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EFFECTS OF SURFACE TREATMENTS ON NATIONAL BRIDGE INVENTORY CONDITION RATINGS FOR CONCRETE BRIDGE DECKS IN UTAH

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16. Abstract

The objectives of this research were to develop and analyze deterioration curves for bare concrete bridge decks and decks with specific treatments commonly used in Utah. The scope of this study was determined by the types and extent of electronically available data, including selected static inventory information; maintenance, rehabilitation, and reconstruction histories; and National Bridge Inventory (NBI) condition ratings for the bridge decks.

Bridge deck selection criteria and analysis procedures were developed to enable evaluation of the effects of surface treatments on monolithic concrete decks, decks with a bituminous overlay, decks with an epoxy overlay, and decks with a latex-modified concrete overlay. Climatic differences were considered by grouping bridges not only by overlay type, but also by Utah Department of Transportation region. Individual bridge deck deterioration curves were then combined to generate average deterioration curves aligned by deck construction time and average deterioration curves aligned by deck treatment time.

The average deterioration curves aligned by deck construction time suggest that certain treatments applied at certain times can achieve average NBI ratings greater than those for monolithic concrete during selected years of bridge deck life. The average deterioration curves aligned by deck treatment time suggest that certain treatments applied at certain times can achieve improvements in NBI ratings that correspond to apparent increases in bridge deck service life. Primarily because the NBI rating system is based mainly on visual inspection, the full benefits of early applications of surface treatments are not apparent in the results of this research.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AADT	annual average daily traffic
DOT	Department of Transportation
FHWA	Federal Highway Administration
ID	identification number
MR&R	maintenance, rehabilitation, and reconstruction
NBI	National Bridge Inventory
SURFTYPE	surface type
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

Although the application of surface treatments on bridge decks is expected to positively impact bridge deck condition, the effectiveness of specific surface treatments on extending bridge deck life has not yet been quantified on Utah bridge decks. Therefore, the objectives of this research were to develop and analyze deterioration curves for bare concrete bridge decks and decks with specific treatments commonly used in Utah. The scope of this study was determined by the types and extent of electronically available data, including selected static inventory information; maintenance, rehabilitation, and reconstruction histories; and National Bridge Inventory (NBI) condition ratings for the bridge decks.

Bridge deck selection criteria and analysis procedures were developed to enable evaluation of the effects of surface treatments on bridge decks in Utah. Characteristics of a typical bridge were defined, and a list of typical bridges was produced to minimize potentially confounding effects of atypical bridge characteristics in comparisons of deterioration curves for monolithic concrete decks, decks with a bituminous overlay, decks with an epoxy overlay, and decks with a latex-modified concrete overlay. Climatic differences were considered by grouping bridges not only by overlay type, but also by Utah Department of Transportation region, which was used in this research as a general surrogate for latitude. Individual bridge deck deterioration curves were then combined to generate average deterioration curves aligned by deck construction time and average deterioration curves aligned by deck treatment time. To at least partially account for the potentially different effects of different treatment times, the bridge groups involving overlays were divided into two treatment time categories, early and late, for analysis.

The average deterioration curves aligned by deck construction time suggest that certain treatments applied at certain times can achieve average NBI ratings greater than those for monolithic concrete during selected years of bridge deck life. The average deterioration curves aligned by deck treatment time suggest that certain treatments applied at certain times can achieve improvements in NBI ratings that correspond to apparent increases in bridge deck service life. Primarily because the NBI rating system is based mainly on visual inspection, the full benefits of early applications of surface treatments are not apparent in the results of this research. Supplemental perspectives may be gained about the performance of specific surface

treatments by evaluating bridge deck deterioration in terms of delamination, half-cell potential, and chloride concentration, for example, which are direct measures of the deterioration process typically experienced by concrete bridge decks in Utah.

1.0 INTRODUCTION

1.1 Problem Statement

Condition assessments have been generated for bridge elements and used over the past 25 years by private and public agencies throughout the United States to aid in bridge management decisions (Agrawal et al. 2010, Bu et al. 2015). Condition assessment data documented over time can be used to develop deterioration curves. These curves help agencies understand how the condition of bridge elements changes over time.

One bridge element that is regularly assessed and subjected to maintenance, rehabilitation, and reconstruction (MR&R) to maintain or improve its condition is the deck. In cold regions, some factors that contribute to bridge deck deterioration include traffic loads, freeze-thaw cycling, and applications of deicing salts. One of the methods used in Utah to delay the deterioration of bare concrete bridge decks is the application of surface treatments, or overlays, as documented in bridge management records maintained by the Utah Department of Transportation (UDOT) and the Federal Highway Administration (FHWA). Although the application of surface treatments is expected to positively impact bridge deck condition, the effectiveness of specific surface treatments on extending bridge deck life has not yet been quantified on Utah bridge decks; previous studies focusing on the effect of surface treatments on deterioration curves were not identified in the literature reviewed for this research. Therefore, given the need to better understand the performance of surface treatment applications on bridge decks in Utah, UDOT commissioned the current study on this subject.

1.2 Research Objectives and Scope

The objectives of this research were to develop and analyze deterioration curves for bare concrete bridge decks and decks with specific treatments commonly used in Utah. The scope of this study was determined by the types and extent of electronically available data from UDOT and the FHWA for concrete bridge decks in Utah. The data included selected static inventory information, MR&R histories, and National Bridge Inventory (NBI) condition ratings for the bridge decks since the year 1992.

1.3 Report Outline

This report contains five chapters. Chapter 1 presents the objectives and scope of the research. Chapter 2 provides background information regarding deterioration curves, bridge deck condition assessment, and standard surface treatments. Chapter 3 describes the procedures used to generate average deterioration curves for bare concrete bridge decks and decks with specific treatments, and Chapter 4 gives the results of the research and a discussion of the findings. Finally, Chapter 5 presents a summary together with findings and recommendations resulting from this research.

2.0 BACKGROUND

2.1 Overview

The following sections provide information regarding deterioration curves, describe the process of assessing bridge deck condition, and present information about standard surface treatments used in Utah.

2.2 Deterioration Curves

Bridge deterioration curves illustrate how NBI condition ratings of bridge elements change over time and are usually based on metrics specified in the NBI rating system. These curves are used to analyze the performance of a bridge element and predict its future condition. To the extent that the effects of MR&R are incorporated, the curves can also be used to determine appropriate MR&R decisions to prolong the service life of a bridge element (Li et al. 2014). Various readily available research articles focus on the accuracy and utility of deterioration curves, and, based on the continuing need to assess bridge condition and provide appropriate MR&R, these curves continue to be a relevant topic in the study of bridge management.

Over the last few decades, extensive research has been conducted on aspects of bridge performance, including concrete durability, corrosion of reinforcing steel, MR&R methods and timing, and condition prediction models (Farhey 2015, Ghodoosi et al. 2015, Morcous et al. 2002). To some degree, many of these studies have addressed the usefulness of deterioration curves and the effects of external factors on bridge condition such as traffic volume and climate (Bu et al. 2015). Future funding estimates and maintenance strategies have been theorized based on these types of studies as well. One study, in particular, used condition data to identify bridge types that exhibited higher rates of deterioration so that agencies could anticipate more frequent maintenance applications and thereby more efficiently manage their infrastructure assets (Farhey 2015).

2.3 Bridge Deck Condition Assessment

Many metrics relating to bridge deck condition assessment have been developed for the purpose of rating and improving existing infrastructure. Specifically, the general inspection process and NBI condition ratings were of primary interest in this research and are discussed in the following sections.

2.3.1 Inspection Process

The FHWA has set forth standards regarding who can perform bridge condition assessments and acceptable methods for evaluating bridge deck deterioration. As dictated by the FHWA, the inspection process for a bridge must be carried out by a bridge inspector with 5 or more years of experience and proper training or by a registered professional engineer (FHWA 1995). The inspector must also follow the guidelines for NBI condition rating provided in the American Association of State Highway and Transportation Officials (AASHTO) Guide Manual for Bridge Element Inspection (AASHTO 2011). These standards help to eliminate the problem of inexperience and subjective judgment in bridge deck NBI condition ratings. However, subjective judgment is inherent in the inspection process, and the margin of error in the condition ratings can be one or two points (Moore et al. 2000).

Various evaluation methods are used to determine the condition of a bridge deck. A survey of several departments of transportation (DOTs) indicated that the most frequently used methods for evaluating bridge deck deterioration are visual inspection, chaining, chloride concentration testing, coring, and half-cell potential testing (Hema et al. 2004). While only visual inspection is necessary to obtain an NBI rating, these other evaluations produce important results such as the percentage of deck area exhibiting delamination, corrosivity of the concrete surrounding the reinforcing steel, delamination depth, and corrosion activity of the reinforcing steel. Bridge deck evaluation results are then used to determine which MR&R options should be chosen.

Table 2-1 presents a list of possible options based on general bridge deck condition (Krauss et al. 2009). For this research, the matter of interest in the inspection process is the relationship between the NBI condition rating of the deck and the use of protective overlays.

Table 2-1: Common MR&R Decisions Based on Bridge Deck Condition

Bridge Deck Condition	Common MR&R Decision
No Deterioration	Do Nothing
Minimal Deterioration	Patching, Crack Repair, Concrete Sealing
More Developed Deterioration	Protective Overlay
Fully Developed Deterioration	Structural Rehabilitation, Partial/Full Deck Replacement

2.3.2 NBI Condition Ratings

The use of NBI condition ratings began in 1995 when the FHWA implemented a standard scale for the quality of bridge elements and a mandatory time interval for inspections. NBI condition ratings are useful because they indicate how the state of the bridge element has changed over time. NBI condition ratings are intended to represent the general condition of a bridge element by reflecting the amount of deterioration throughout the element under inspection instead of focusing on localized instances of distress (FHWA 1995). NBI condition ratings are given on a scale from 1 to 9, with "1" representing terminal condition and "9" representing excellent condition (FHWA 1995). All NBI condition ratings used to assess bridge decks are integers. While the original descriptions of the type and extent of deterioration that were correlated with these integer ratings was not thorough, research in the industry allowed for more comprehensive descriptions over time. Table 2-2 provides detailed descriptions of deck deterioration associated with each NBI condition rating from 1 to 9 (Krauss et al. 2009). Phrases such as "present desirable criteria," "present minimum criteria," and "minimum tolerable limits" shown in Table 2-2 may have slightly different interpretations among different DOTs. Similarly, the tests used to produce these NBI condition ratings may also vary among DOTs.

These NBI condition ratings are frequently used by DOTs throughout the United States to select MR&R actions. For example, protective overlays are normally applied when the NBI condition rating of a bridge deck is greater than or equal to 4; however, bridge decks with an NBI condition rating less than 4 are evaluated for more extensive rehabilitation (Krauss et al. 2009). As expected, heavy trafficking, chloride-induced corrosion of reinforcing steel, freeze-thaw cycling, and other factors can lead to the decline of bridge deck NBI condition ratings over time (Krauss et al. 2009).

Table 2-2: Condition Rating Descriptions for a Bridge Deck (Krauss et al. 2009)

Rating	Condition	Description
9	Excellent	Superior to present desirable criteria; no visible distress
8	Very Good	No problems noted; equal to present desirable criteria; no visible distress except minor areas or fine cracking
7	Good	Some minor problems; better than present minimum criteria; less than 1% patches and spalls
6	Satisfactory	Structural elements show some minor deterioration; equal to present minimum criteria; deck shows minor spalling or moderate cracking
5	Fair	All primary structural elements are sound but may have minor section loss, cracking, spalling; somewhat better than minimum adequacy to tolerate the deck being left in place as is; less than 10% patches and spalls
4	Poor	Advanced section loss, deterioration, and spalling; meets minimum tolerable limits for the deck to be left in place as is
3	Serious	Loss of section, deterioration, and spalling have seriously affected primary structural components; local failures are possible; basically intolerable requiring high priority of corrective action; more than 35% deck distress
2	Critical	Advanced deterioration of primary structural concrete may be present; unless closely monitored it may be necessary to close the bridge until corrective action is taken; basically intolerable requiring high priority of replacement
1	Terminal	Bridge deck has failed; too dangerous to allow traffic on the structure; requires immediate replacement

According to UDOT, the percentage of the deck area exhibiting spalling and delamination, half-cell potential, and chloride concentration can be related to specific NBI condition ratings. Table 2-3 shows how UDOT associates the test results with specific NBI condition ratings. The percentages shown in Table 2-3 refer to fractions of the total deck area. For the regular biannual inspection process mandated by the FHWA, UDOT does not perform all of these tests for all bridges statewide. Instead, they generally correlate the results of specific tests shown in the table with individual NBI ratings for decks in Utah.

Table 2-3: UDOT Criteria for Bridge Deck NBI Condition Ratings (UDOT 2014)

Rating	Condition Indicators			
	Spalls	Delamination	Half-Cell Potential	Chloride Concentration
9	None	None	0	0
8	None	None	None is < -0.35 V	None is > 1.0 lb Cl^-/yd^3 concrete
7	None	< 2%	0 – 5% is < -0.35 V	None is > 2.0 lb Cl^-/yd^3 concrete
6	< 2% spalls OR sum of all deteriorated/contaminated deck concrete is < 20%			
5	< 5% spalls OR sum of all deteriorated/contaminated deck concrete is 20 – 40%			
4	> 5% spalls OR sum of all deteriorated/contaminated deck concrete is 40 – 60%			
3	> 5% spalls OR sum of all deteriorated/contaminated deck concrete is > 60%			
2	Deck structural capacity is grossly inadequate			
1	Deck has failed completely; repairable by replacement only			

2.4 Standard Surface Treatments

The performance of bare concrete decks, bituminous overlays, epoxy overlays, and latex-modified concrete overlays is discussed in the following sections. In the databases used to investigate the performance of these wearing surfaces for this research, bare concrete bridge decks are referred to as “monolithic,” and this term is therefore also used in this report. In general, the main purpose of surface treatments applied to a monolithic concrete deck are to extend the service life by sealing the deck against further chemical attack, providing a protective layer against physical attack, correcting drainage and cross slopes, improving skid resistance, improving rideability, and smoothing joint transitions (Krauss et al. 2009).

2.4.1 Monolithic Concrete Decks

In the absence of an overlay, the wearing surface of a bridge deck is monolithic concrete. With no protection, the concrete surface is subject to physical and chemical attack from trafficking, freeze-thaw cycling, and the penetration of deicing salts applied during winter maintenance in cold regions (Hema et al. 2004). Therefore, the performance of a monolithic concrete bridge deck depends to a great degree on the durability of the concrete with which it is constructed. In areas with mild weather conditions, monolithic concrete decks can have a longer service life than concrete decks in harsher climates such as the northern regions of Utah (AASHTO 2007, Mindess et al. 2003, Pigeon and Pleau 1995). Because physical and chemical attack of the deck can lead to scaling, cracking, and delamination of the concrete, overlays are frequently used to protect concrete bridge decks in cold regions (Guthrie et al. 2005).

2.4.2 Bituminous Overlays

One of the most common forms of maintenance used historically on monolithic concrete bridge decks in Utah is the application of bituminous overlays. This overlay system typically consists of a bonding primer, a waterproof membrane, a base layer of asphalt, and a wearing surface of asphalt (Krauss et al. 2009). The waterproof membrane serves as a bonding agent at the concrete-asphalt interface and provides the deck with protection against water and chlorides, which can accelerate corrosion of the reinforcing steel. The asphalt serves as a durable traffic-bearing surface and protects the waterproof membrane. The typical thickness of this overlay is 2.5 in. to 3.0 in. (Lachemi et al. 2007). Installation of the overlay involves cleaning and smoothing of the concrete surface with sandblasting to avoid localized damage to the membrane potentially caused by roughness (Krauss et al. 2009). After the sandblasting process, loose debris is removed from the surface, which is also dried according to the discretion of the inspector to ensure a secure bond between the membrane and the concrete (UDOT 2012b). Many agencies have reported that the installation process takes approximately 3 days, depending on the size of the bridge (Krauss et al. 2009).

The time at which a bituminous overlay is applied to a bridge deck can vary. For most agencies, it is used for preventative maintenance, either before or just after the deck has cracked and begun to exhibit signs of active reinforcement corrosion, but it has also been applied after more advanced deterioration has occurred (Krauss et al. 2009). A bituminous overlay with a waterproofing membrane is an attractive option because it is comparatively inexpensive at $3 to $8 per square foot, and the majority of personnel in the transportation industry are already familiar with its construction (Krauss et al. 2009). The service life of bituminous overlays typically ranges from 12 to 19 years according to several state agencies (Krauss et al. 2009). Although bituminous overlays can fail prematurely due to inadequate mixture design and/or poor construction, the typical causes of failure include longitudinal and transverse cracking (Battaglia and Peters 2012). According to one study, the amount of traffic loading over time seems to have little effect on the performance of bituminous overlays (Chou et al. 2008).

2.4.3 Epoxy Overlays

In recent years, application of epoxy overlays for bridge deck maintenance has become increasingly popular in Utah. An epoxy overlay consists of a thin layer of epoxy resin with fine aggregate broadcast on top. The epoxy resin seals the bridge deck, which prevents water and chloride penetration, and the aggregate protects the epoxy from damage and provides a skid-resistant surface. The aggregate particle size typically ranges from 0.033 in. to 0.187 in., passing the No. 4 sieve while being retained on the No. 20 sieve (UDOT 2012a). The thickness of this overlay is typically less than 1 in., which corresponds to a minimal additional dead load on the substructure (Stenko and Chawalwala 2001). Prior to application of the overlay, the deck surface is commonly shot blasted to clean and roughen it, and any debris, including deteriorated concrete, is removed using compressed air or a vacuum to improve the quality of the bond between the concrete and the epoxy resin (Stenko and Chawalwala 2001, UDOT 2012a). The entire epoxy overlay installation process usually takes less than 24 hours (Krauss et al. 2009).

Epoxy overlays are typically applied to decks that may have cracks but are otherwise in good condition with no significant signs of active corrosion. The cost per square foot for epoxy overlays is $10 to $17 (Krauss et al. 2009), and the reported service life ranges from 15 to 30 years (Guthrie et al. 2005, Knight et al. 2004). While epoxy overlays can perform well under heavy traffic conditions (Guthrie et al. 2005), poor construction, especially inadequate deck preparation, can lead to premature failure, which is usually manifest as delamination of the overlay (Rogers et al. 2011). Additionally, use of soft aggregates can lead to excessive wear of the epoxy overlay under trafficking and/or snow plows (Guthrie et al. 2005, Rogers et al. 2011).

2.4.4 Latex-Modified Concrete Overlays

Although latex-modified concrete has been shown in laboratory testing to have lower permeability than conventional concrete, use of latex-modified concrete overlays is becoming a less common bridge deck rehabilitation option in Utah as UDOT has been using more epoxy overlays instead. As the name suggests, latex-modified concrete contains polymer latex, which is added during concrete batching. The latex offers several benefits, including improving workability, reducing water demand, decreasing permeability, increasing tensile strength, and increasing the strength of the bond between aggregate, paste, and steel (Mindess et al. 2003). The thickness of a latex-modified concrete overlay typically ranges from 1.5 in. to 3.0 in. (Krauss et al. 2009). The deck surface is prepared for latex-modified concrete with milling or hydrodemolition, which is intended to remove any deteriorated concrete. The latex-modified concrete mixture normally requires 3 to 4 days to cure (Krauss et al. 2009), during which time all trafficking is restricted.

A latex-modified concrete overlay is typically applied after a deck has developed visible cracking and/or active corrosion of the reinforcing steel (Krauss et al. 2009). The cost per square foot of latex-modified concrete is \$18 to \$39, and the reported service life ranges from 15 to 30 years (Krauss et al. 2009). Bonding failure may occur prematurely because of low tensile strength of the original concrete deck or because of poor surface preparation prior to overlay placement. Cracking can also occur in the overlay; one study documented the development of shallow cracks in properly installed latex-modified concrete overlays after 5 years of service (Sprinkel 2000). When cracks that penetrate the full depth of the overlay are not sealed, they can significantly reduce protection against water and chlorides.

2.5 Summary

Bridge deterioration curves illustrate how NBI condition ratings of bridge elements change over time and are usually based on metrics specified in the NBI rating system. These curves are used to analyze the performance of a bridge element and predict its future condition.

The FHWA has set forth standards regarding who can perform bridge condition assessments and acceptable methods for evaluating bridge deck deterioration. Various evaluation methods are used to determine the condition of a bridge deck, but only visual inspection is necessary to obtain an NBI rating. NBI condition ratings are intended to represent the general condition of a bridge element by reflecting the amount of deterioration throughout the element. NBI condition ratings are given on a scale from 1 to 9, with “1” representing terminal condition and “9” representing excellent condition.

In the absence of an overlay, the wearing surface of a bridge deck is monolithic concrete. With no protection, the concrete surface is subject to physical and chemical attack from trafficking, freeze-thaw cycling, and the penetration of deicing salts applied during winter maintenance in cold regions. Because physical and chemical attack of the deck can lead to scaling, cracking, and delamination of the concrete, overlays are frequently used to protect concrete bridge decks in cold regions. Bituminous overlays, epoxy overlays, and latex-modified concrete overlays were of particular interest in this study.

3.0 PROCEDURES

3.1 Overview

Among the 2,848 bridges in Utah for which UDOT maintains records, bridges with characteristics relevant to this study were selected for analysis. Development of criteria for typical bridges, extraction of data from the FHWA online database, generation of individual deterioration curves, data filtering, and deterioration curve comparisons are discussed in the following sections.

3.2 Typical Bridge Criteria

The inventory data that UDOT provided for this study included 21 static characteristics, which were identified as either categorical or numerical as indicated in Table 3-1. The 10 categorical characteristics are qualitative and include data such as span design, type of rebar, and deck material. The 11 numerical characteristics are quantitative and include data such as bridge length, deck thickness, and annual average daily traffic (AADT).

The categorical characteristics of the bridges were analyzed using pie charts. From the charts, the most common classes were visually identified for each characteristic. The pie chart used to determine the most common bridge deck materials employed in construction is shown as

Table 3-1: Bridge Inventory Data

Numerical	Categorical
Construction Date	Owner
Number of Spans	Span Material
Bridge Length	Span Design
Bridge Width	Deck Material
Deck Thickness	Deck Type
Surface Thickness	Rebar
Rehabilitation Year	Surface Type
AADT	Road Over
Latitude	Functional Class
Longitude	Region
Altitude	

an example in Figure 3-1. The most common bridge deck materials, based on this pie chart, are cast-in-place concrete and concrete precast panels. In the charts, "N/A" indicates that the data were not available. Of the 10 categorical bridge characteristics, five had classes that were clearly more common than others according to a visual assessment of their respective pie charts. The most common, or "typical," classes for each bridge characteristic are listed in Table 3-2. All of the pie charts used to assess the categorical characteristics and identify typical classes are displayed in Appendix A.

The numerical characteristics of the bridges were analyzed using histograms and statistics. In this process, outliers as well as a "typical" range of values for each characteristic were identified. The histogram showing a typical range for the numerical characteristic of bridge length is shown as an example in Figure 3-2. The typical range, which is generally indicated by striped bars in the histogram, encompassed the middle 95 percent of the values for a particular bridge characteristic. The typical bridge deck length was calculated to range from 20 ft to 600 ft. Numerical characteristics for which data were missing for several bridges were excluded from

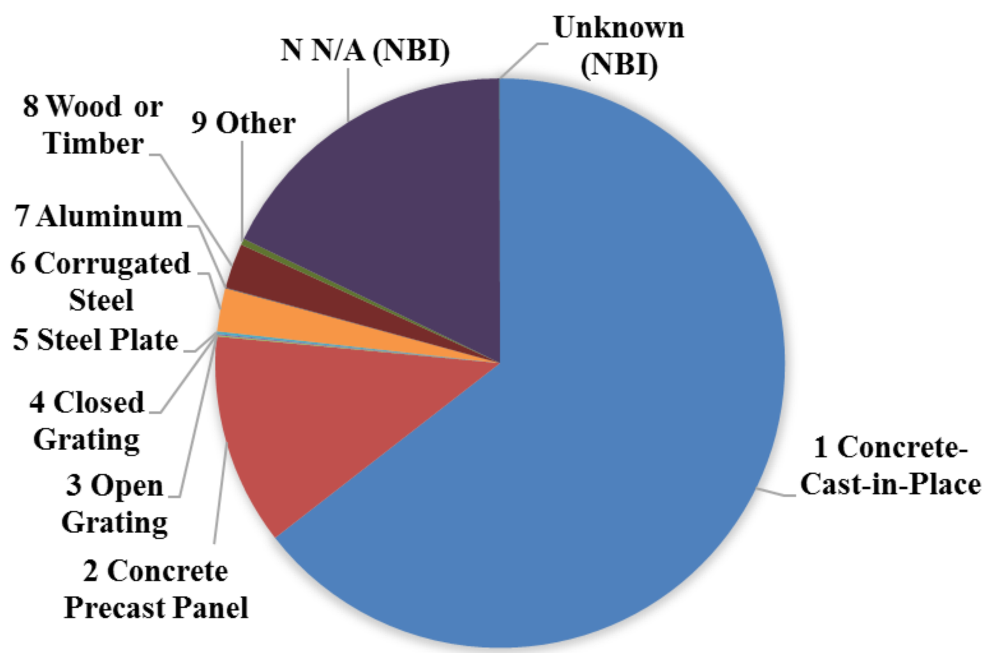


Figure 3-1: Example pie chart of a categorical characteristic (bridge deck material).

