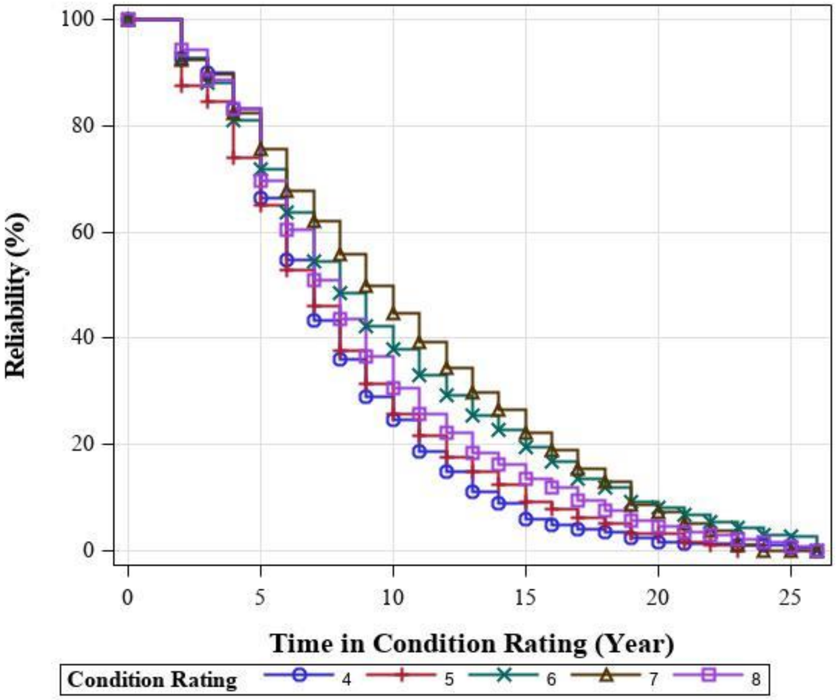

Figure C-96. Reliability graph for bridge Decks in Wisconsin

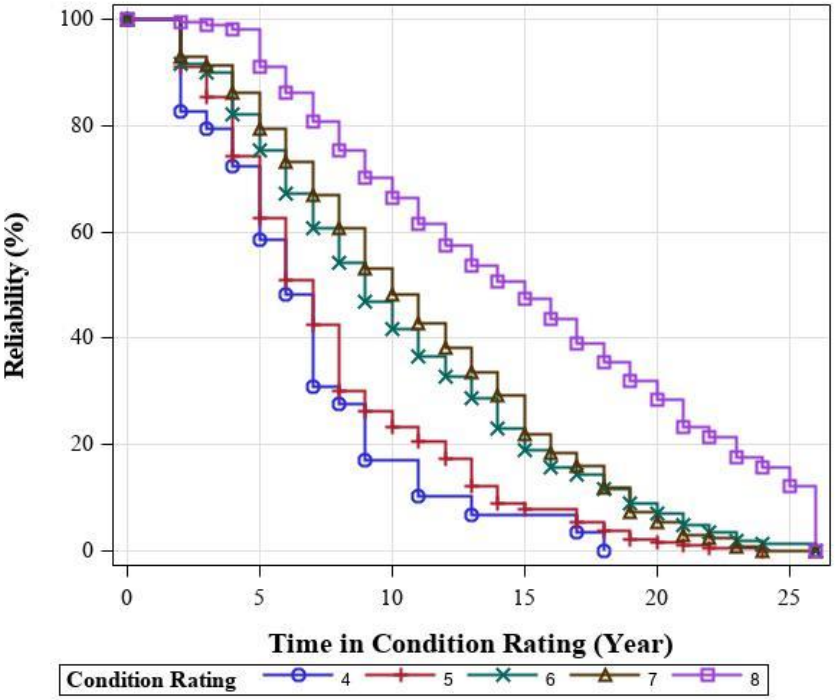

Figure C-97. Reliability graph for PSC Superstructures in Wisconsin

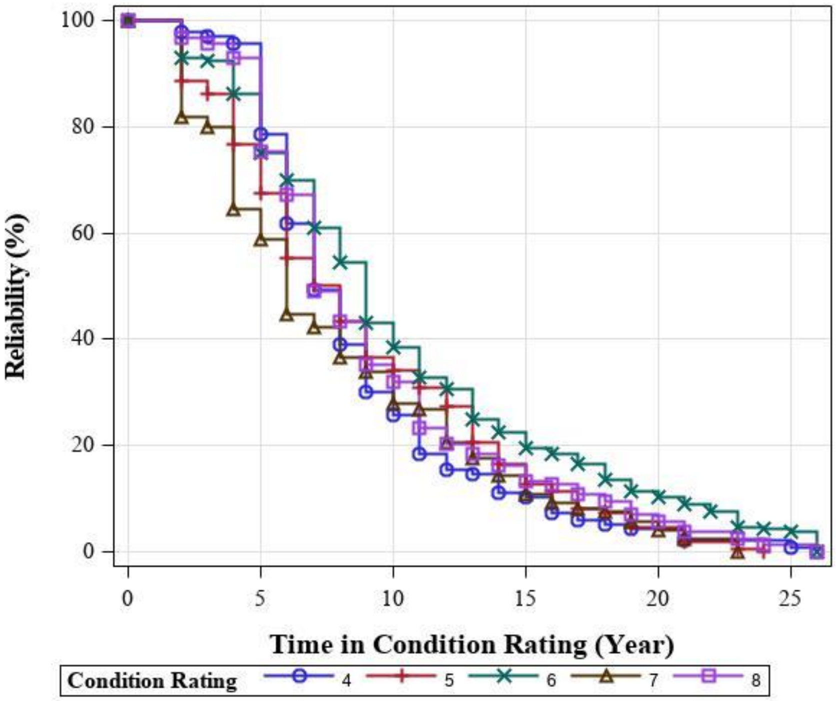

Figure C-98. Reliability graph for RCC Superstructures in Wisconsin

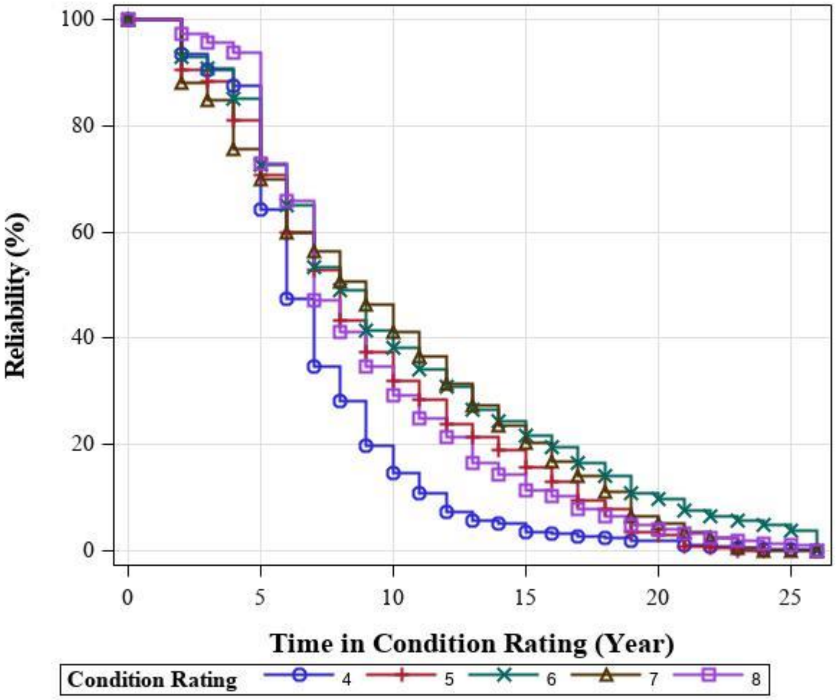