Table 3-2: Categorical Characteristics of Utah Bridges

Bridge Characteristic	Typical Classes
Owner	City/Municipal Highway Agency, County Highway Agency, State Highway Agency
Span Design	Slab, Stringer/Girder, Tee Beam, Frame, Culvert
Deck Material	Concrete Cast-In-Place, Concrete Precast Panel, N/A
UDOT Surface Type	Asphalt Overlay with Membrane, Asphalt Overlay without Membrane, Healer/Sealer, Polymer Overlay
FHWA Surface Type	None, Monolithic Concrete, Latex Concrete/Similar, Epoxy Overlay, Bituminous

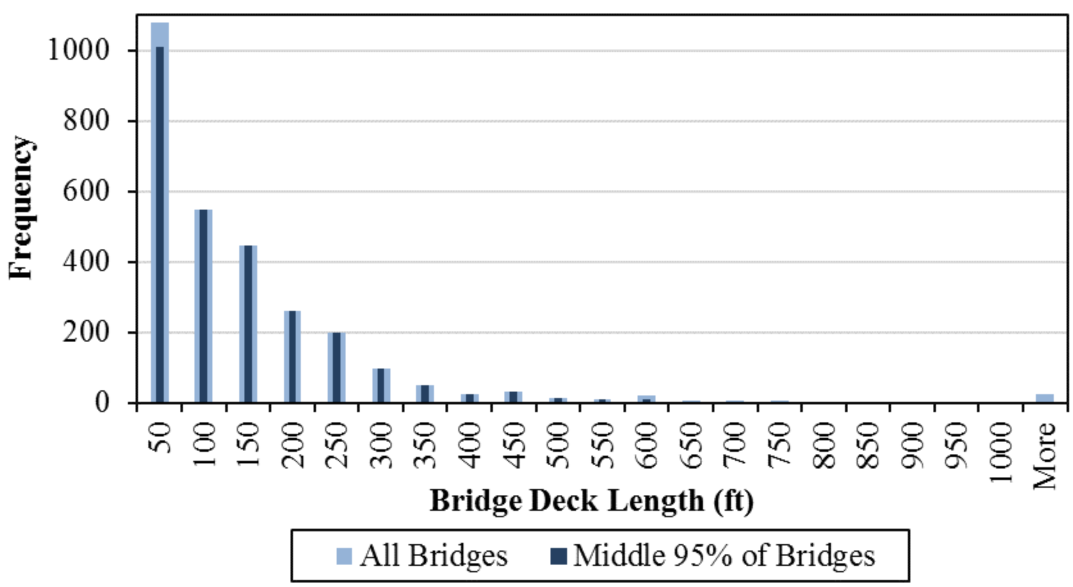


Figure 3-2: Example histogram of a numerical characteristic (bridge deck length).

the process of determining typical bridges. Of the 11 numerical characteristics, seven had easily identifiable typical ranges that were determined from the maximum and minimum values associated with the middle 95 percent of the values. All of the histograms used to assess the numerical characteristics and identify typical ranges of values are displayed in Appendix A. The typical ranges of values for these seven numerical characteristics are listed in Table 3-3.

A filtering program was developed in Visual Basic for the purpose of generating a list of typical bridges from the Utah bridge inventory. This program produced a list of bridges from the inventory that exhibited typical ranges of the 12 characteristics outlined in Table 3-2 and Table 3-3. Because each bridge in the list was considered representative of typical bridges in Utah, potentially confounding effects of atypical bridge characteristics were minimized in comparisons of deterioration curves for monolithic concrete decks, decks with a bituminous overlay, decks with an epoxy overlay, and decks with a latex-modified concrete overlay. Climatic differences were considered by grouping bridges not only by overlay type, but also by UDOT region, which was used in this research as a general surrogate for latitude. The four UDOT regions are shown in Figure 3-3. Of the 2,848 bridges in the UDOT database, 1,057, or 37 percent, exhibited all 12 typical characteristics.

Table 3-3: Numerical Characteristics of Utah Bridges

Bridge Characteristic	Typical Range
Number of Spans	1 – 4
Length (ft)	20 – 600
Width (ft)	16 – 148
Deck Thickness (in.)	6 – 9
Surface Thickness (in.)	0 – 10
AADT (vehicles/yr)	1,000 – 85,000
Altitude (ft)	3,500 – 7,000

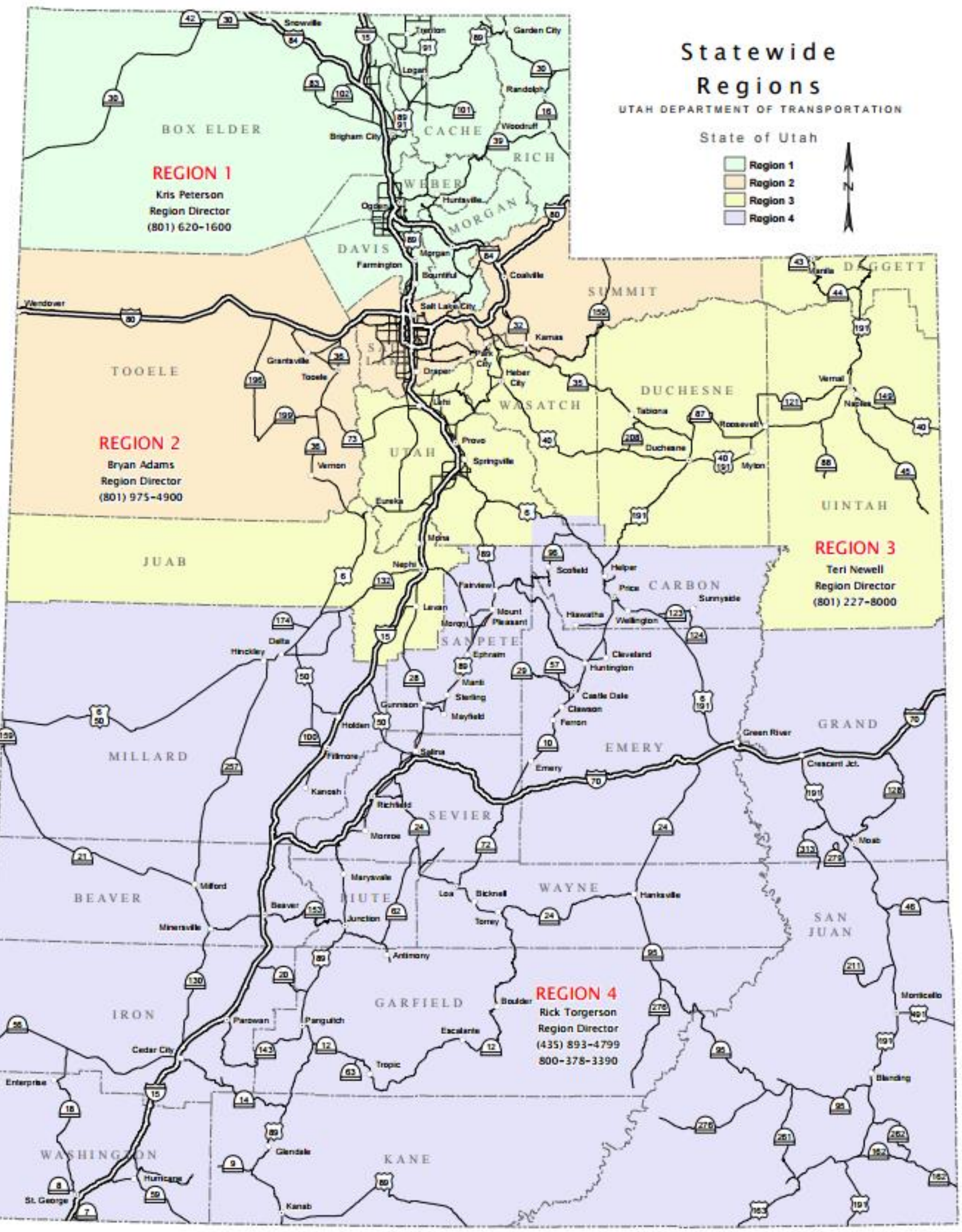


Figure 3-3: Map of UDOT regions (UDOT 2017).

3.3 FHWA Online Database

Once the typical bridge list was generated from the UDOT database, the FHWA website was searched for more data related to bridge histories. Through comparisons of the surface types recorded in the UDOT and FHWA databases, inconsistencies were discovered between the current surface types listed in the UDOT database under the category SURFTYPE and current surface types that UDOT had submitted to the FHWA for annual reports. However, the current surface types listed in the UDOT database under the category SURFTYPE2 matched the current surface types that UDOT had submitted to the FHWA for annual reports. Therefore, the conclusion was drawn that the current surface types listed under the category of SURFTYPE2 were better to use for identifying the current deck surface types. Additionally, although UDOT personnel were also able to extract some of the past NBI condition ratings for the selected bridge decks, the ratings were limited to biannual values and dated back only to the year 2000. Because the FHWA database had a complete NBI condition rating history for each deck, with annual ratings and surface types dating back to 1992, it was instead utilized for this research.

The FHWA bridge data for Utah were subsequently downloaded as annual summary reports and imported into a worksheet for analysis. Specifically, the data were written in a text format that required interpretation using an index table provided on the FHWA website, and Visual Basic code was written to extract the surface type and NBI condition rating histories from this worksheet for each selected bridge deck for every year dating back to 1992.

3.4 Individual Deterioration Curves

Matching the identification number (bridge ID) of a single bridge to the corresponding surface type and NBI condition rating for each year of available data was also performed using Visual Basic code to automate the process. From a list of bridge IDs, the program would automatically generate a new worksheet for each bridge that displayed the following information relevant to this study:

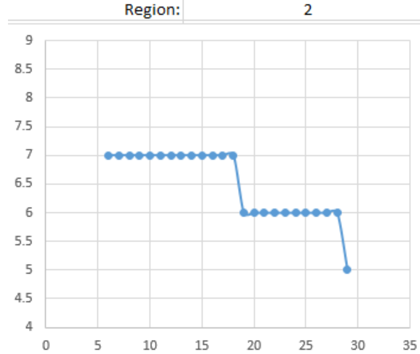
- Bridge ID
- Year in which the bridge was originally constructed
- UDOT region in which the bridge is located

- Bridge deck surface type according to UDOT as of 2015 (SURFTYPE)
- Bridge deck surface type according to the FHWA database as of 2015 (SURFTYPE2)
- Bridge deck surface type history according to the FHWA database
- Biannual NBI condition rating history of the bridge deck according to UDOT
- Annual NBI condition rating history of the bridge deck according to the FHWA database

Within each worksheet, a graph of NBI condition rating, according to the FHWA database, and bridge age in years was automatically generated. A screenshot of the worksheet for the bridge with ID 1C 628 is presented in Figure 3-4 as an example.

The numerical entries for "surface type number" in Figure 3-4 correspond to different deck surface types as defined in Table 3-4. The rows that are bolded in Table 3-4 are the surface types that were analyzed in this study. In this analysis, monolithic concrete decks included surface types 1 and 0. Bituminous overlays, epoxy overlays, and latex-modified concrete overlays included surface types 6, 5, and 3, respectively. Because monolithic concrete decks lack an additional layer of protection, they serve as the control for comparisons between different wearing surfaces for this study.

Bridge ID:	1C 628
Construction Date:	1986
Typical:	yes
Surface Type:	Asphalt Overlay w/o Membrane
Surface Type 2 (NBI):	6 Bituminous
Region:	2



Bridge Age	Year	Condition Rating 1	Condition Rating 2	Surface Type Number
30	2016			
29	2015		5	6
28	2014	5	6	6
27	2013		6	6
26	2012	6	6	6
25	2011		6	6
24	2010	6	6	1
23	2009		6	1
22	2008	6	6	1
21	2007	6	6	1
20	2006		6	1
19	2005	6	6	1
18	2004		7	1
17	2003	7	7	1
16	2002		7	1
15	2001		7	1
14	2000	7	7	1
13	1999		7	1
12	1998		7	1
11	1997		7	1
10	1996		7	1
9	1995		7	1
8	1994		7	1

Figure 3-4: Screenshot of a worksheet with information about bridge 1C 628.

Table 3-4: Surface Type Summary (FHWA 1995)

Surface Type Number	Description
1	**Monolithic Concrete (concurrently placed with structural deck)**
2	Integral Concrete (separate non-modified layer of concrete added to structural deck)
3	**Latex Concrete or Similar Additive**
4	Low-Slump Concrete
5	**Epoxy Overlay**
6	**Bituminous**
7	Wood or Timber
8	Gravel
9	Other
0	**None (no additional concrete thickness or wearing surface is included in the bridge deck)**
N	Not Applicable (applies only to structures with no deck)

Again using Visual Basic code, several workbooks were created, with each workbook containing information about bridges for a specific combination of UDOT region and surface treatment, as illustrated in Table 3-5. The entries in the table indicate the number of bridges from the typical bridge list that were included in the given combination of UDOT region and surface type. The total number of typical bridges was 1,039. The age of the typical bridges ranged from about 2 years to 100 years; however, only the most recent 24 years of NBI condition ratings and surface type changes were recorded for each bridge in the FHWA database.

Table 3-5: Initial Number of Bridges Grouped by Surface Type and UDOT Region for Each Workbook

	Number of Bridges by Indicated UDOT Region				
Surface Type	1	2	3	4	Total
Monolithic Concrete	38	76	44	78	236
Bituminous Overlay	120	193	51	168	532
Epoxy Overlay	65	51	75	10	201
Latex Concrete	6	51	11	2	70

3.5 Data Filtering

Data filtering was needed to remove irregularities that were observed during inspection of selected worksheets. The filtering involved modifications of certain deterioration curves and deletions of other deterioration curves, which reduced the number of eligible typical bridges for this study from 1,057 to 454. The filtering specifically addressed deterioration curves for bridge decks with multiple or irrelevant surface types, invalid or missing condition ratings, condition rating histories that did not correlate logically with their surface type histories, and/or overlays placed earlier than 1992.

The bridge decks with multiple or irrelevant surface types were either removed from the study or modified to be eligible for the study. Any deck that was reported to be monolithic concrete at the time of this research but had a different surface type in the past was removed from the monolithic concrete deck group. Any deck that had a bituminous overlay at the time of this research but previously had some other overlay besides a monolithic concrete deck was either removed from the bituminous overlay group or truncated at the time the bituminous overlay was applied and placed in the overlay group corresponding to the previous overlay type; the truncating option was chosen only if the previous overlay was one of interest for this study. This method of filtering was also performed on the deterioration curves for decks that were reported to have epoxy overlays and latex-modified concrete overlays at the time of this research.

The deterioration curves that had invalid or missing condition ratings were resolved by removal or interpolation, depending on the situation. Some of the bridge worksheets had an "N" in place of an NBI condition rating for the given deck. These "N" values usually applied to smaller structures such as concrete box culverts, tunnels, and other miscellaneous structures for which monitoring of the deck was not crucial in evaluating the condition of the structure. These structures were therefore excluded from further analysis. Some bridge decks were missing a year or two of NBI condition ratings. Interpolation was used to predict the value of the missing NBI condition rating; however, if several years of NBI condition ratings were missing, the bridge history was truncated to exclude the years that did not have NBI condition ratings and all subsequent years as well.

Other bridge decks had NBI condition rating histories that did not correlate logically with their surface type histories. The NBI condition rating histories for bridge decks that had an increase in NBI condition rating with no associated surface change (for example, an overlay placed on monolithic concrete) within 3 years of the increased NBI condition rating were truncated before the year when the increase in NBI condition rating occurred.

The final step in the filtering process was to exclude bridge decks for which the year of overlay application was not known because the overlay was applied before 1992. If a bridge was constructed before 1992 (which is the earliest year of available data) and had the same overlay on the deck since 1992, it was excluded from further consideration because a reliable and efficient way to determine the year of overlay application was not available for bridge decks constructed before 1992.

These filters were applied to all of the typical bridge worksheets in each workbook using Visual Basic code. Table 3-6 shows the breakdown by UDOT region and surface type of the remaining typical bridges used to develop average deterioration curves, with the total number of bridges being 454.

Table 3-6: Final Number of Bridges Grouped by Surface Type and UDOT Region for Each Workbook

Surface Type	Number of Bridges by Indicated UDOT Region				Total
	1	2	3	4	
Monolithic Concrete	27	60	40	67	194
Bituminous Overlay	17	63	11	23	114
Epoxy Overlay	61	6	12	7	86
Latex Concrete	4	46	10	0	60

3.6 Deterioration Curve Comparisons

Grouping of individual bridge deck deterioration curves in specific combinations was necessary to investigate the effects of surface type on bridge deck deterioration. Specifically, individual bridge deck deterioration curves were combined to generate average deterioration curves aligned by deck construction time and average deterioration curves aligned by deck treatment time as explained in the following sections.

3.6.1 Average Deterioration Curves Aligned by Deck Construction Time

Visual Basic code was written to extract deterioration curves for individual bridges from a particular workbook (this workbook could contain all the bridges with bituminous overlays in Region 1 or all the bridges with monolithic concrete decks in Region 3, for example), and combine them into one graph, with the deck construction times aligned at a value of 0 on the *x*-axis. As illustrated in Figure 3-5, which shows individual deterioration curves for bridges with bituminous overlays in Region 2 as an example, an average deterioration curve, which is shown as a black line, was then calculated. Greater variability occurs in the average deterioration curve as the number of available bridge decks for a given age decreases. Beyond displaying the NBI ratings with age for each bridge deck, Figure 3-5 also indicates with a vertical line the age at which the surface type changed for each bridge deck.

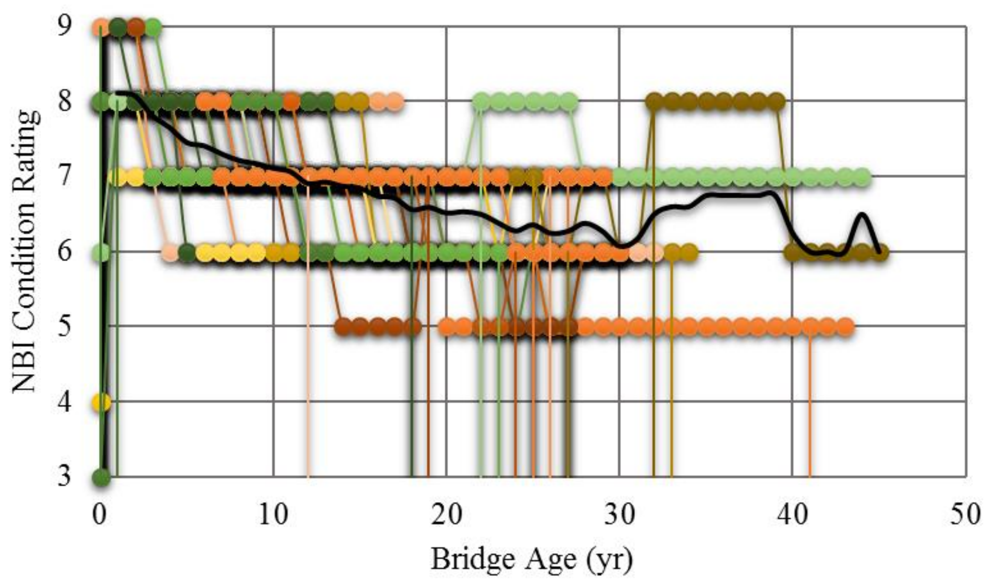


Figure 3-5: NBI ratings aligned by deck construction time for bridge decks with a bituminous overlay in Region 2.

These average deterioration curves were generated to enable comparisons between different groups of bridges across a wide range in bridge age from 2 years to 45 years. Based on the wide range in age, each average curve provided a longer continuous NBI condition rating history than that associated with any individual deterioration curve, but the average curve also incorporated a wide range in overlay placement times. Averaging the effects of an overlay placed over a wide range in bridge age was not desirable in this research because, for example, an epoxy overlay applied 5 years after construction of a bridge deck could have significantly different effects on deck deterioration than would be expected for an epoxy overlay applied 20 years later. Therefore, to at least partially account for these potentially different effects, the bridge groups involving overlays were divided into two treatment time categories, early and late, as listed in Table 3-7. Early treatment was defined as treatment within the first 15 years of bridge deck life, and late treatment was defined as 16 years or later after bridge deck construction. While sufficient data to support these two categories were available for decks with a bituminous or epoxy overlay, no data were available in the late treatment category for decks with a latex-modified concrete overlay. Table 3-8 shows the number of bridges in each group, as organized by surface type, UDOT region, and treatment time. (The groups without any bridge decks were necessarily omitted from the study.) An average deterioration curve was generated for each group; as an example, Figure 3-6 shows an average deterioration curve for decks with early application (0 to 15 years after bridge deck construction) of a bituminous overlay in Region 2. Several different comparisons among these average deterioration curves were performed by superimposing the curves with a relationship of interest onto one another in the same graph. These graphs allowed visual identification of differences between the curves over time. Specifically, graphs were prepared to show curves for surface types and treatment times by

Table 3-7: Treatment Time Categories by Overlay Type

Surface Type	Age at Time of Application (yr) by Indicated Treatment Time Category	
	Early	Late
Bituminous Overlay	0 – 15	16+
Epoxy Overlay	0 – 15	16+
Latex-Modified Concrete	0 – 15	-

Table 3-8: Final Number of Bridges Grouped by Surface Type, UDOT Region, and Treatment Time for Each Workbook

Surface Type	Number of Bridges by Indicated UDOT Region and Treatment Time Category								Total
	1		2		3		4		
	Early	Late	Early	Late	Early	Late	Early	Late	
Monolithic Concrete	27		60		40		67		194
Bituminous Overlay	9	8	26	37	5	6	6	17	114
Epoxy Overlay	32	29	4	2	8	4	0	7	86
Latex-Modified Concrete	4	0	46	0	8	2	0	0	60

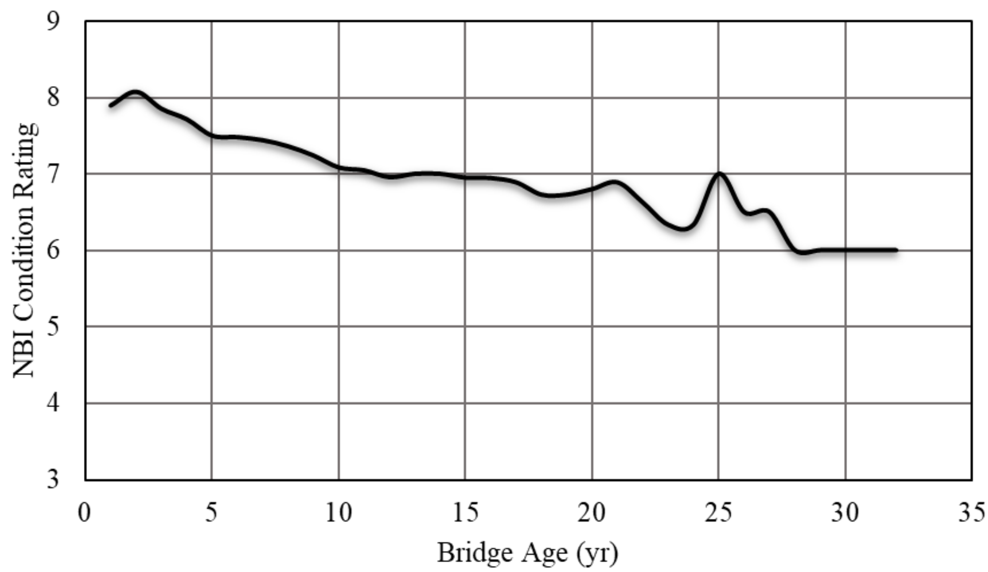


Figure 3-6: Average deterioration curve for bridge decks with early application of a bituminous overlay in Region 2.

UDOT region. Each column in Table 3-9 represents a different graph, and the rows in a given column indicate the specific average deterioration curves included in the graph.

Table 3-9: Comparison Groups for Surface Types, Treatment Times, and UDOT Region

Comparison Groups			
Region 1	Region 2	Region 3	Region 4
Monolithic Concrete	Monolithic Concrete	Monolithic Concrete	Monolithic Concrete
Bituminous Overlay Early Treatment	Bituminous Overlay Early Treatment	Bituminous Overlay Early Treatment	Bituminous Overlay Early Treatment
Bituminous Overlay Late Treatment	Bituminous Overlay Late Treatment	Bituminous Overlay Late Treatment	Bituminous Overlay Late Treatment
Epoxy Overlay Early Treatment	Epoxy Overlay Early Treatment	Epoxy Overlay Early Treatment	Epoxy Overlay Late Treatment
Epoxy Overlay Late Treatment	Epoxy Overlay Late Treatment	Epoxy Overlay Late Treatment	
Latex-Modified Concrete Early Treatment	Latex-Modified Concrete Early Treatment	Latex-Modified Concrete Early Treatment	
		Latex-Modified Concrete Late Treatment	

3.6.2 Average Deterioration Curves Aligned by Deck Treatment Time

With the individual bridge worksheets divided according to UDOT region, current wearing surface type, and treatment time, Visual Basic code was written to generate additional graphs illustrating surface treatment effects. From the workbooks containing data for bridges with overlays, the code extracted the NBI condition ratings of each bridge deck from a maximum of 10 years before to a maximum of 10 years after a treatment was applied and then combined them into one graph, with the treatment times aligned at a value of 0 on the *x*-axis. With this graph layout, negative *x* values represent years before the surface treatment, and positive *x* values represent years after the surface treatment. An average deterioration curve was then calculated from the individual deterioration curves as illustrated in Table 3-7, which shows data for bridge decks with late application of a bituminous overlay in Region 2 as an example. The graph allows for a visual assessment of the immediate effects of surface treatment placement on NBI ratings. Once these average curves were generated, they could be superimposed on one another to enable different comparisons. Specifically, the same structure described previously in Table 3-9 was used in these comparisons.

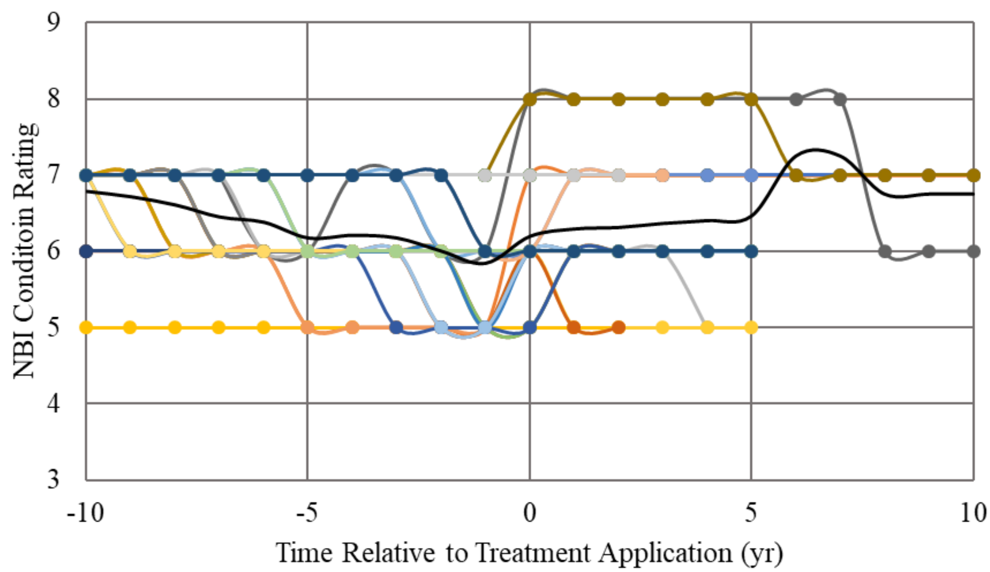


Figure 3-7: NBI ratings aligned by deck treatment time for bridge decks with late application of a bituminous overlay in Region 2.

3.7 Summary

Bridge deck selection criteria and analysis procedures were developed to enable evaluation of the effects of surface treatments on bridge decks in Utah. Characteristics of a typical bridge were defined, with categorical characteristics being analyzed using pie charts and numerical characteristics being analyzed using histograms and statistics. A filtering program developed in Visual Basic was then used to generate a list of bridges from the UDOT inventory that exhibited typical ranges of 12 selected categorical and numerical characteristics. Because each bridge in the list was considered representative of typical bridges in Utah, potentially confounding effects of atypical bridge characteristics were minimized in comparisons of deterioration curves for monolithic concrete decks, decks with a bituminous overlay, decks with an epoxy overlay, and decks with a latex-modified concrete overlay. Climatic differences were considered by grouping bridges not only by overlay type, but also by UDOT region, which was used in this research as a general surrogate for latitude.

Additional Visual Basic code was written to extract the surface type and NBI condition rating histories from the FHWA database for each typical bridge deck for every year dating back to 1992. Workbooks containing information about bridges and their corresponding individual deterioration curves for a specific combination of UDOT region and surface treatment were then created. Data filtering was needed to remove irregularities that were observed during inspection of selected worksheets. The workbooks were filtered to specifically address deterioration curves for bridge decks with multiple or irrelevant surface types, invalid or missing condition ratings, condition rating histories that did not correlate logically with their surface type histories, and/or overlays placed earlier than 1992.

Grouping of individual bridge deck deterioration curves in specific combinations was necessary to investigate the effects of surface type on bridge deck deterioration. Specifically, individual bridge deck deterioration curves were combined to generate average deterioration curves aligned by deck construction time and average deterioration curves aligned by deck treatment time. For analysis of average deterioration curves aligned by deck construction time, Visual Basic code was written to extract deterioration curves of individual bridges from a particular workbook and combine them into one graph, with the deck construction times aligned at a value of 0 on the *x*-axis. For analysis of average deterioration curves aligned by deck treatment time, the code extracted the NBI condition ratings of each bridge deck from a maximum of 10 years before to a maximum of 10 years after a treatment was applied and then combined them into one graph, with the treatment times aligned at a value of 0 on the *x*-axis. In both cases, an average deterioration curve was then calculated from the individual deterioration curves. To at least partially account for the potentially different effects of different treatment times, the bridge groups involving overlays were divided into two treatment time categories, early and late, and the average deterioration curve for each of these groups was generated. To allow visual identification of differences between the curves over time, graphs were prepared to show curves for surface types and treatment times by UDOT region.

4.0 RESULTS

4.1 Overview

The average deterioration curves developed in this research are presented and discussed in the following sections. Average deterioration curves aligned by deck construction time and average deterioration curves aligned by deck treatment time are presented for each UDOT region and for the entire state. As stated previously, early treatment was defined as treatment within the first 15 years of bridge deck life, and late treatment was defined as 16 years or later after bridge deck construction.

4.2 Average Deterioration Curves

Two individual sets of average deterioration curves, with NBI ratings generally ranging from 5 to 9, are presented in the following sections. In the figures, the length of a given deterioration curve aligned by deck construction time depends on the availability of the data, which in turn reflects the usage history of a given surface type. For example, monolithic decks and decks with bituminous overlays generally have longer deterioration curves because they have been specified by UDOT for a longer period of time, while decks with epoxy overlays and latex-modified concrete overlays have shorter deterioration curves because they have been specified by UDOT for a shorter period of time. In the figures, the length of a given deterioration curve aligned by deck treatment time depends on the availability of NBI condition ratings during the 10 years before and the 10 years after the time of deck treatment.

In the figures showing deterioration curves aligned by deck construction time, and sometimes in the figures showing deterioration curves aligned by deck treatment time, the apparent increase in variability especially towards the end(s) of some of these curves is caused by a decreasing number of data points available to be averaged at the given point in time; while higher numbers of data points increase the stability of the average, lower numbers of data points decrease the stability of the average. The individual deterioration curves from which the average deterioration curves were computed are provided in Appendices B and C.

4.2.1 Average Deterioration Curves Aligned by Deck Construction Time

The average deterioration curves aligned by deck construction time are displayed in Figures 4-1 to 4-5. These figures allow a visual comparison of the effects of different surface types and treatment times on NBI ratings for each UDOT region and for the entire state. While the differences among curves are generally within the expected margin of error of 1 to 2 points for NBI condition ratings (Moore et al. 2000), the figures suggest that certain treatments applied at certain times can achieve average NBI ratings greater than those for monolithic concrete during selected years of bridge deck life.

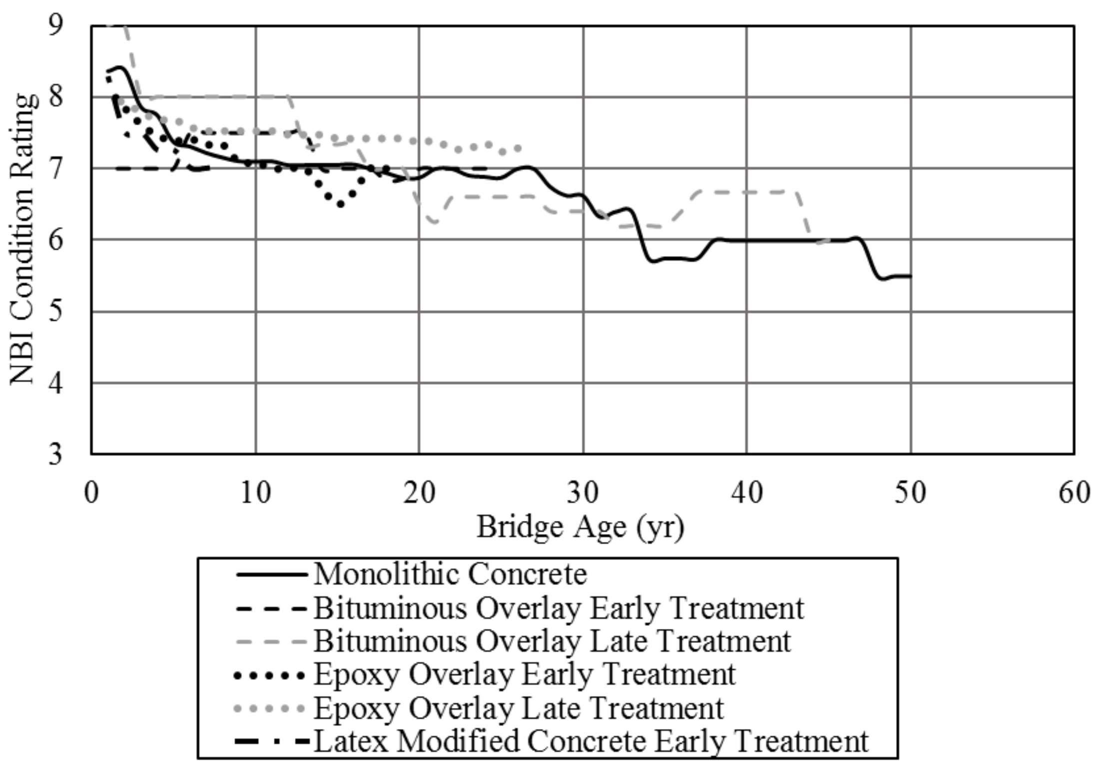


Figure 4-1: Average deterioration curves aligned by deck construction time for Region 1.

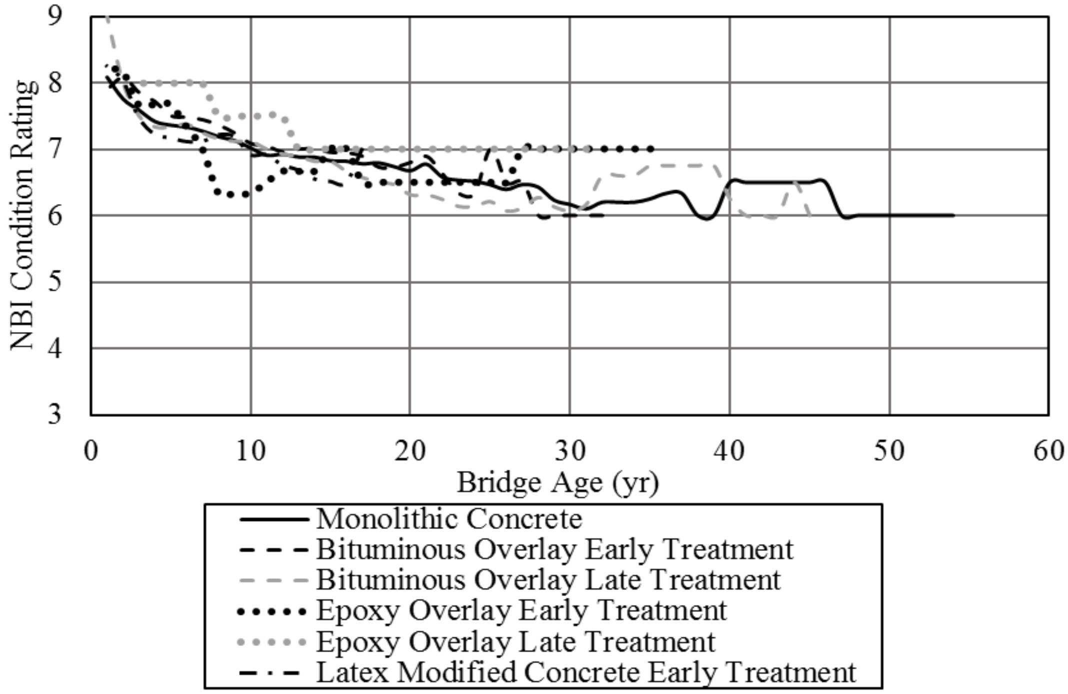


Figure 4-2: Average deterioration curves aligned by deck construction time for Region 2.

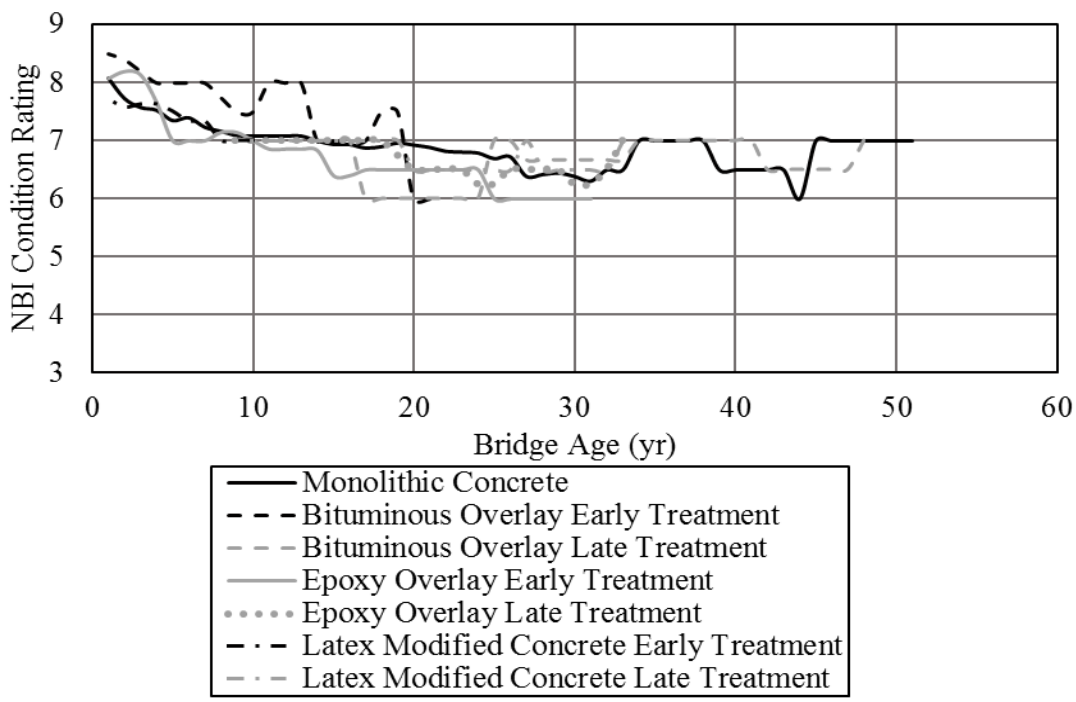


Figure 4-3: Average deterioration curves aligned by deck construction time for Region 3.

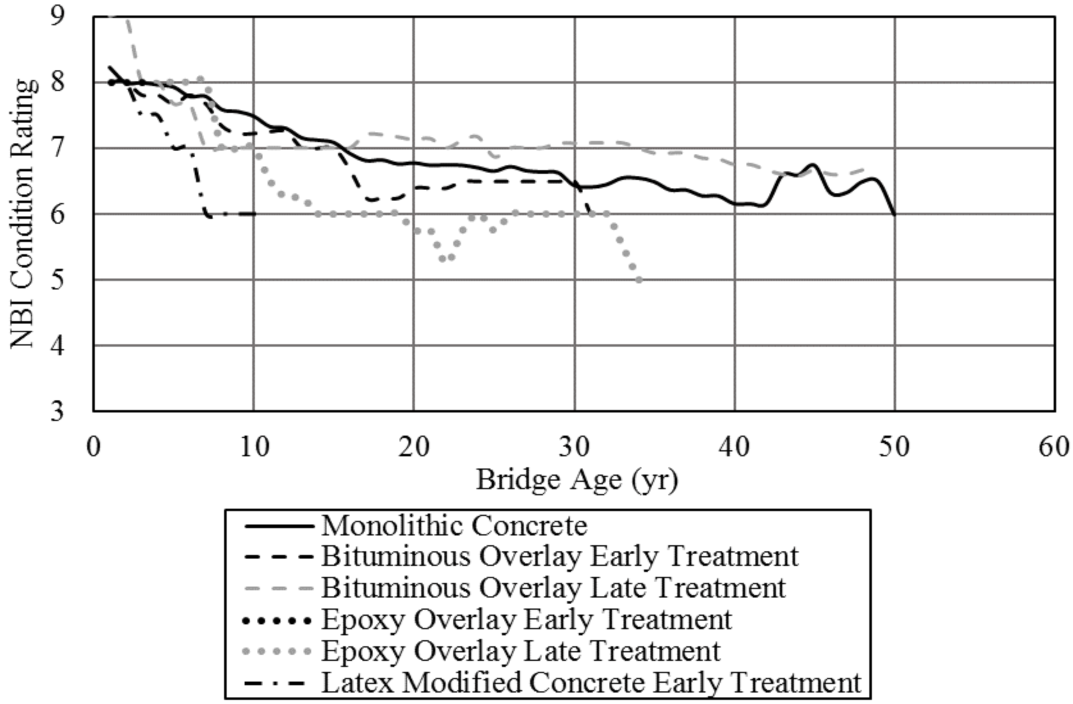


Figure 4-4: Average deterioration curves aligned by deck construction time for Region 4.

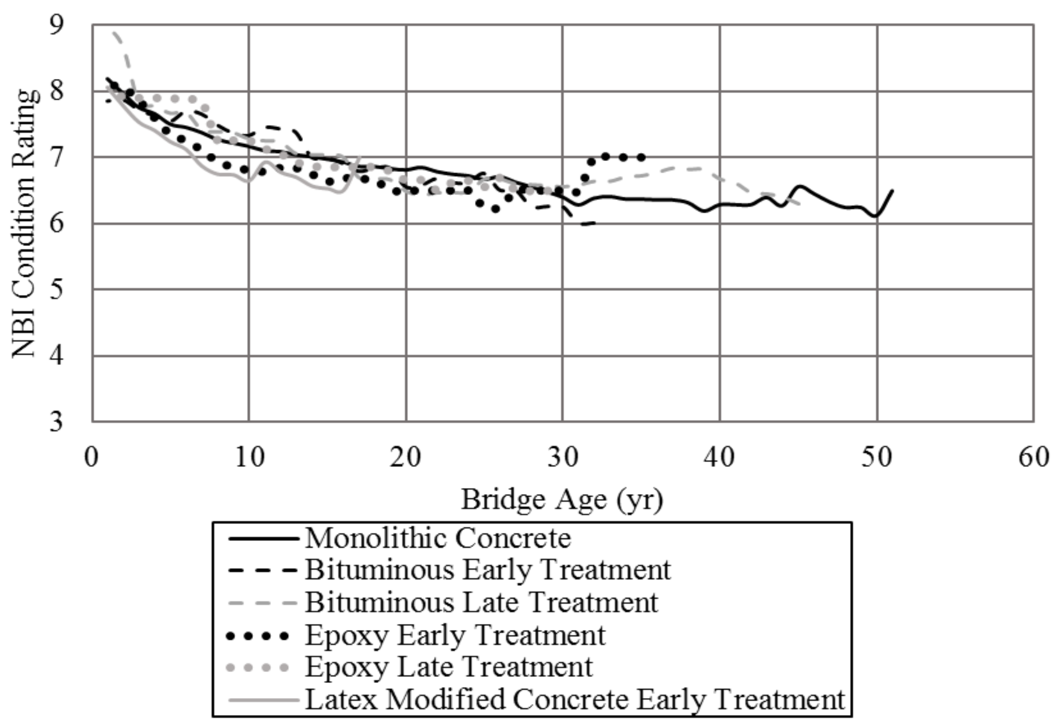


Figure 4-5: Statewide average deterioration curves aligned by deck construction time.

A summary of specific ranges in bridge age when average NBI ratings for bridges with surface treatments exceed those for monolithic concrete bridge decks is presented in Table 4-1. In the table, an asterisk indicates that the given age range includes years prior to the application of the given treatment, an entry of "0-0" indicates that NBI ratings for the given treatment do not exceed those for monolithic concrete at any point in the available NBI rating histories, and an entry of "N/A" indicates that NBI ratings for the given treatment are not available.

According to the data for individual regions in Table 4-1, early treatment with a bituminous overlay achieves NBI ratings higher than those for monolithic concrete for up to 26 years of bridge deck service life, while the benefits of late treatment with a bituminous overlay occur mainly from 16 to 48 years of bridge deck service life. Early treatment with an epoxy overlay achieves NBI ratings higher than those for monolithic concrete for up to 35 years of

Table 4-1: Analysis of Average Deterioration Curves Aligned by Deck Construction Time

	Ranges in Bridge Age When Average NBI Ratings for Specified Treatments Exceed Those for Monolithic Concrete (yr)				
Surface Treatment	Region 1	Region 2	Region 3	Region 4	Statewide
Bituminous Overlay Early Treatment	6-13 20 23-24	0-17 20-21 25-26	0-13 15-19	0-0	6-13, 25
Bituminous Overlay Late Treatment	0-16 18-19 34-43	0-2* 10-12* 32-39	15-16* 25-33 39-41 44	0-2* 16-42 46-48	0-12* 29-43
Epoxy Overlay Early Treatment	6-8, 18	0-5, 15-16 25-35	2-4, 9	0-0	2-3 29-35
Epoxy Overlay Late Treatment	5-26*	0-31*	15-18* 26-29 33	5-7	3-7* 10*
Latex Modified Concrete Early Treatment	0-0	0-2 17	3-5 6	0-0	17
Latex Modified Concrete Late Treatment	N/A	N/A	15-19* 27-31 33	N/A	N/A

bridge deck service life, while the benefits of late treatment with an epoxy overlay occur mainly from 16 to 33 years of bridge deck service life. Early treatment with latex-modified concrete achieves NBI ratings higher than those for monolithic concrete for up to 17 years of bridge deck service life, while the benefits of late treatment with latex-modified concrete occur mainly from 16 to 33 years of bridge deck service life. The only cases in which measurable improvements in NBI ratings were not observed include early treatment with a bituminous overlay in Region 4, early treatment with an epoxy overlay in Region 4, and early treatment with latex-modified concrete in Regions 1 and 4. A possible reason for the apparent reduction in the effects of these early treatments in Region 4 is the more mild climate in that region compared to Regions 1, 2, and 3. With substantially fewer occurrences of freezing temperatures in Region 4, less deicing salt is applied, less chloride-induced corrosion of the reinforcing steel occurs, and less deterioration of monolithic concrete bridge decks is expected.

4.2.2 Average Deterioration Curves Aligned by Deck Treatment Time

The average deterioration curves aligned by deck treatment time are displayed in Figures 4-6 to 4-10. These figures allow a visual comparison of the effects of different surface types and

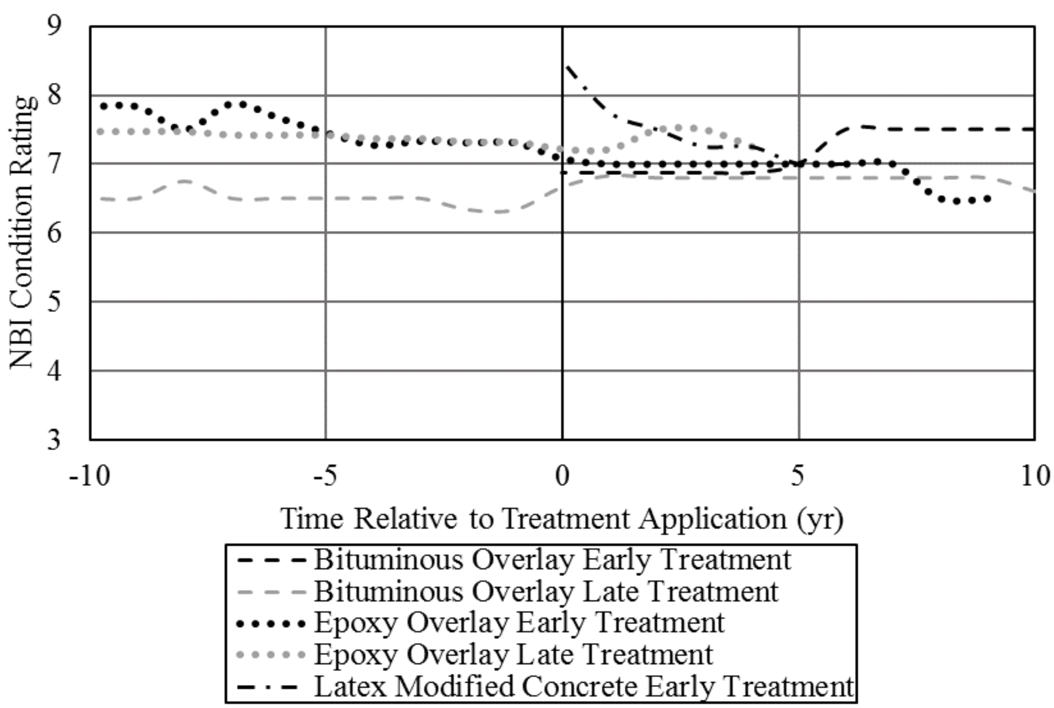


Figure 4-6: Average deterioration curves aligned by deck treatment time for Region 1.