Figure C-99. Reliability graph for Steel Superstructures in Wisconsin

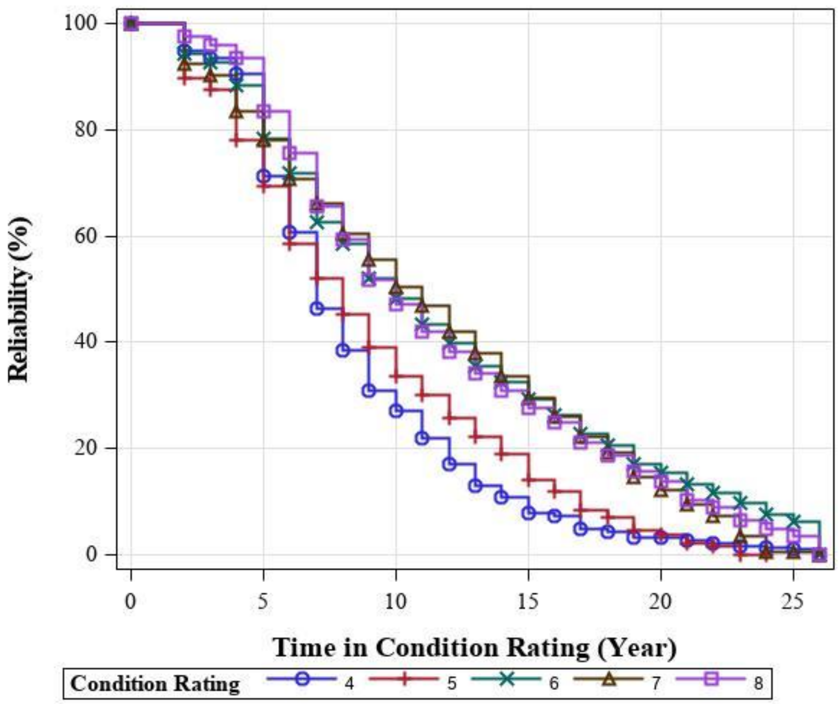

Figure C-100. Reliability graph for bridge Substructures in Wisconsin

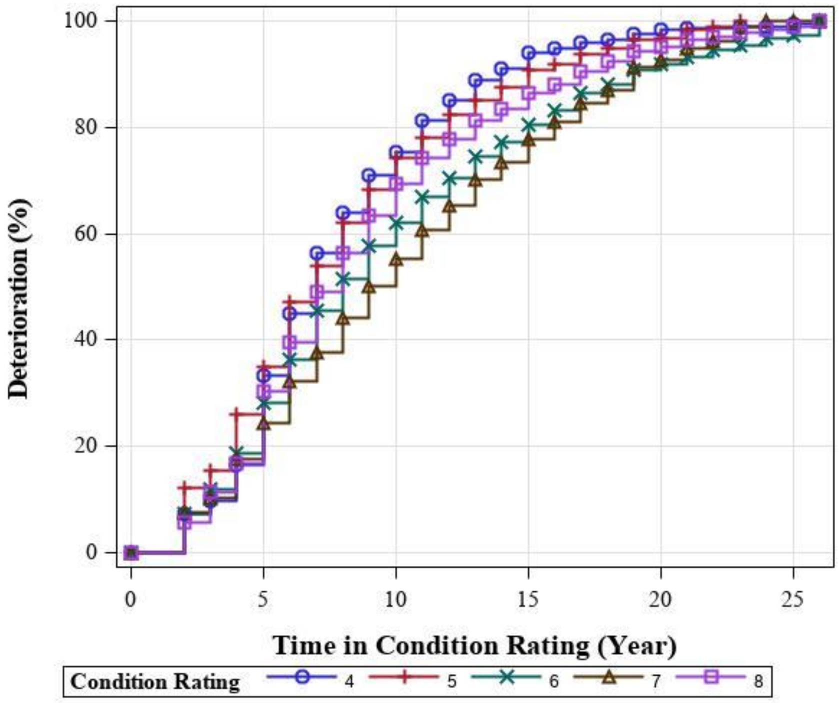

Figure C-101. Deterioration graph for bridge Decks in Wisconsin

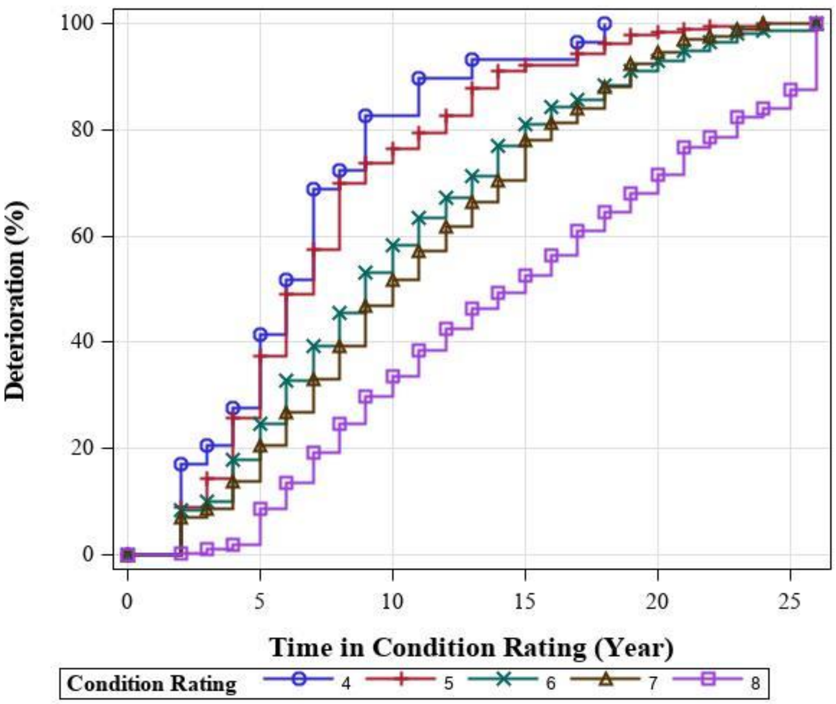