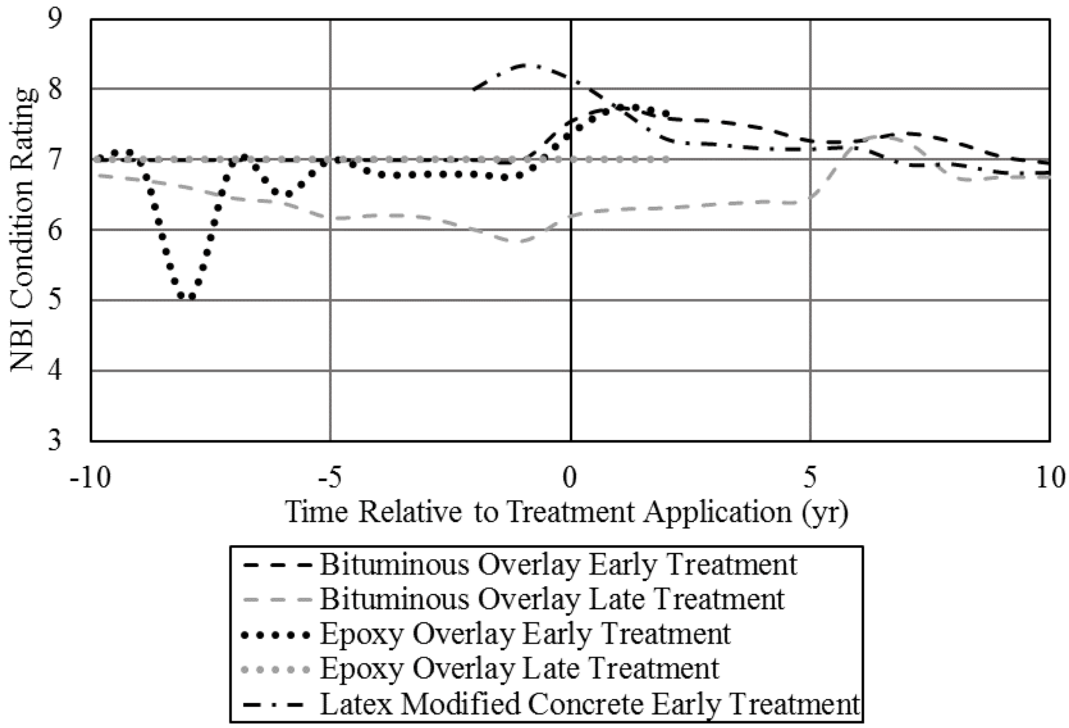


Figure 4-7: Average deterioration curves aligned by deck treatment time for Region 2.

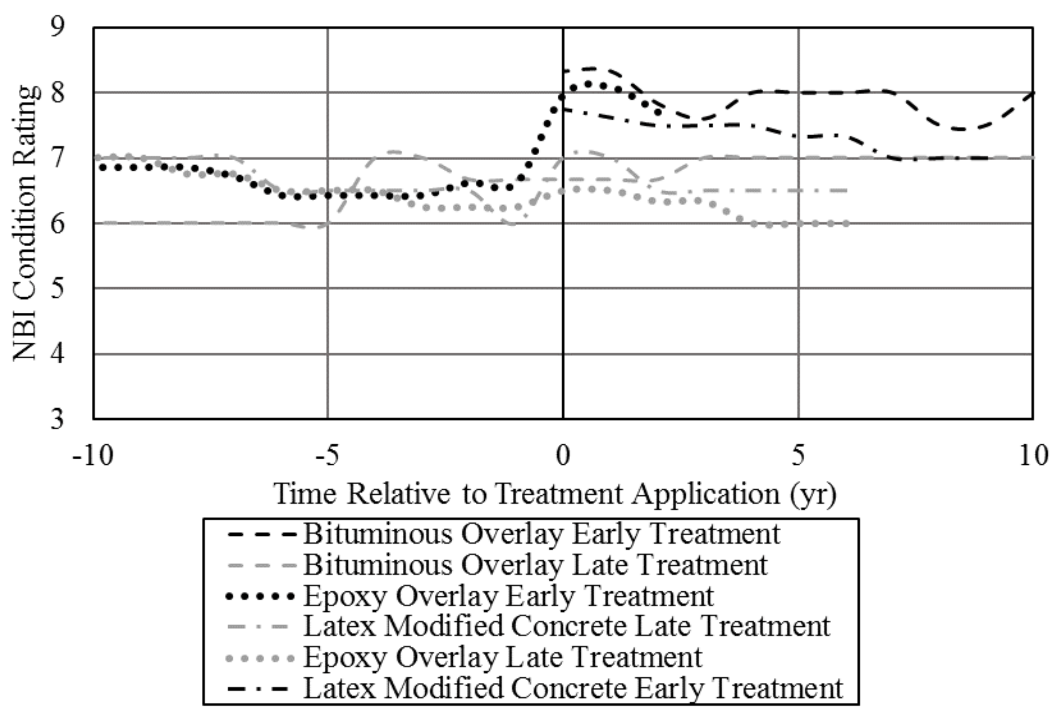


Figure 4-8: Average deterioration curves aligned by deck treatment time for Region 3.

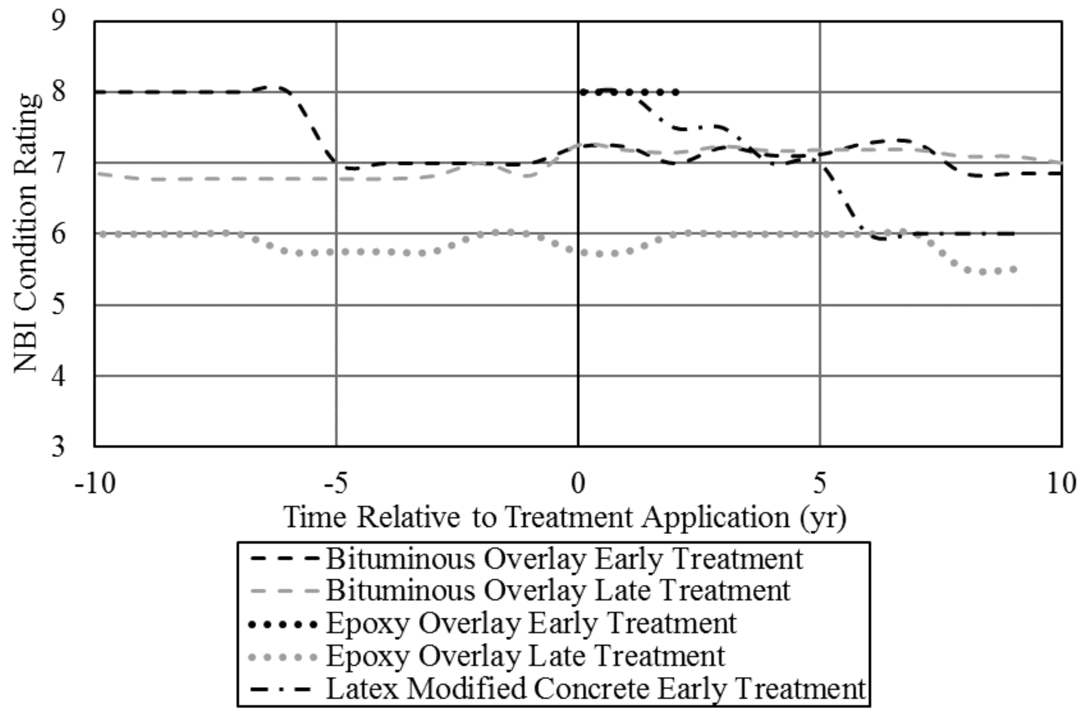


Figure 4-9: Average deterioration curves aligned by deck treatment time for Region 4.

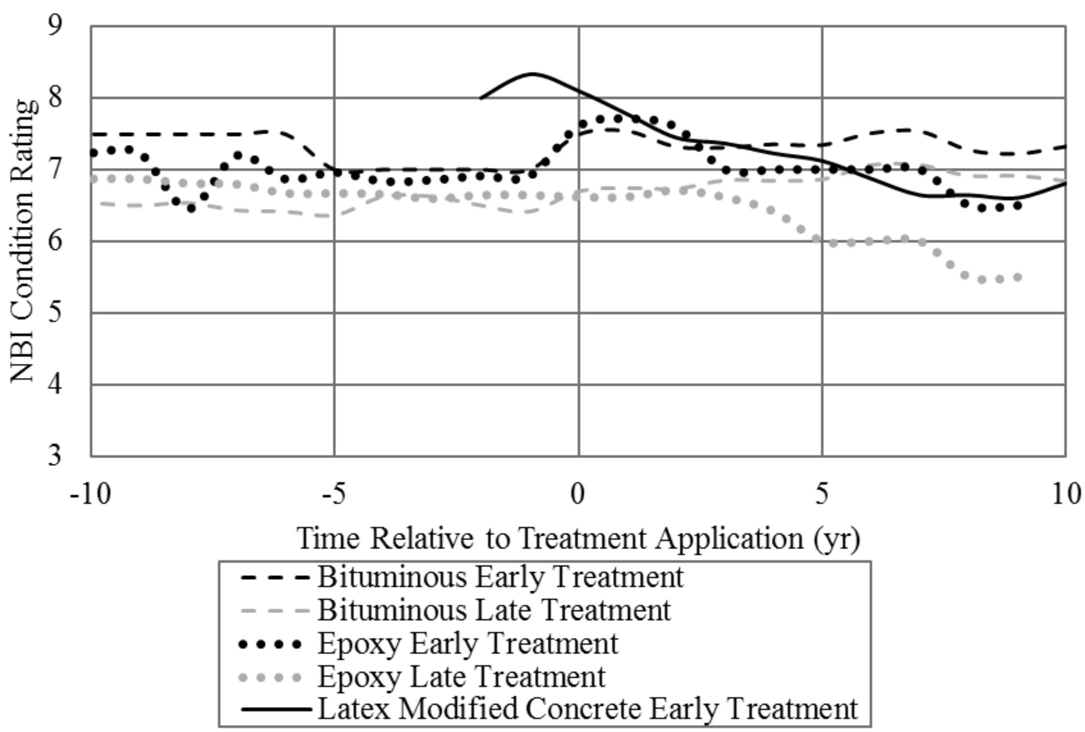


Figure 4-10: Statewide average deterioration curves aligned by deck treatment time.

treatment times on changes in NBI ratings that occur at the time of deck treatment for each UDOT region and for the entire state. While the differences among curves are again generally within the expected margin of error of 1 to 2 points for NBI condition ratings (Moore et al. 2000), the figures suggest that certain treatments applied at certain times can achieve improvements in NBI ratings that correspond to apparent increases in bridge deck service life.

A summary of bridge deck service life extensions is presented in Table 4-2. Each value given in the table is the number of years between the time of treatment application, which in many cases is marked by an increase in the NBI rating, and the time when the NBI rating returns to the pre-treatment level. In the table, an entry of "0" indicates that the NBI rating for the given treatment does not increase after treatment application, a hyphen indicates that NBI ratings for the given treatment are not available for years before the treatment application (generally because the treatment was applied at the time of deck construction), and an entry of "N/A" indicates that NBI ratings for the given treatment are not available for years before or after the treatment application.

Table 4-2: Analysis of Average Deterioration Curves Aligned by Deck Treatment Time

	Apparent Bridge Deck Life Extensions for Specific Treatments (yr)				
Surface Treatment	Region 1	Region 2	Region 3	Region 4	Statewide
Bituminous Overlay Early Treatment	-	9	-	8	>10
Bituminous Overlay Late Treatment	>10	>10	>10	10	>10
Epoxy Overlay Early Treatment	0	>2	2	-	3
Epoxy Overlay Late Treatment	4	0	3	7	3
Latex Modified Concrete Early Treatment	0	0	-	-	0
Latex Modified Concrete Late Treatment	N/A	N/A	6	N/A	N/A

According to the data for individual regions in Table 4-2, early treatment with a bituminous overlay achieves an extension of 8 years to more than 10 years of bridge deck service life, while late treatment with a bituminous overlay achieves an extension of more than 10 years of bridge deck service life. Early treatment with an epoxy overlay achieves an extension of 0 years to more than 2 years of bridge deck service life, while late treatment with an epoxy overlay achieves an extension of 0 years to 7 years of bridge deck service life. Early treatment with latex-modified concrete does not achieve a measurable extension in bridge deck service life, but late treatment with latex-modified concrete achieves an extension of 6 years of bridge deck service life. The only cases in which NBI ratings for the given treatment are not available for years before the treatment application include early treatment with a bituminous overlay in Regions 1 and 3, early treatment with an epoxy overlay in Region 4, and early treatment with latex-modified concrete in Regions 3 and 4. The only cases in which NBI ratings for the given treatment are not available for years before or after the treatment application include late treatment with latex-modified concrete in Regions 1, 2, and 4.

4.3 Discussion of Surface Treatment Effects on Deterioration of Bridge Decks

While the objectives of this research were met through development and analysis of deterioration curves for bare concrete bridge decks and decks with specific treatments commonly used in Utah, the results are inherently limited in their applications. Because the scope of this study was determined by the types and extent of data available from UDOT and the FHWA for concrete bridge decks in Utah, the deterioration curves are most applicable to bridges with similar design, construction, materials, trafficking, environmental conditions, and maintenance practices as those included in this study. Furthermore, because the deterioration curves were developed through an observational study rather than a controlled experiment, not all factors that may have potentially influenced the results were documented, measured, or accounted for in the analyses. Therefore, although efforts were made to include only typical bridges in the analyses and to evaluate deterioration curves by UDOT region as a general surrogate for latitude, some uncontrolled sources of variability may have affected the results.

As described previously, a degree of variability stems from the bridge deck inspection process itself. Although the AASHTO Guide Manual for Bridge Element Inspection provides inspectors with standards to help eliminate the problem of inexperience and subjective judgment in bridge deck NBI condition ratings, the margin of error in the condition ratings can be one or two points (Moore et al. 2000). Some reasons for variability in the inspection process potentially include limited access to bridge decks being rated, inadequate inspection time, absence of traffic control, inclement weather, poor visibility, and bias derived from knowledge of NBI ratings assigned to a given bridge deck in previous years.

Finally, because the NBI rating system is based mainly on visual inspection, the full benefits of early applications of surface treatments are not apparent in the results of this research. Because the deterioration process develops gradually over time, a bridge deck may still appear to be in good condition within the first 15 years following construction, such that a measurable improvement in the appearance of the deck may not be achieved by early application of a surface treatment. However, previous research has documented the value of early applications of surface treatments to bridge decks to prevent chloride ingress before damage occurs (Birdsall et al. 2007). Supplemental perspectives may be gained about the performance of specific surface treatments by evaluating bridge deck deterioration in terms of delamination, half-cell potential, and chloride concentration, for example, which are direct measures of the deterioration process typically experienced by concrete bridge decks in Utah (Guthrie et al. 2007).

4.4 Summary

The results of this research included average deterioration curves aligned by deck construction time and average deterioration curves aligned by deck treatment time for each UDOT region and for the entire state. The average deterioration curves aligned by deck construction time suggest that certain treatments applied at certain times can achieve average NBI ratings greater than those for monolithic concrete during selected years of bridge deck life. Compared to NBI ratings for monolithic concrete, the data for individual regions indicate that early treatment with a bituminous overlay achieves higher NBI ratings for up to 26 years of bridge deck service life, late treatment with a bituminous overlay achieves higher NBI ratings from 16 years to 48 years of bridge deck service life, early treatment with an epoxy overlay higher ratings for up to 35 years of bridge deck service life, late treatment with an epoxy overlay achieves higher ratings for 16 years to 33 years of bridge deck service life, early treatment with latex-modified concrete achieves higher NBI ratings for up to 17 years of bridge deck service life, and late treatment with latex-modified concrete achieves higher NBI ratings from 16 years to 33 years of bridge deck service life. The only cases in which measurable improvements in NBI ratings were not observed include early treatment with a bituminous overlay in Region 4, early treatment with an epoxy overlay in Region 4, and early treatment with latex-modified concrete in Regions 1 and 4. A possible reason for the apparent reduction in the effects of these early treatments in Region 4 is the more mild climate in that region compared to Regions 1, 2, and 3.

The average deterioration curves aligned by deck treatment time suggest that certain treatments applied at certain times can achieve improvements in NBI ratings that correspond to apparent increases in bridge deck service life. According to the data for individual regions, an early treatment with a bituminous overlay achieves an extension of 8 years to more than 10 years of bridge deck service life, late treatment with a bituminous overlay achieves an extension of more than 10 years of bridge deck service life, early treatment with an epoxy overlay achieves an extension of 0 years to more than 2 years of bridge deck service life, late treatment with an epoxy overlay achieves an extension of 0 years to 7 years of bridge deck service life, early treatment with latex-modified concrete does not achieve a measurable extension in bridge deck service life, and late treatment with latex-modified concrete achieves an extension of 6 years of bridge deck service life.

While the objectives of this research were met through development and analysis of deterioration curves for bare concrete bridge decks and decks with specific treatments commonly used in Utah, the results are inherently limited by the available data in their applications to bridges similar to those included in this study. Furthermore, although efforts were made to include only typical bridges in the analyses and to evaluate deterioration curves by UDOT region as a general surrogate for latitude, some uncontrolled sources of variability in this observational study may have affected the results; regarding the bridge deck inspection process itself, the margin of error in the NBI condition ratings can be one or two points. Finally, supplemental perspectives may be gained about the performance of specific surface treatments by evaluating bridge deck deterioration in terms of delamination, half-cell potential, and chloride concentration, for example, which are direct measures of the deterioration process typically experienced by concrete bridge decks in Utah.

5.0 CONCLUSION

5.1 Summary

The objectives of this research were to develop and analyze deterioration curves for bare concrete bridge decks and decks with specific treatments commonly used in Utah. The scope of this study was determined by the types and extent of electronically available data from UDOT and the FHWA for concrete bridge decks in Utah. The data included selected static inventory information, MR&R histories, and National Bridge Inventory (NBI) condition ratings for the bridge decks since the year 1992.

Bridge deck selection criteria and analysis procedures were developed to enable evaluation of the effects of surface treatments on bridge decks in Utah. Characteristics of a typical bridge were defined, with categorical characteristics being analyzed using pie charts and numerical characteristics being analyzed using histograms and statistics. A filtering program developed in Visual Basic was then used to generate a list of bridges from the UDOT inventory that exhibited typical ranges of 12 selected categorical and numerical characteristics. Because each bridge in the list was considered representative of typical bridges in Utah, potentially confounding effects of atypical bridge characteristics were minimized in comparisons of deterioration curves for monolithic concrete decks, decks with a bituminous overlay, decks with an epoxy overlay, and decks with a latex-modified concrete overlay. Climatic differences were considered by grouping bridges not only by overlay type, but also by UDOT region, which was used in this research as a general surrogate for latitude.

Additional Visual Basic code was written to extract the surface type and NBI condition rating histories from the FHWA database for each typical bridge deck for every year dating back to 1992. Workbooks containing information about bridges and their corresponding individual deterioration curves for a specific combination of UDOT region and surface treatment were then created. Data filtering was needed to remove irregularities that were observed during inspection of selected worksheets. The workbooks were filtered to specifically address deterioration curves for bridge decks with multiple or irrelevant surface types, invalid or missing condition ratings, condition rating histories that did not correlate logically with their surface type histories, and/or overlays placed earlier than 1992.

Grouping of individual bridge deck deterioration curves in specific combinations was necessary to investigate the effects of surface type on bridge deck deterioration. Specifically, individual bridge deck deterioration curves were combined to generate average deterioration curves aligned by deck construction time and average deterioration curves aligned by deck treatment time. For analysis of average deterioration curves aligned by deck construction time, Visual Basic code was written to extract deterioration curves of individual bridges from a particular workbook and combine them into one graph, with the deck construction times aligned at a value of 0 on the *x*-axis. For analysis of average deterioration curves aligned by deck treatment time, the code extracted the NBI condition ratings of each bridge deck from a maximum of 10 years before to a maximum of 10 years after a treatment was applied and then combined them into one graph, with the treatment times aligned at a value of 0 on the *x*-axis. In both cases, an average deterioration curve was then calculated from the individual deterioration curves. To at least partially account for the potentially different effects of different treatment times, the bridge groups involving overlays were divided into two treatment time categories, early and late, and the average deterioration curve for each of these groups was generated. To allow visual identification of differences between the curves over time, graphs were prepared to show curves for surface types and treatment times by UDOT region.

5.2 Findings

The results of this research included average deterioration curves aligned by deck construction time and average deterioration curves aligned by deck treatment time for each UDOT region and for the entire state. The average deterioration curves aligned by deck construction time suggest that certain treatments applied at certain times can achieve average NBI ratings greater than those for monolithic concrete during selected years of bridge deck life. Compared to NBI ratings for monolithic concrete, the data for individual regions indicate that early treatment with a bituminous overlay achieves higher NBI ratings for up to 26 years of bridge deck service life, late treatment with a bituminous overlay achieves higher NBI ratings from 16 years to 48 years of bridge deck service life, early treatment with an epoxy overlay higher ratings for up to 35 years of bridge deck service life, late treatment with an epoxy overlay achieves higher ratings for 16 years to 33 years of bridge deck service life, early treatment with latex-modified concrete achieves higher NBI ratings for up to 17 years of bridge deck service life, and late treatment with latex-modified concrete achieves higher NBI ratings from 16 years to 33 years of bridge deck service life. The only cases in which measurable improvements in NBI ratings were not observed include early treatment with a bituminous overlay in Region 4, early treatment with an epoxy overlay in Region 4, and early treatment with latex-modified concrete in Regions 1 and 4. A possible reason for the apparent reduction in the effects of these early treatments in Region 4 is the more mild climate in that region compared to Regions 1, 2, and 3.

The average deterioration curves aligned by deck treatment time suggest that certain treatments applied at certain times can achieve improvements in NBI ratings that correspond to apparent increases in bridge deck service life. According to the data for individual regions, an early treatment with a bituminous overlay achieves an extension of 8 years to more than 10 years of bridge deck service life, late treatment with a bituminous overlay achieves an extension of more than 10 years of bridge deck service life, early treatment with an epoxy overlay achieves an extension of 0 years to more than 2 years of bridge deck service life, late treatment with an epoxy overlay achieves an extension of 0 years to 7 years of bridge deck service life, early treatment with latex-modified concrete does not achieve a measurable extension in bridge deck service life, and late treatment with latex-modified concrete achieves an extension of 6 years of bridge deck service life.

While the objectives of this research were met through development and analysis of deterioration curves for bare concrete bridge decks and decks with specific treatments commonly used in Utah, the results are inherently limited by the available data in their applications to bridges similar to those included in this study. Furthermore, although efforts were made to include only typical bridges in the analyses and to evaluate deterioration curves by UDOT region as a general surrogate for latitude, some uncontrolled sources of variability in this observational study may have affected the results; regarding the bridge deck inspection process itself, the margin of error in the NBI condition ratings can be one or two points.

5.3 Recommendations

Given the findings of this research, UDOT should continue to utilize surface treatments to delay the deterioration of bare concrete bridge decks. Although benefits are evident in all regions of the state, the benefits are most pronounced in Regions 1, 2, and 3, where more deicing salt is applied, more chloride-induced corrosion of the reinforcing steel occurs, and more deterioration of monolithic concrete bridge decks is expected. Primarily because the NBI rating system is based mainly on visual inspection, the full benefits of early applications of surface treatments are not apparent in the results of this research. However, previous research has documented the value of early applications of surface treatments to bridge decks to prevent chloride ingress before damage occurs (Birdsall et al. 2007), and UDOT should continue to apply surface treatments to bridge decks early in their service life. Supplemental perspectives may be gained about the performance of specific surface treatments by evaluating bridge deck deterioration in terms of delamination, half-cell potential, and chloride concentration, for example, which are direct measures of the deterioration process typically experienced by concrete bridge decks in Utah. Additional research to develop deterioration curves based on these other measurements is recommended.