Figure C-102. Deterioration graph for PSC Superstructures in Wisconsin

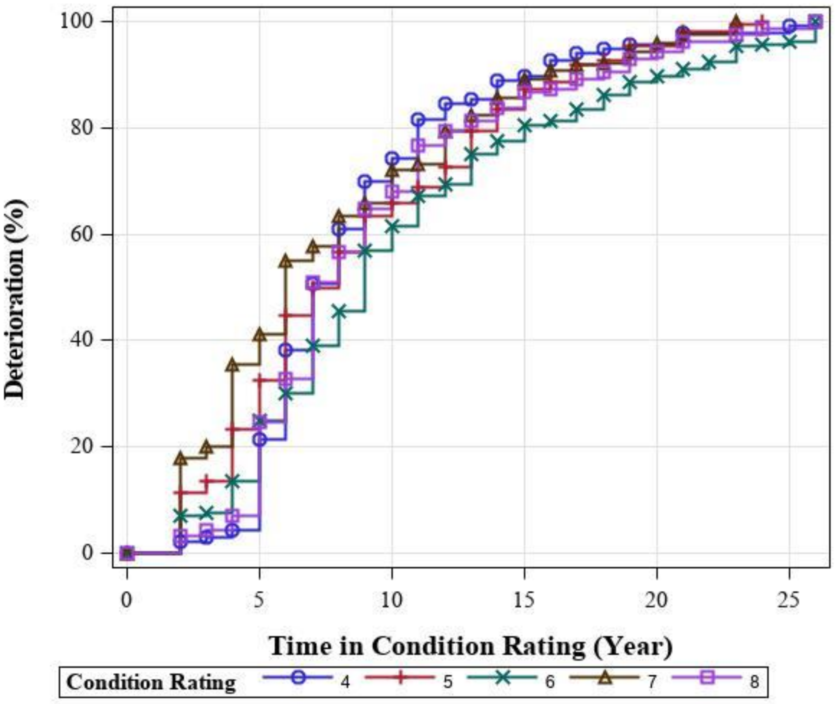

Figure C-103. Deterioration graph for RCC Superstructures in Wisconsin

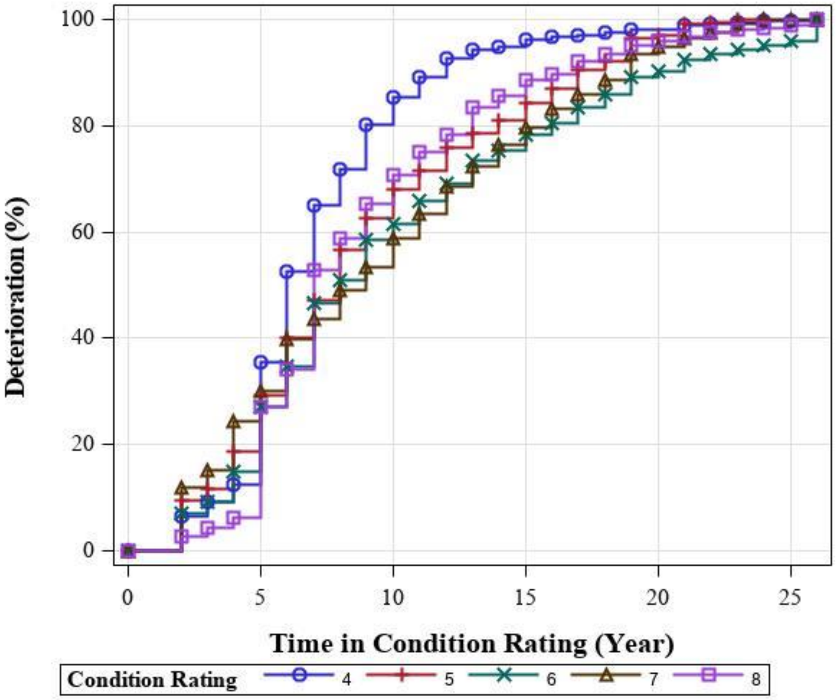

Figure C-104. Deterioration graph for Steel Superstructures in Wisconsin

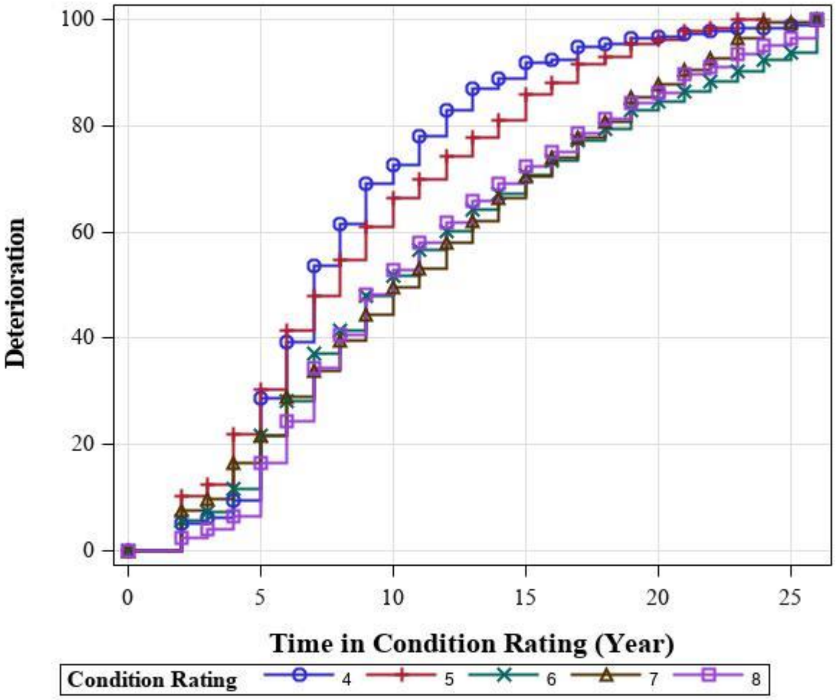

Figure C-105. Deterioration graph for bridge Substructures in Wisconsin

VITA

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- Developing Implementation Strategies for Risk-Based Inspection, TPF (5)-388, Missouri Department of Transportation
- Guidelines to Improve the Quality of Element-Level Bridge Inspection, NCHRP 12-104, Transportation Research Board
- Improving the Reliability of Element-Level Inspections, Midwest Transportation Center, Iowa State University
- Developing Risk-Based Bridge Inspection Practices, Midwest Transportation Center, Iowa State University
- Bridge Maintenance Program for the City of Columbia, Missouri, Midwest Transportation Center, Iowa State University