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APPENDIX A: DISTRIBUTIONS OF BRIDGE CHARACTERISTICS

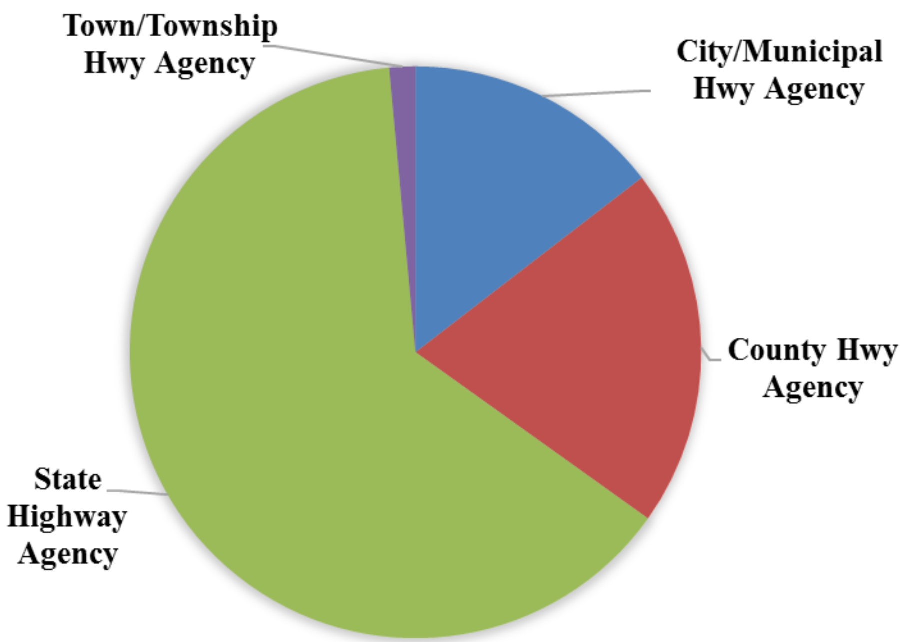


Figure A.1 Pie chart of bridges in Utah grouped by owner.

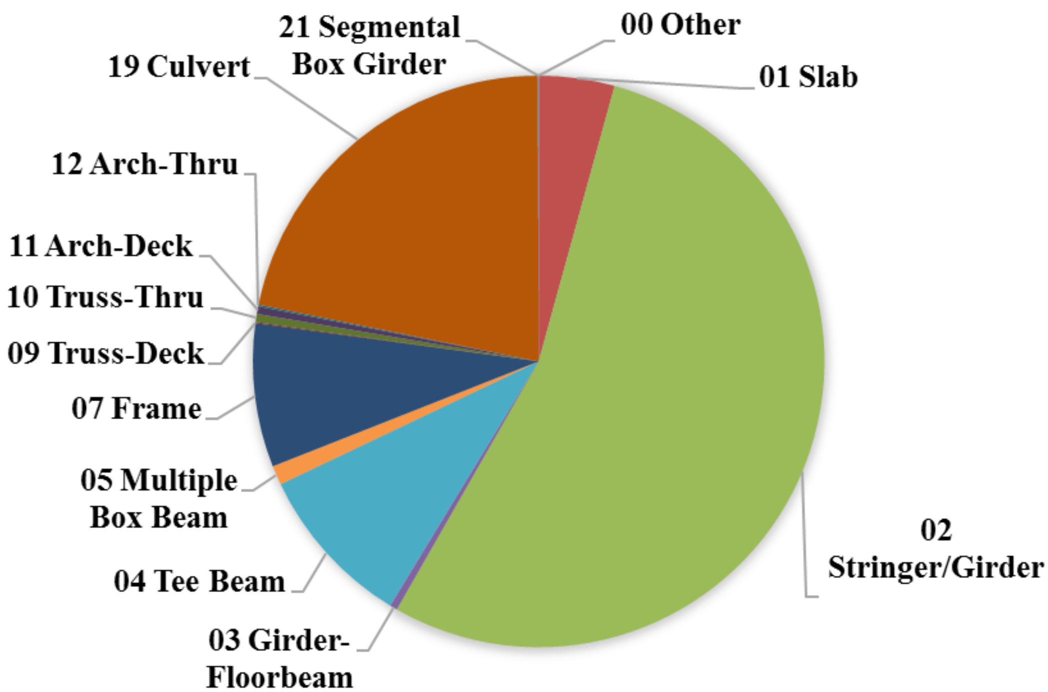


Figure A.2 Pie chart of bridges in Utah grouped by span design.

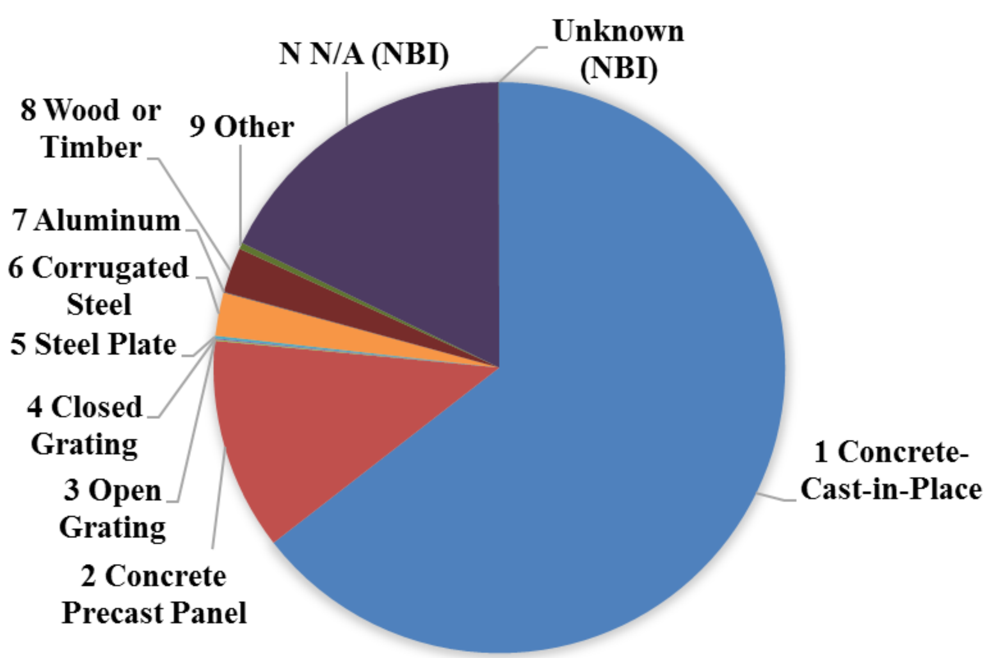


Figure A.3 Pie chart of bridges in Utah grouped by deck material.

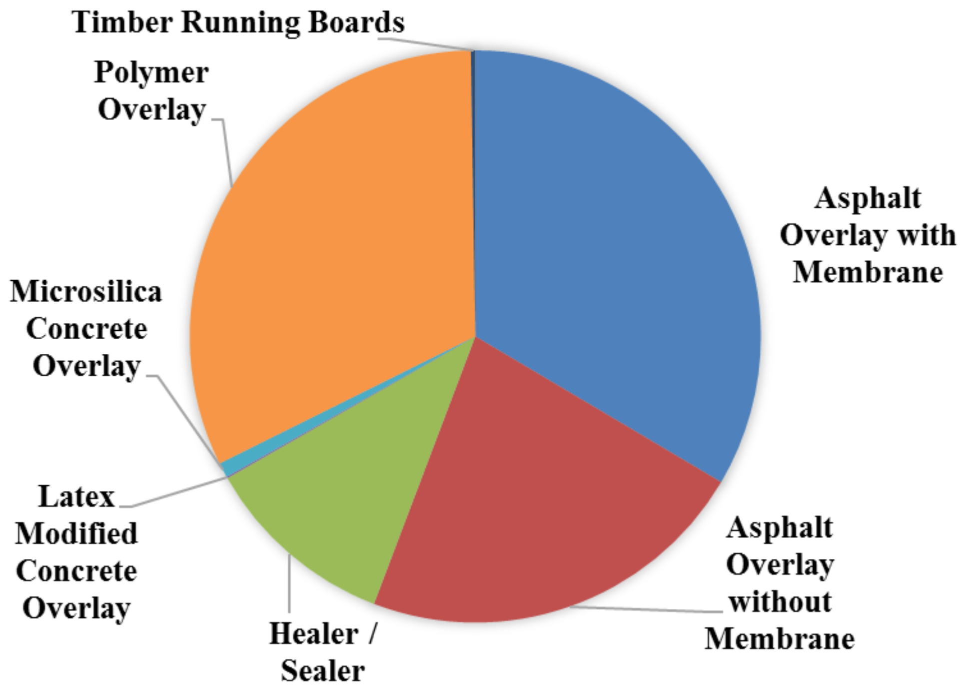


Figure A.4 Pie chart of bridges in Utah grouped by surface type based on UDOT classifications.

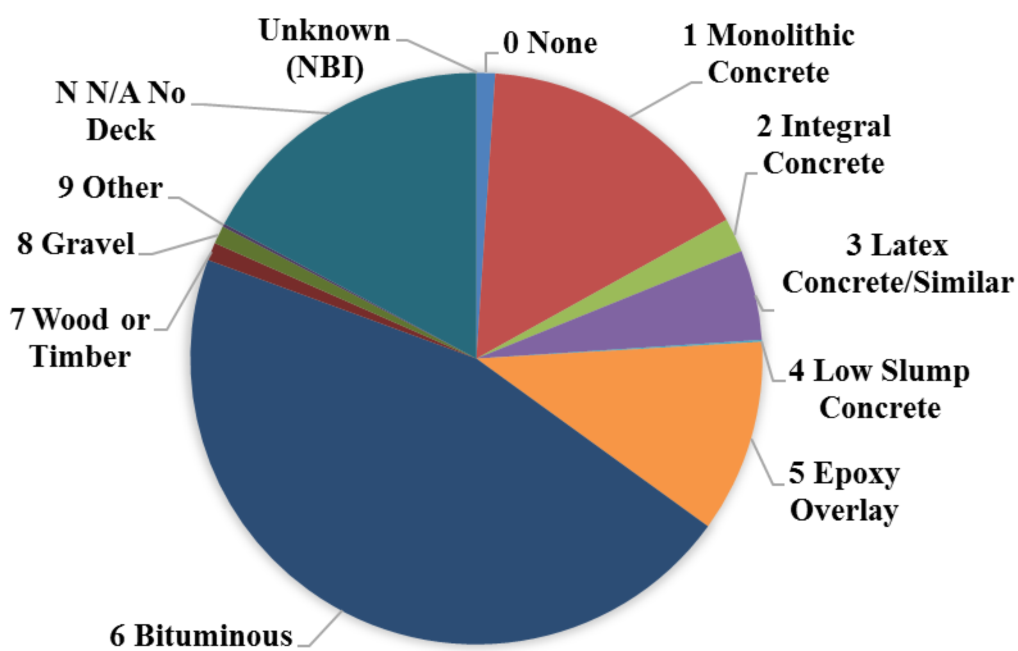


Figure A.5 Pie chart of bridges in Utah grouped by surface type based on FHWA classifications.

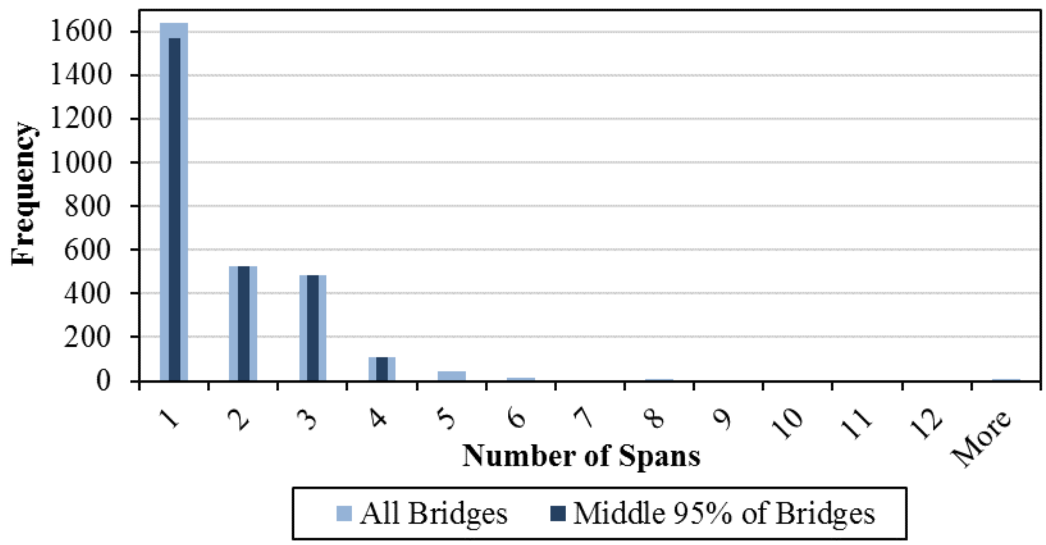


Figure A.6 Histogram of bridges in Utah grouped by number of spans.

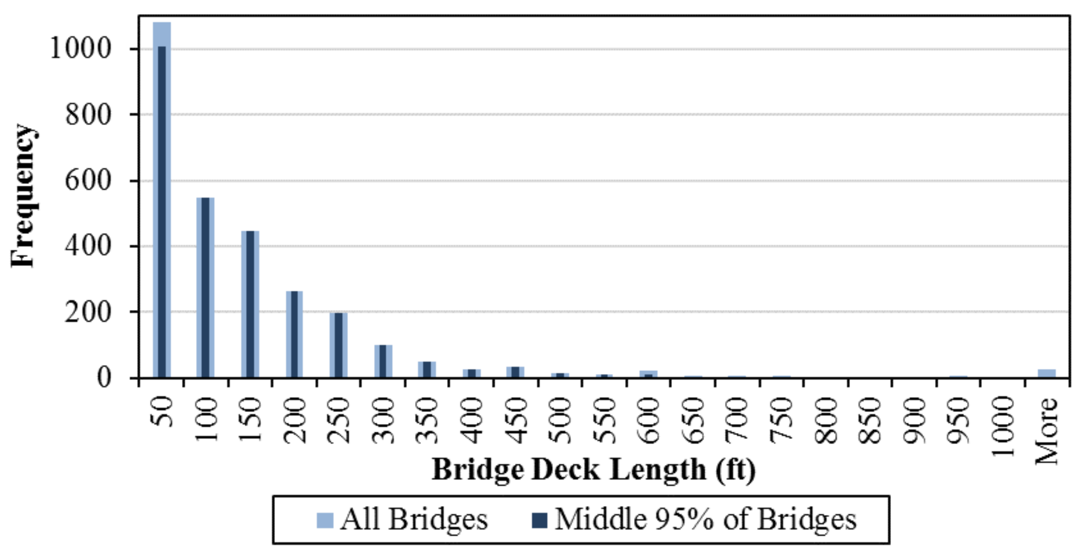


Figure A.6 Histogram of bridges in Utah grouped by bridge deck length.

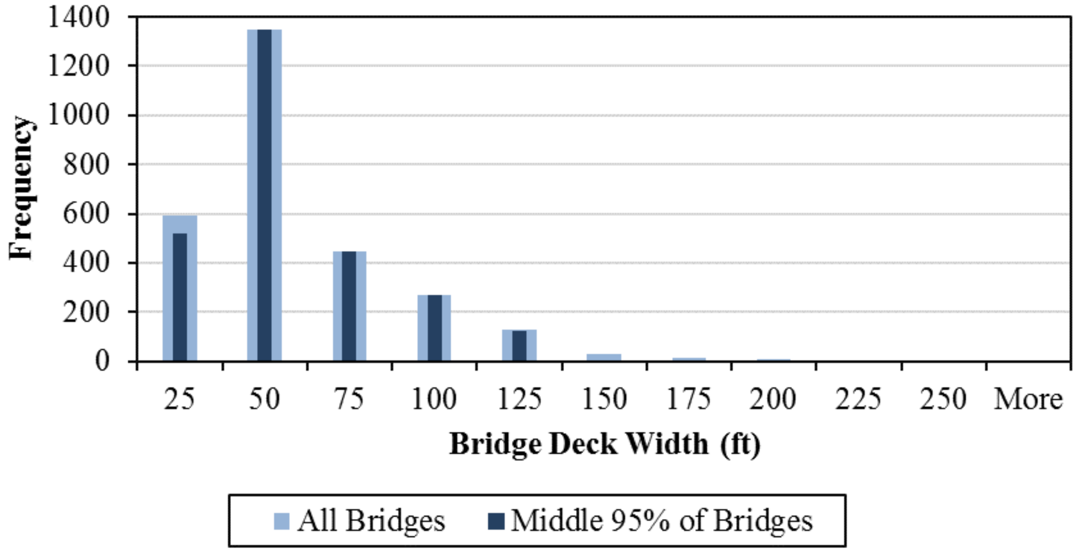
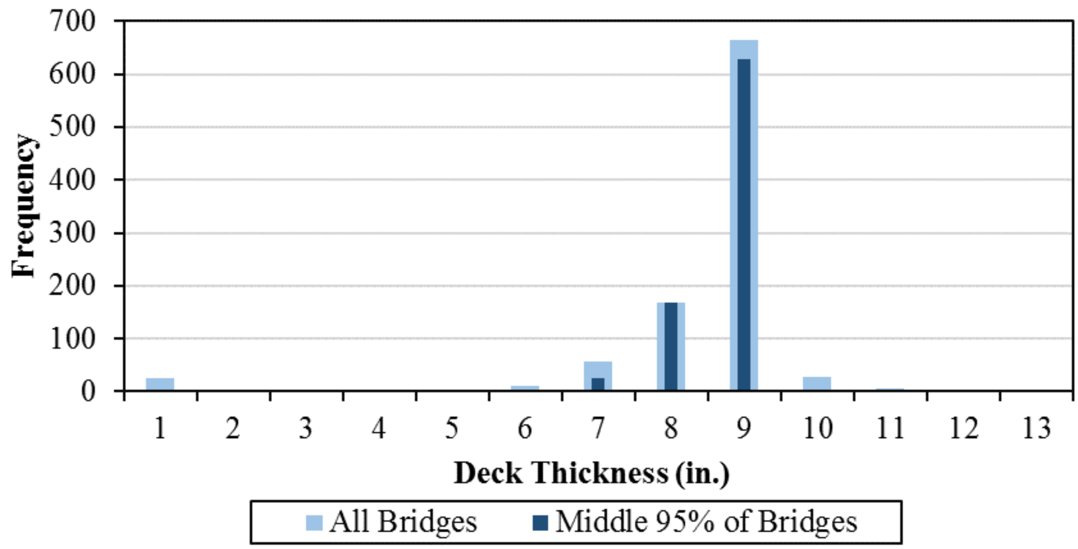
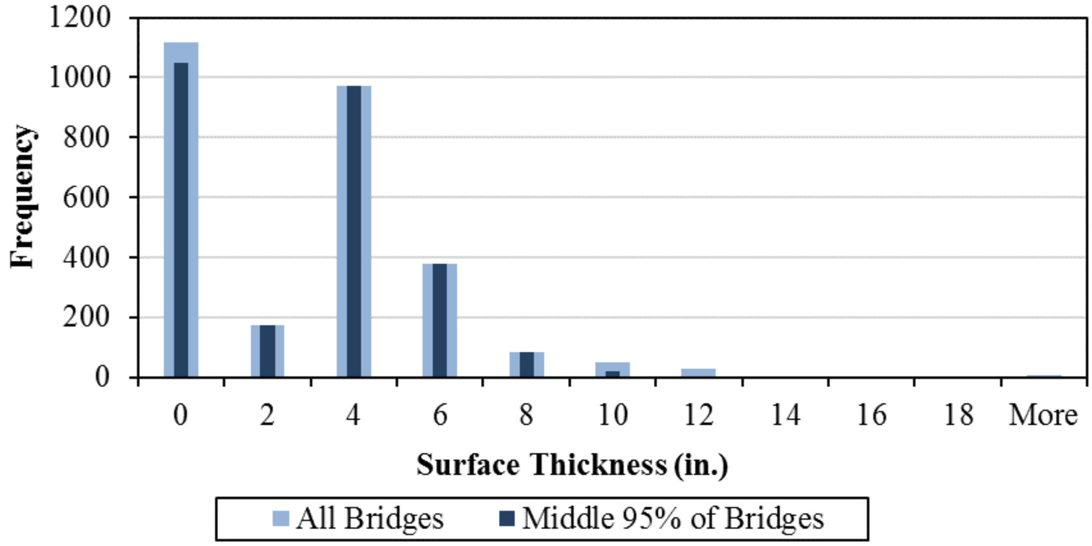


Figure A.7 Histogram of bridges in Utah grouped by bridge deck width.



NOTE: This graph includes only 963 of the 2849 bridges from the database. The other 1886 bridges did not have an entry for deck thickness but were considered to be typical.

Figure A.8 Histogram of bridges in Utah grouped by bridge deck thickness.



NOTE: This graph includes only 2817 of the 2849 bridges from the database. The other 32 bridges did not have an entry for surface thickness but were considered to be typical.

Figure A.9 Histogram of bridges in Utah grouped by bridge surface treatment thickness.

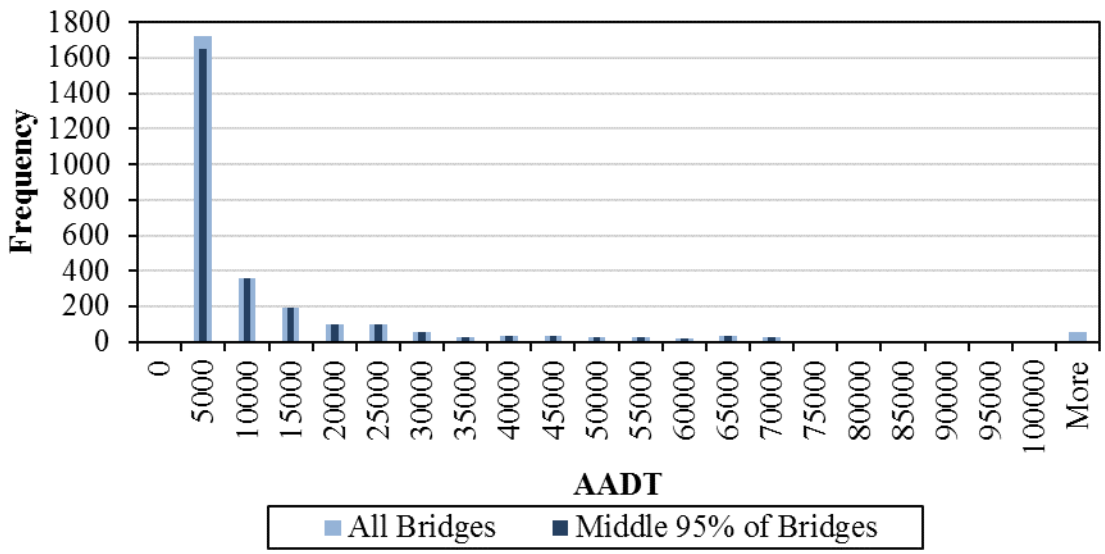
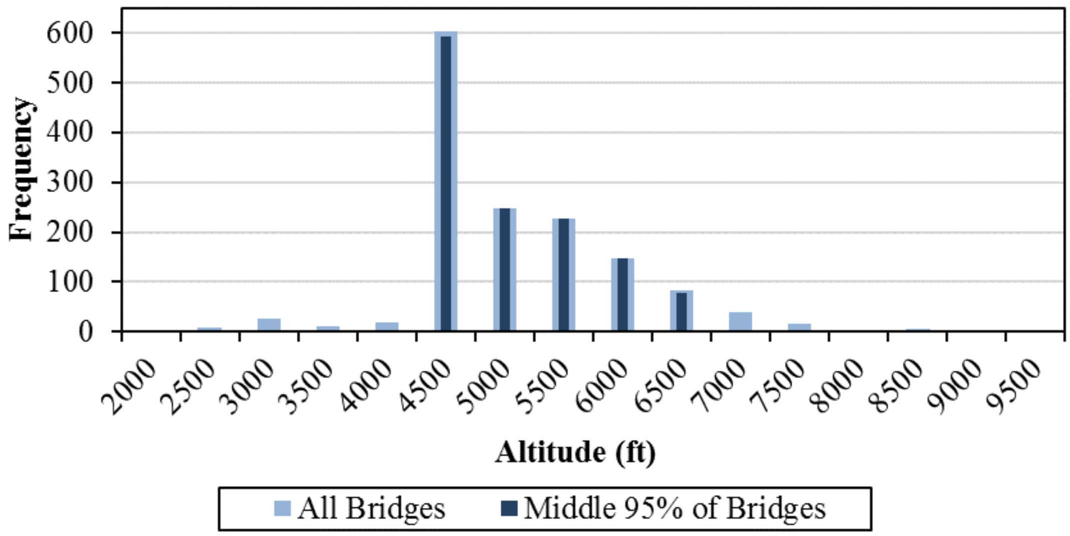


Figure A.10 Histogram of bridges in Utah grouped by AADT.



NOTE: This graph includes only 1435 of the 2849 bridges from the database. The other 1414 bridges did not have an entry for altitude but were considered to be typical.

Figure A.11 Histogram of bridges in Utah grouped by altitude.

APPENDIX B: INDIVIDUAL DETERIORATION CURVES ALIGNED BY DECK CONSTRUCTION TIME

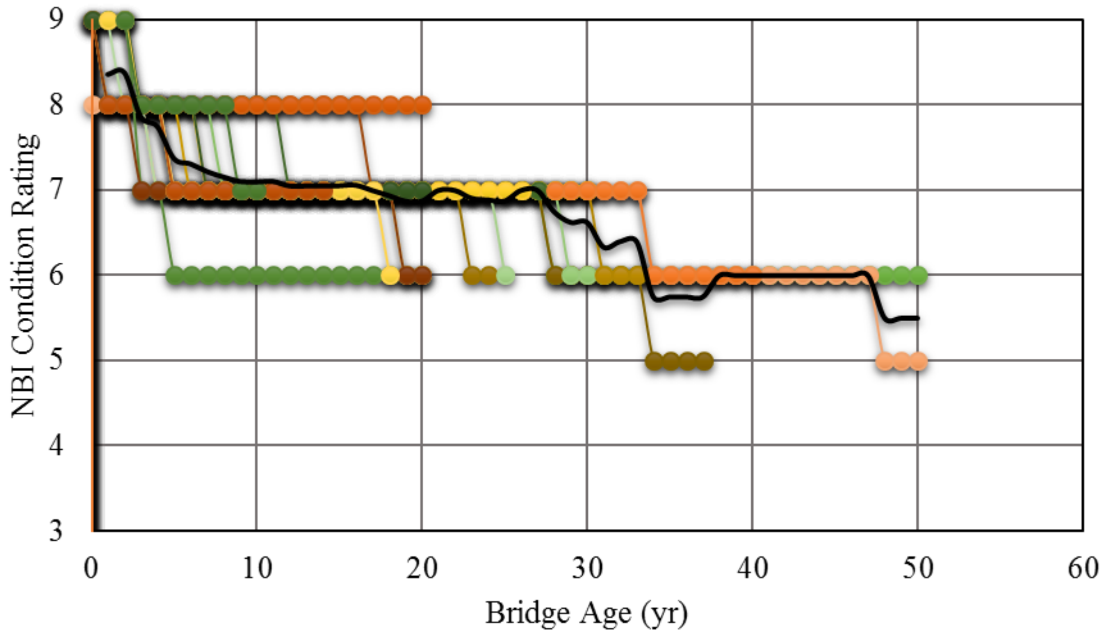


Figure B-1: Individual deterioration curves and average curve aligned by deck construction time for monolithic concrete bridge decks in Region 1.

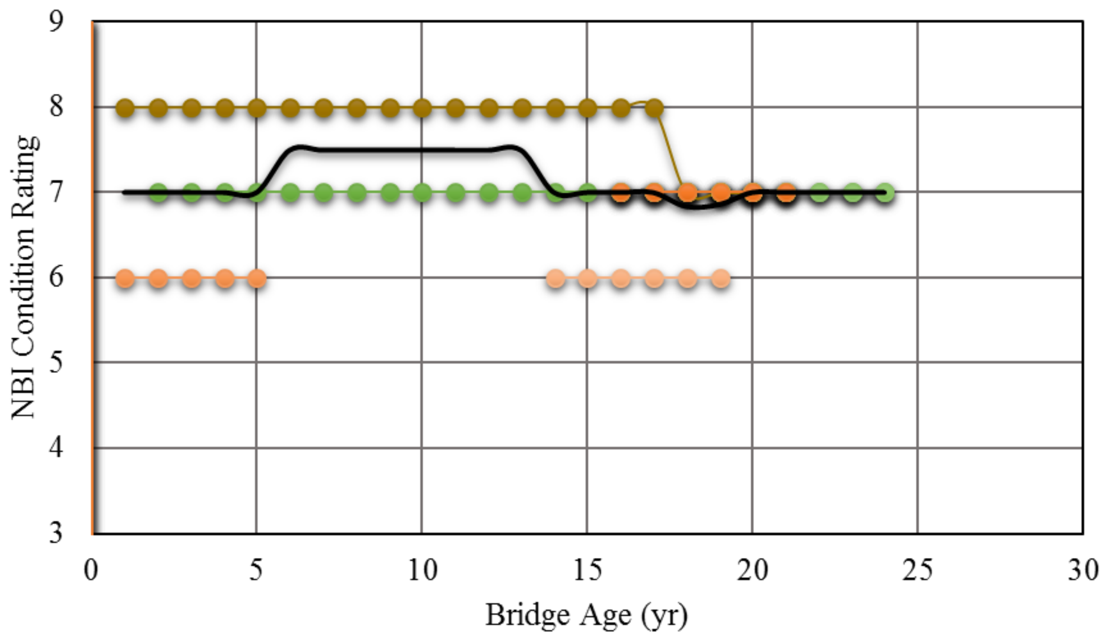


Figure B-2: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of a bituminous overlay in Region 1.

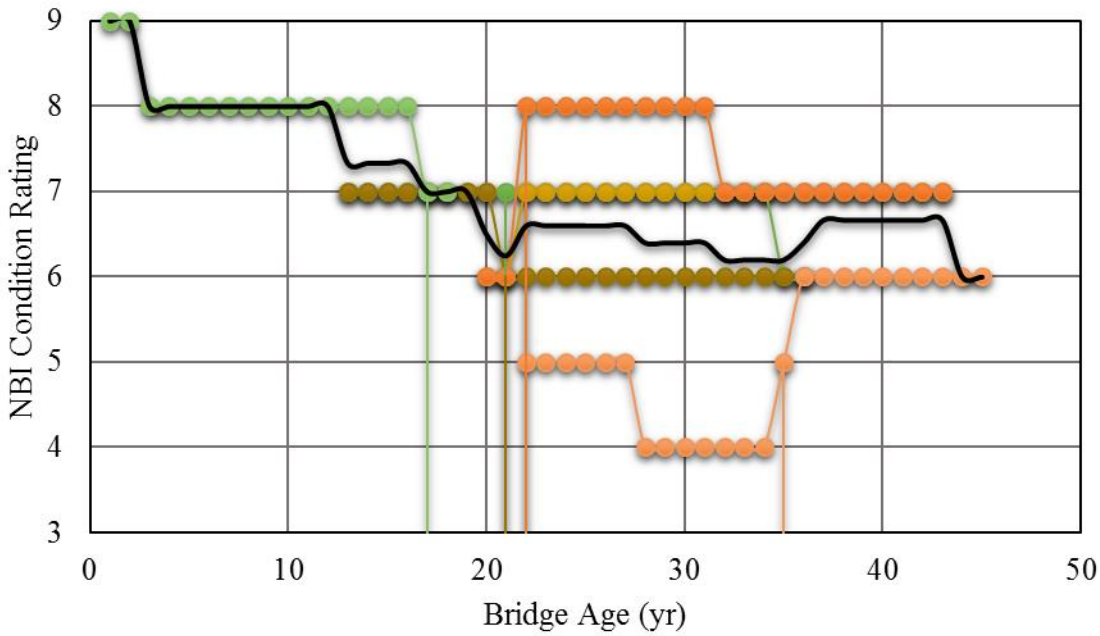


Figure B-3: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of a bituminous overlay in Region 1.

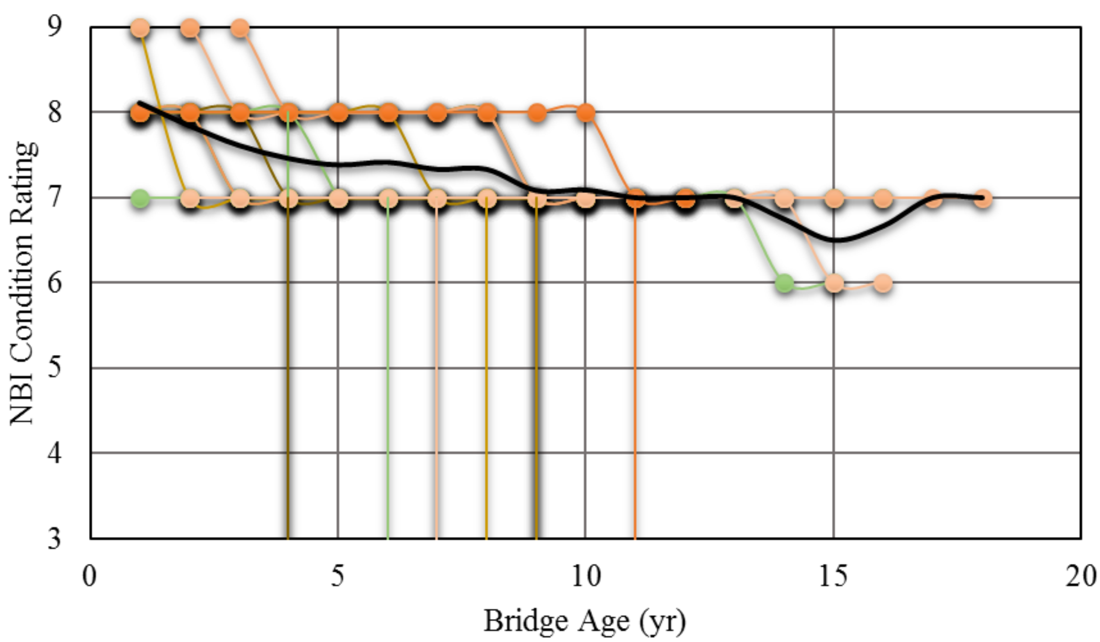


Figure B-4: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of an epoxy overlay in Region 1.

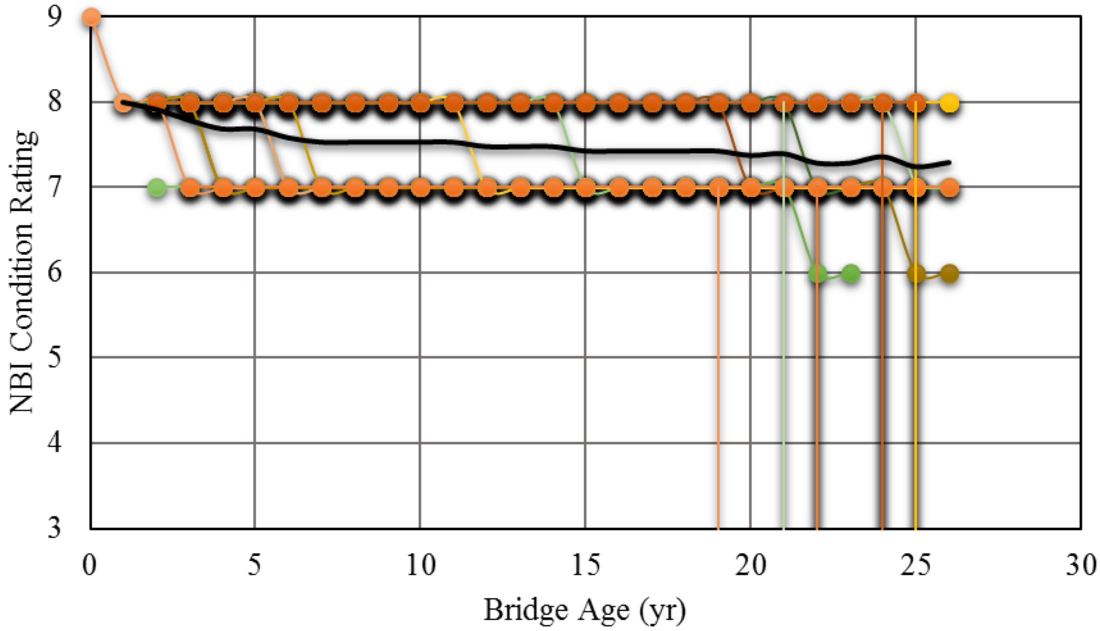


Figure B-5: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of an epoxy overlay in Region 1.

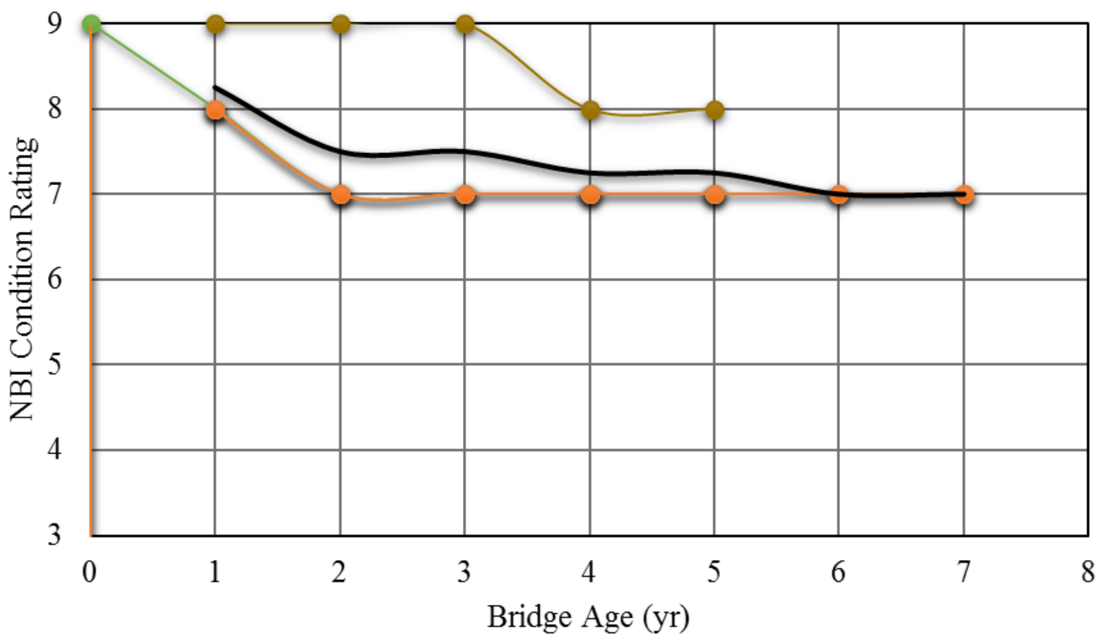


Figure B-6: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of latex-modified concrete in Region 1.

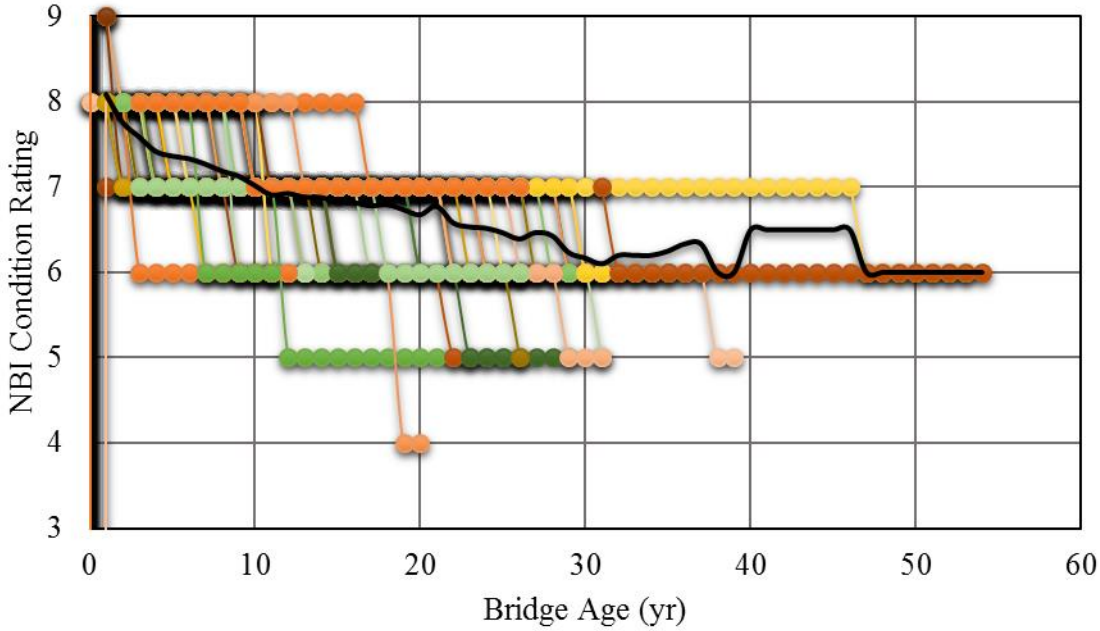


Figure B-7: Individual deterioration curves and average curve aligned by deck construction time for monolithic concrete bridge decks in Region 2.

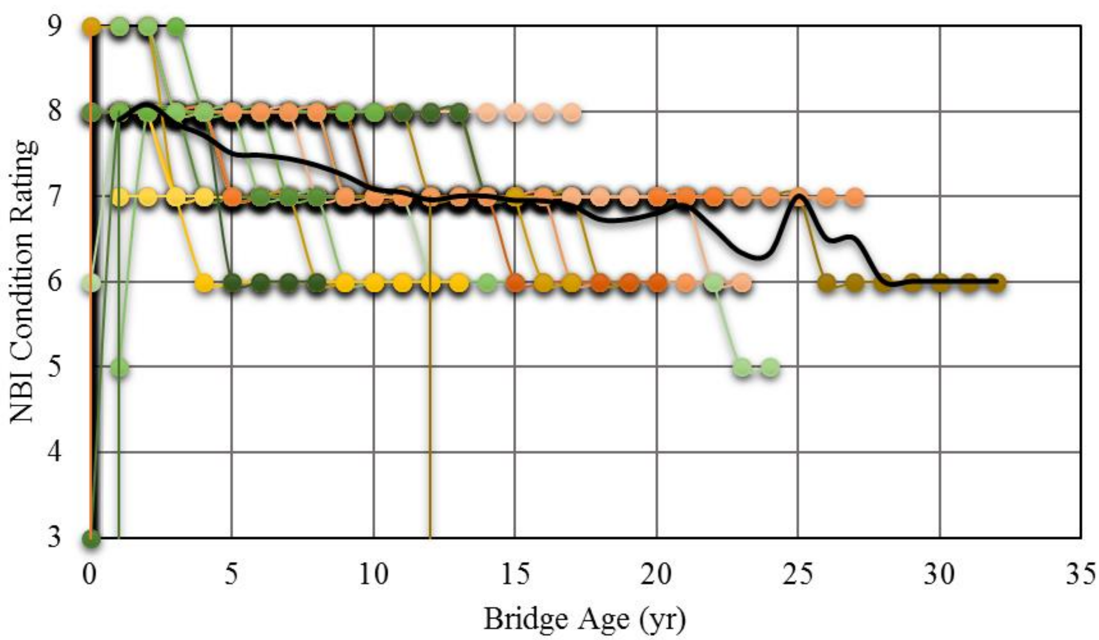


Figure B-8: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of a bituminous overlay in Region 2.

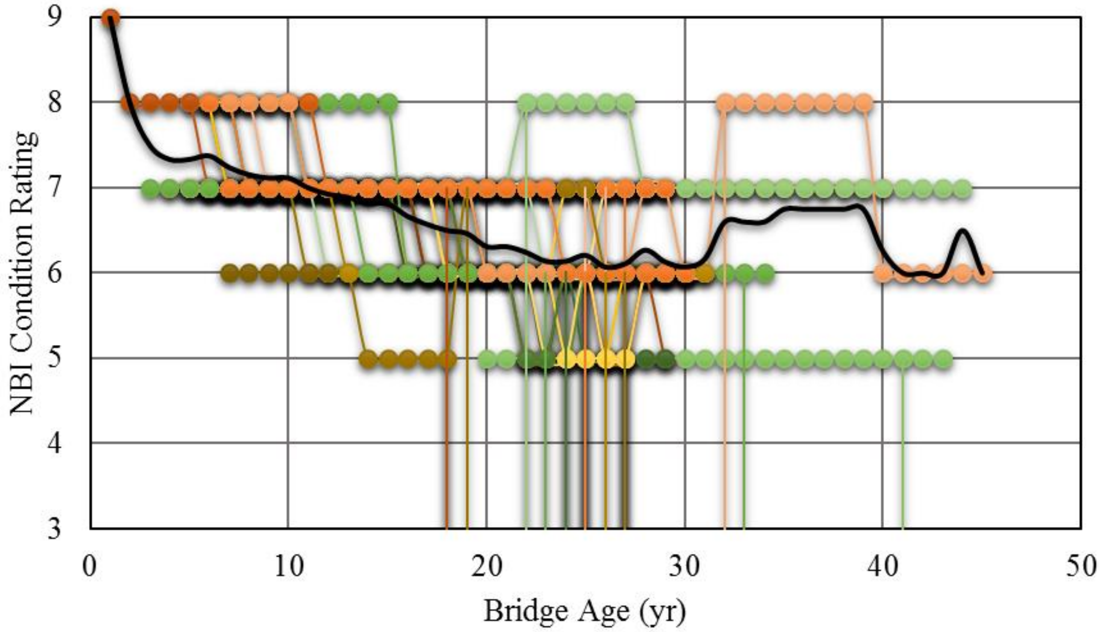


Figure B-9: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of a bituminous overlay in Region 2.

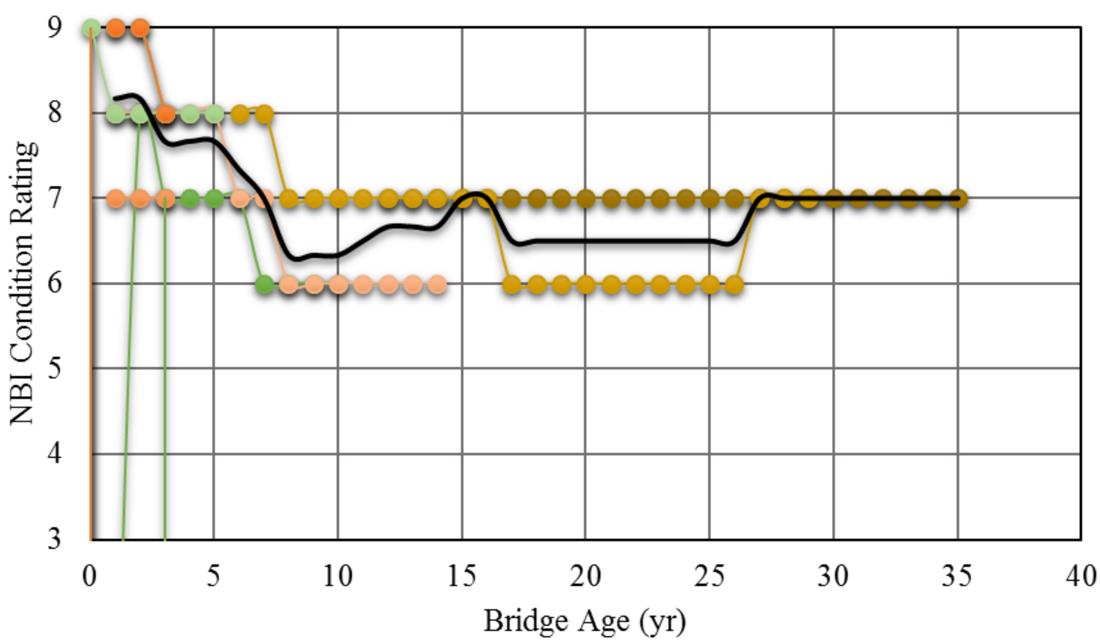


Figure B-10: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of an epoxy overlay in Region 2.

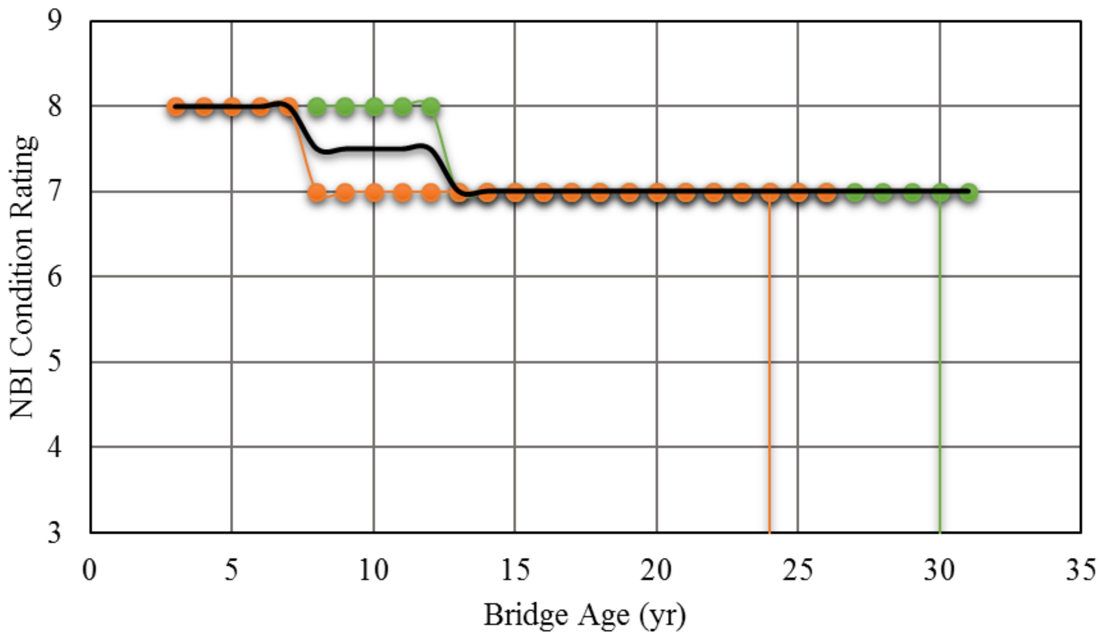


Figure B-11: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of an epoxy overlay in Region 2.

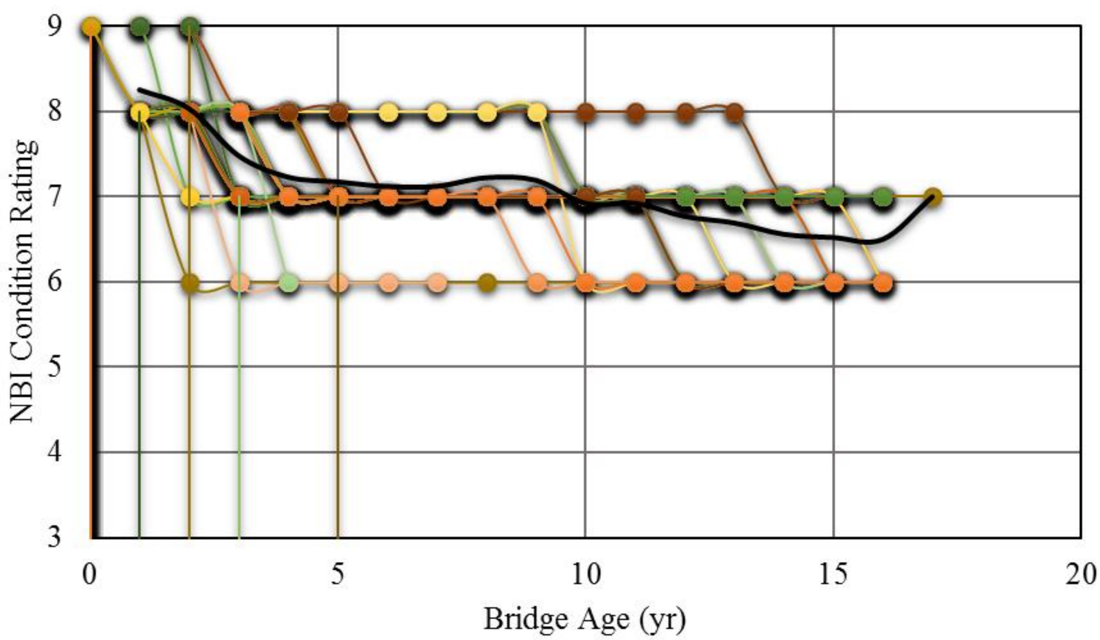


Figure B-12: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of latex-modified concrete in Region 2.

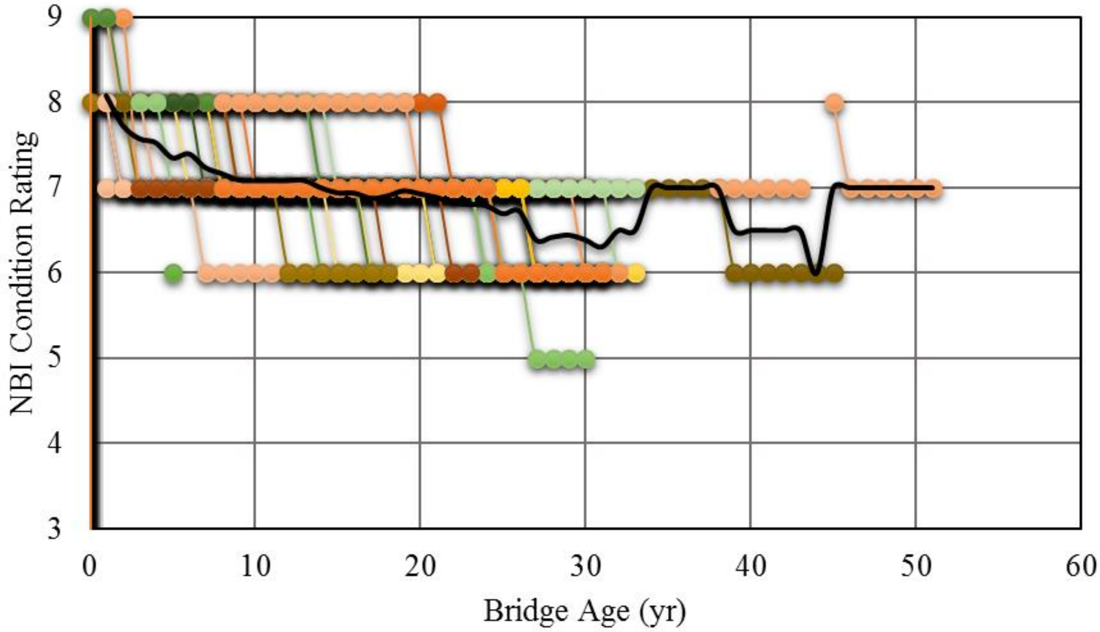


Figure B-13: Individual deterioration curves and average curve aligned by deck construction time for monolithic concrete bridge decks in Region 3.

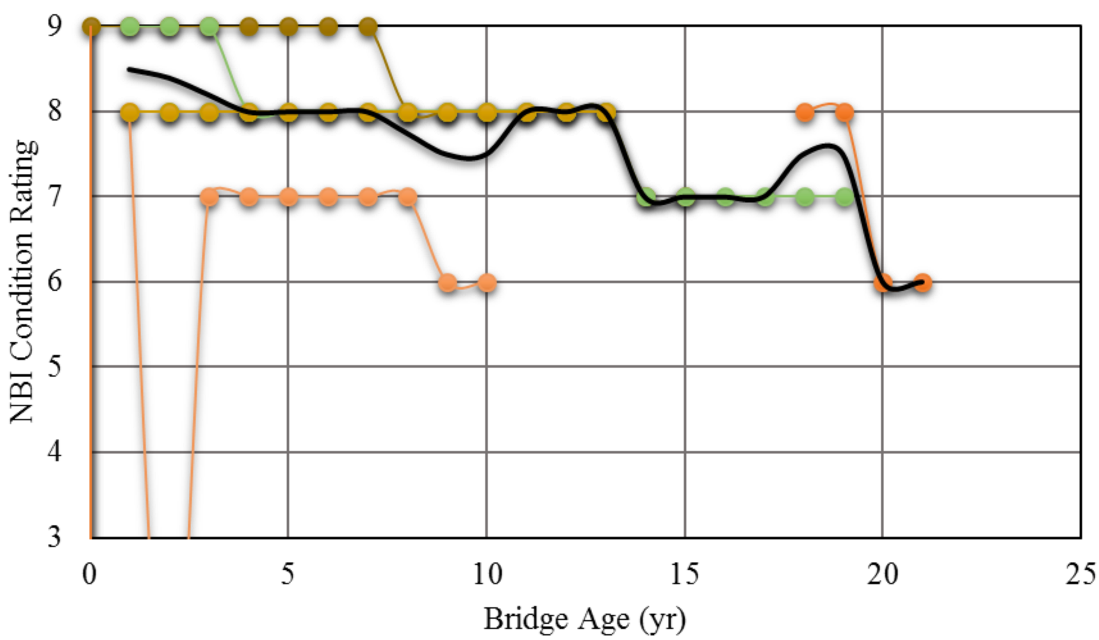


Figure B-14: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of a bituminous overlay in Region 3.

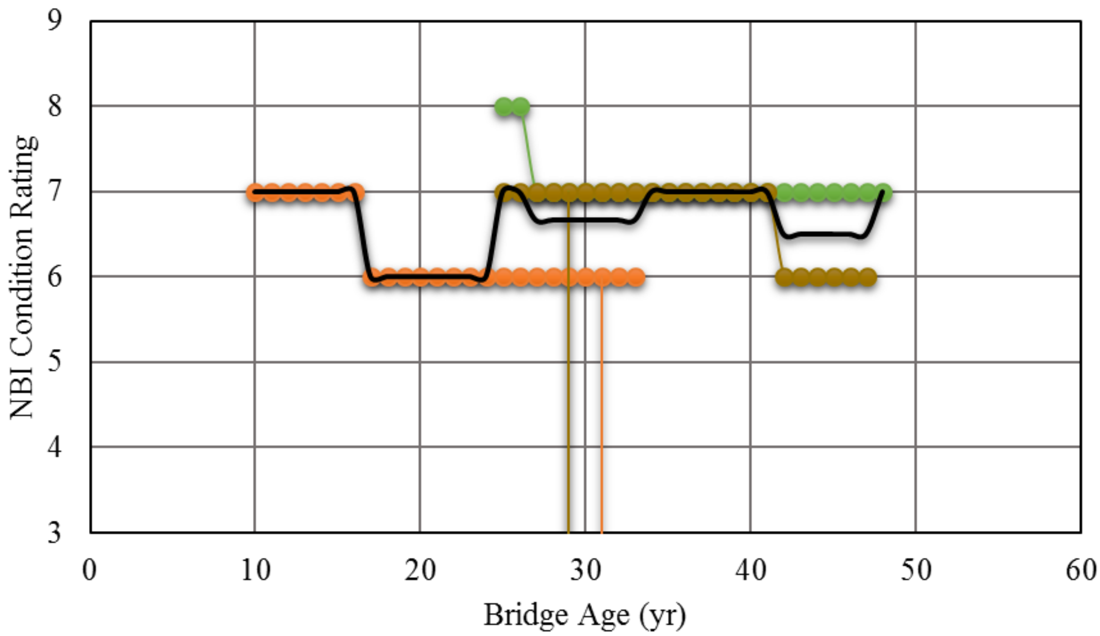


Figure B-15: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of a bituminous overlay in Region 3.

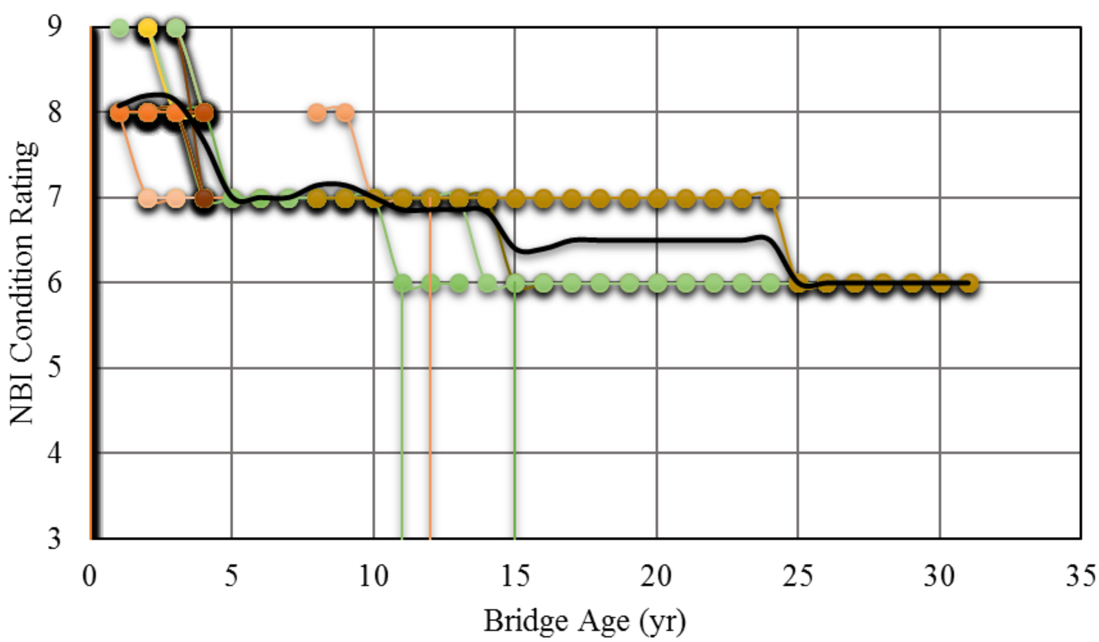


Figure B-16: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of an epoxy overlay in Region 3.

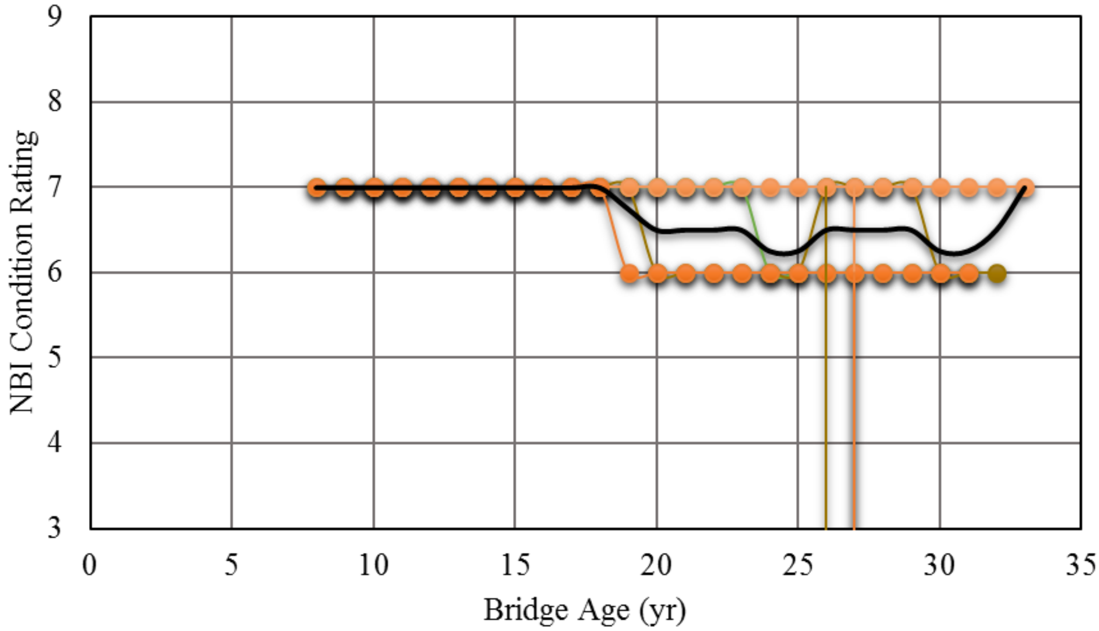


Figure B-17: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of an epoxy overlay in Region 3.

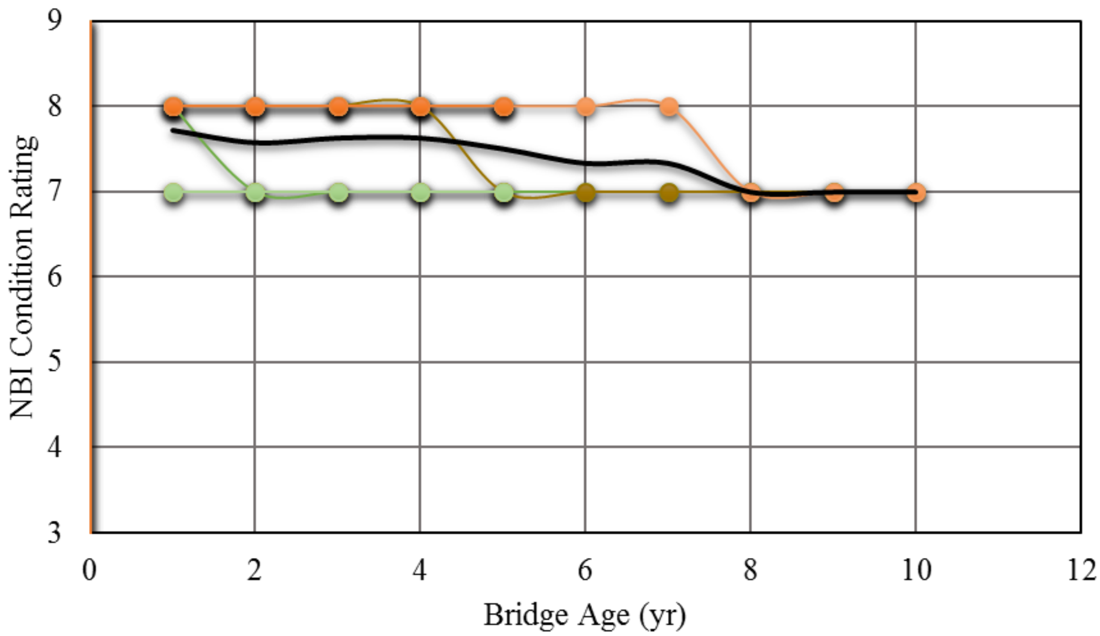


Figure B-18: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of latex-modified concrete in Region 3.

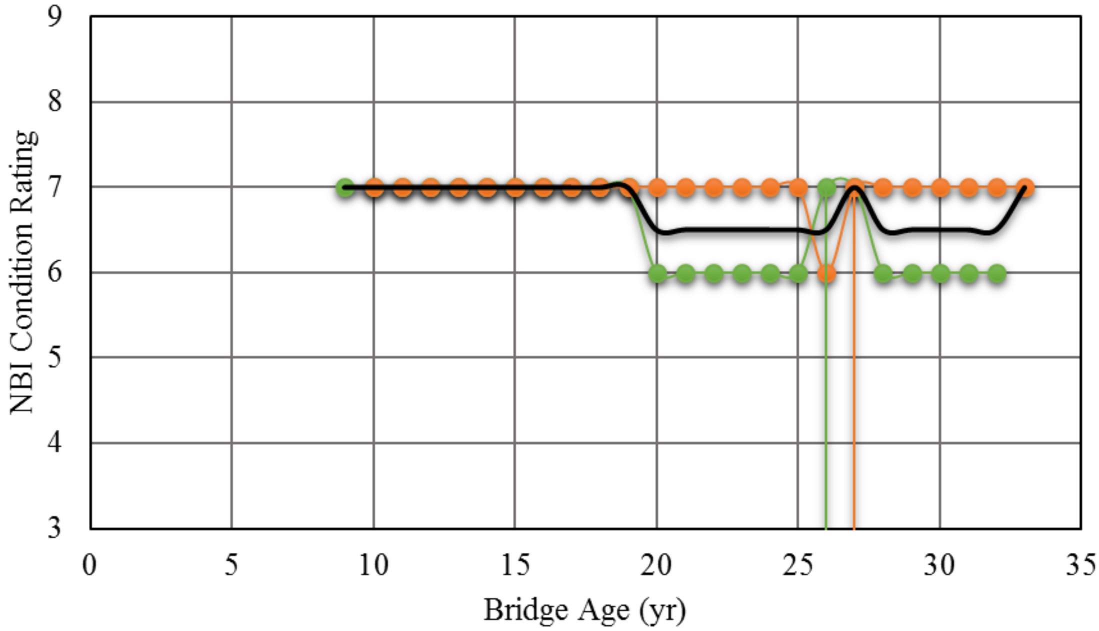


Figure B-19: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of latex-modified concrete in Region 3.

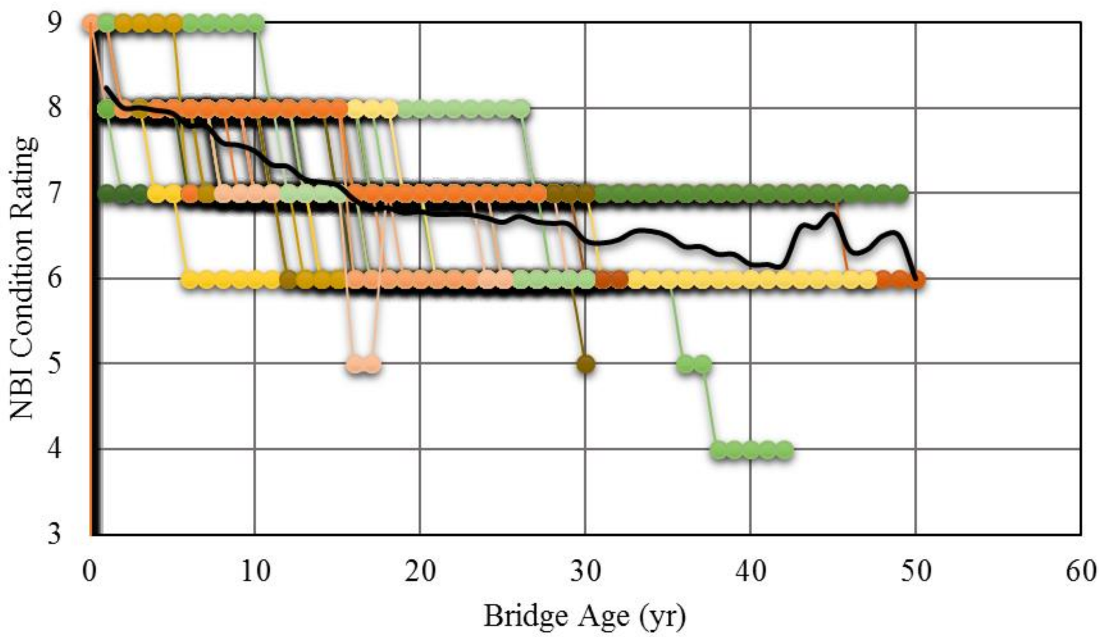


Figure B-13: Individual deterioration curves and average curve aligned by deck construction time for monolithic concrete bridge decks in Region 4.

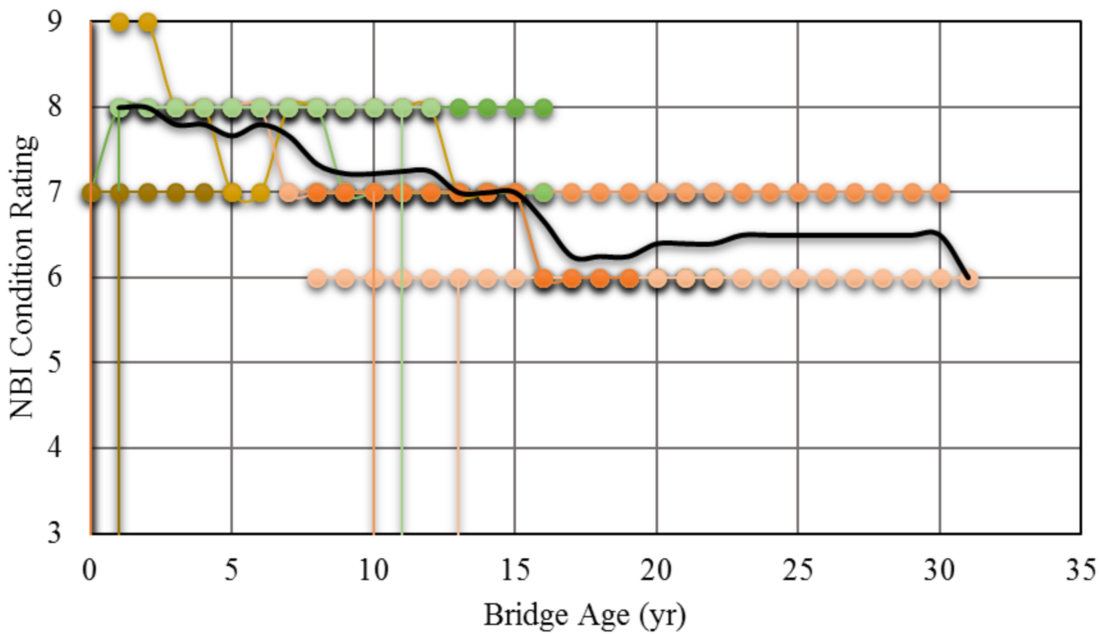


Figure B-14: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of a bituminous overlay in Region 4.

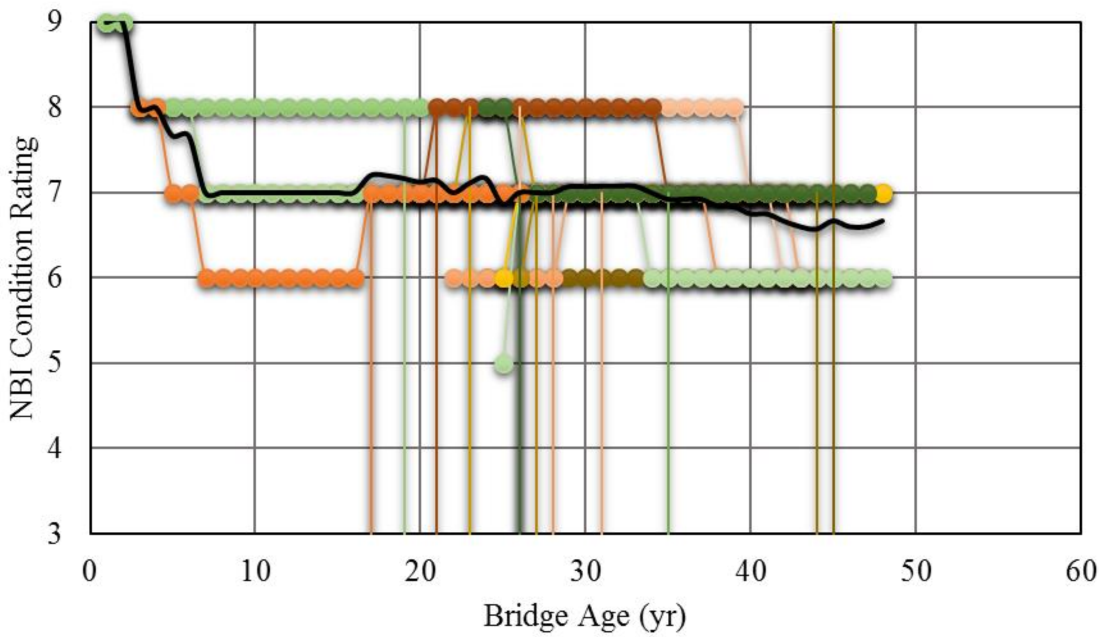


Figure B-15: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of a bituminous overlay in Region 4.

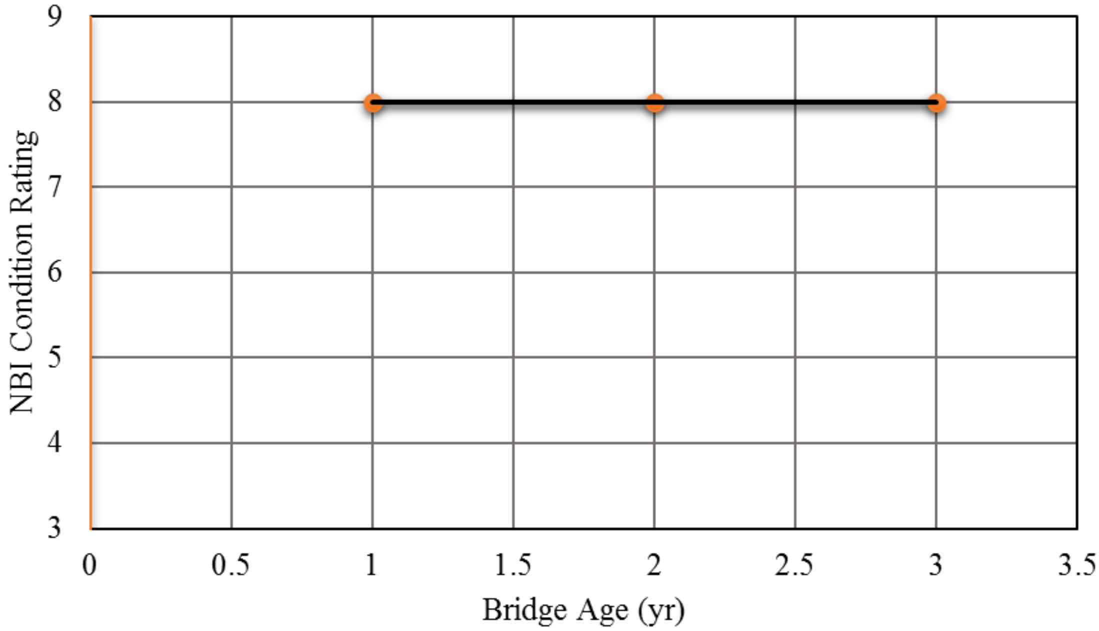


Figure B-16: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of an epoxy overlay in Region 4.

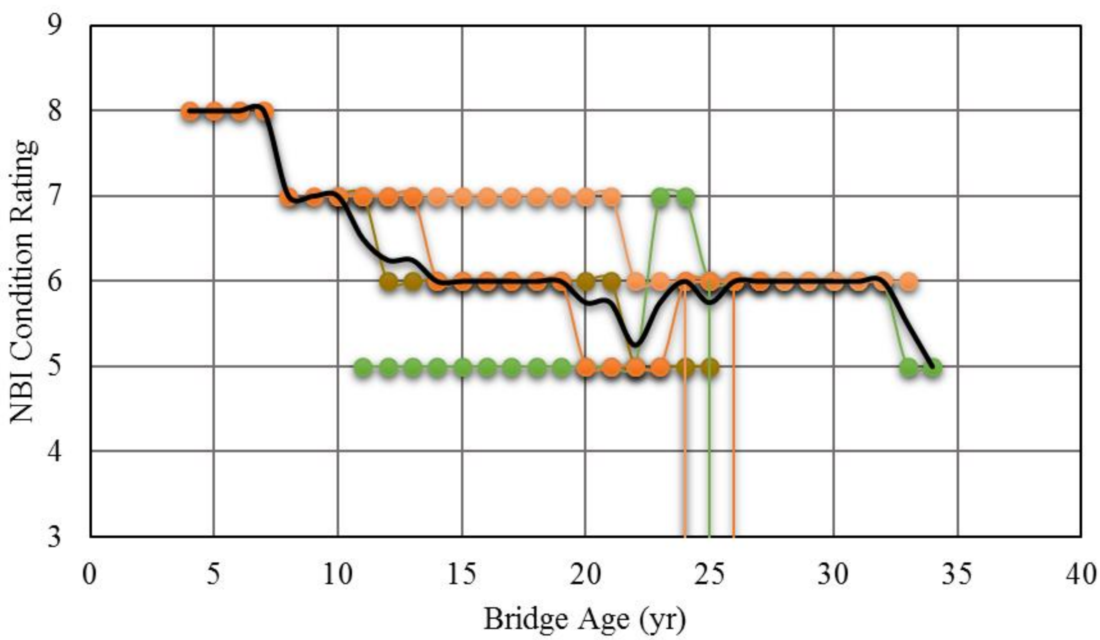


Figure B-17: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with late application of an epoxy overlay in Region 4.

Figure B-18: Individual deterioration curves and average curve aligned by deck construction time for bridge decks with early application of latex-modified concrete in Region 4.

APPENDIX C: INDIVIDUAL DETERIORATION CURVES ALIGNED BY DECK TREATMENT TIME

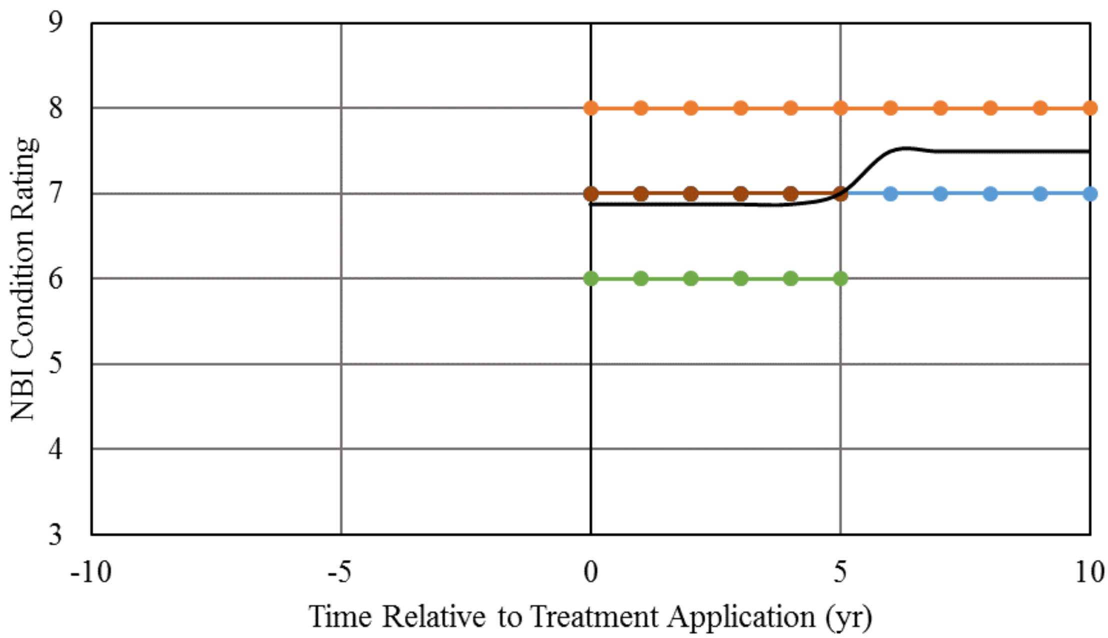


Figure C-1: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of a bituminous overlay in Region 1.

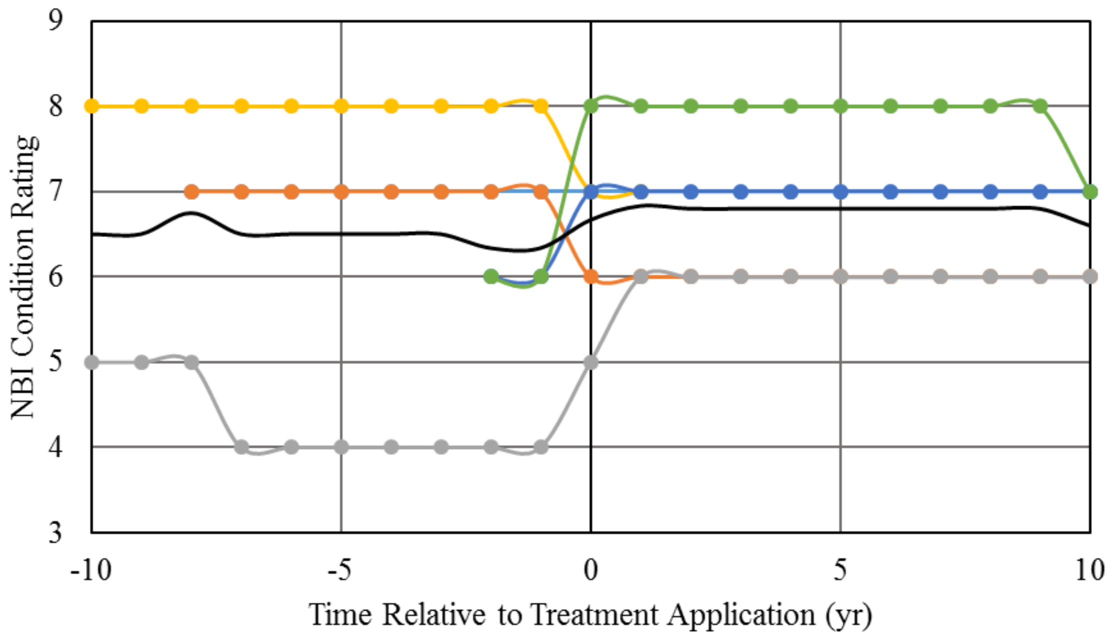


Figure C-2: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of a bituminous overlay in Region 1.

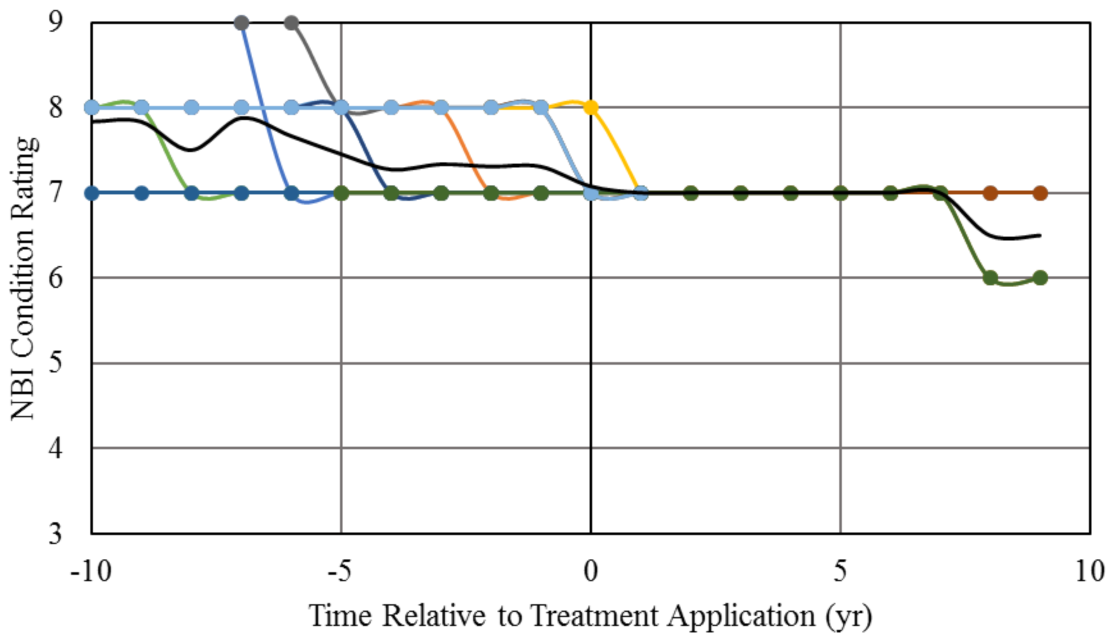


Figure C-3: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of an epoxy overlay in Region 1.

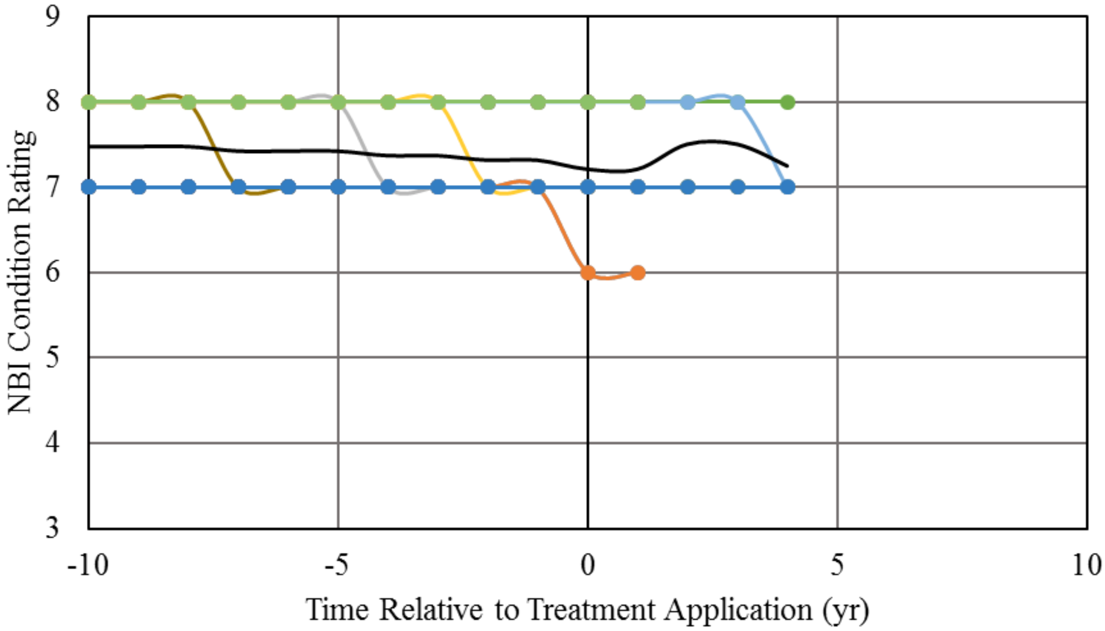


Figure C-4: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of an epoxy overlay in Region 1.

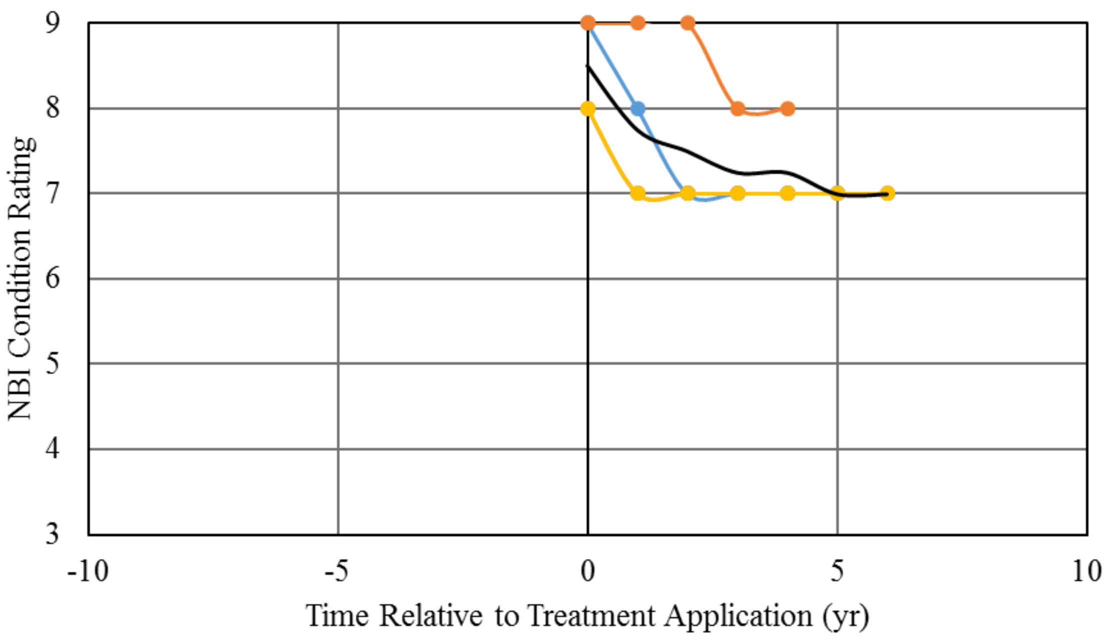


Figure C-5: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of latex-modified concrete in Region 1.

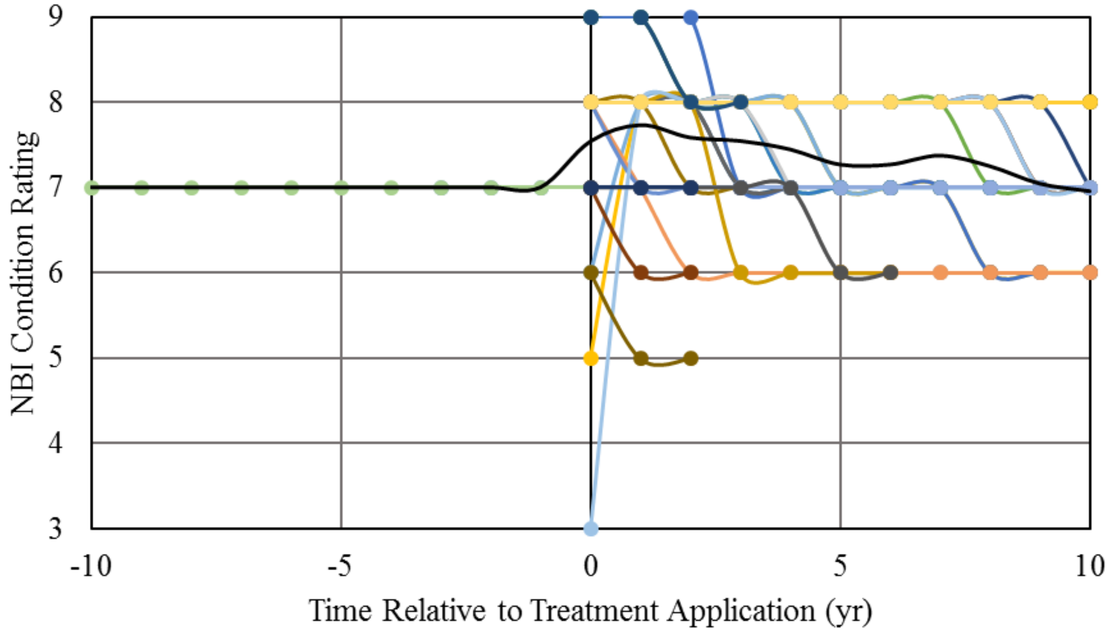


Figure C-6: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of a bituminous overlay in Region 2.

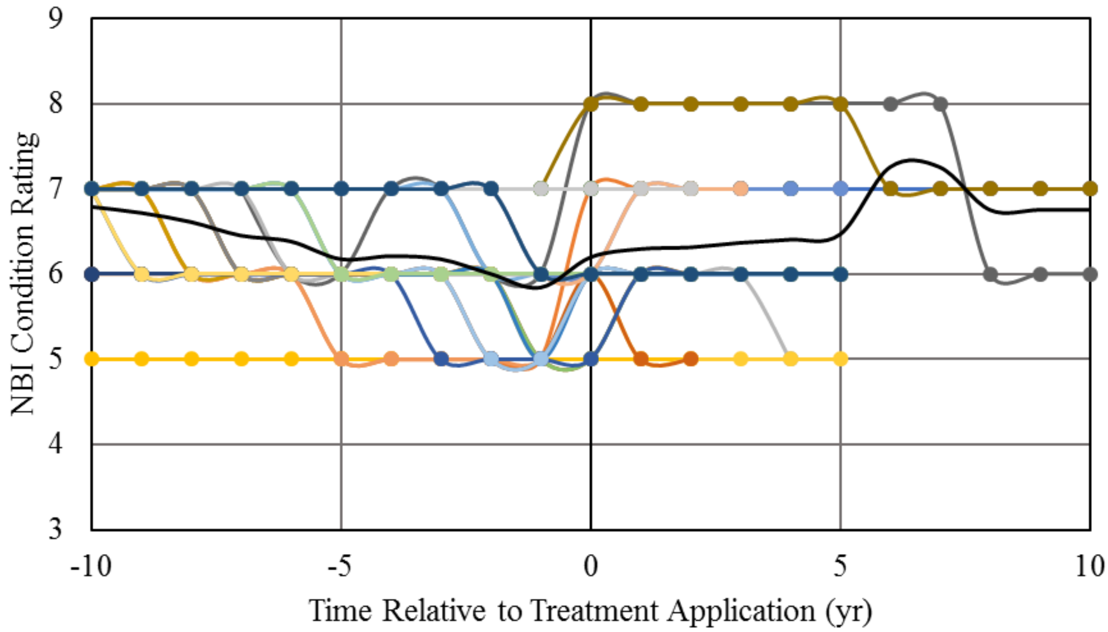


Figure C-7: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of a bituminous overlay in Region 2.

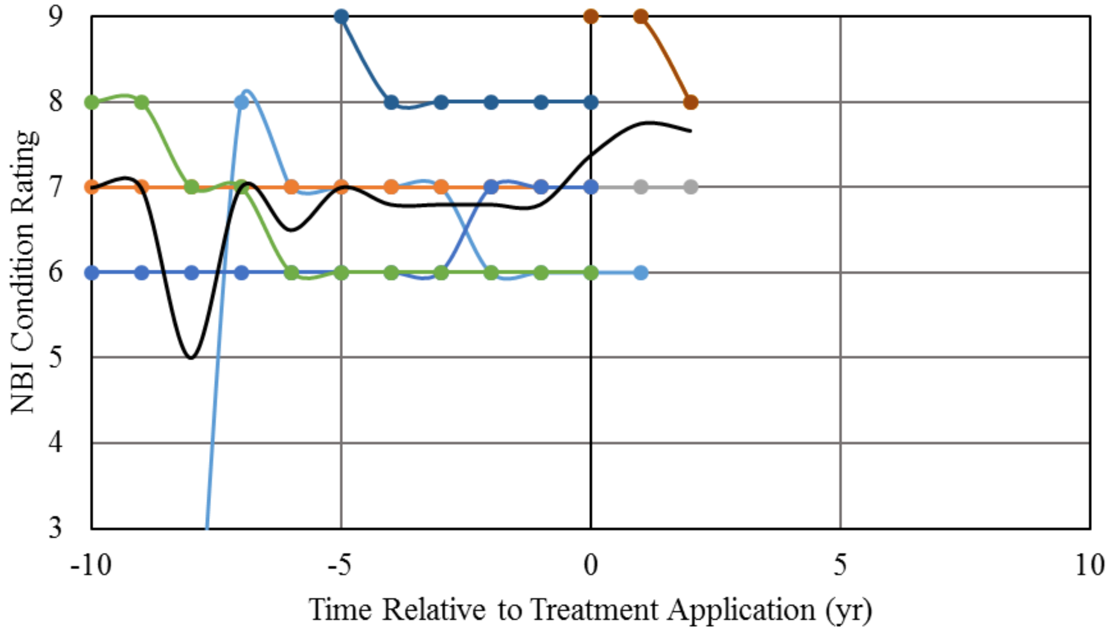


Figure C-8: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of an epoxy overlay in Region 2.

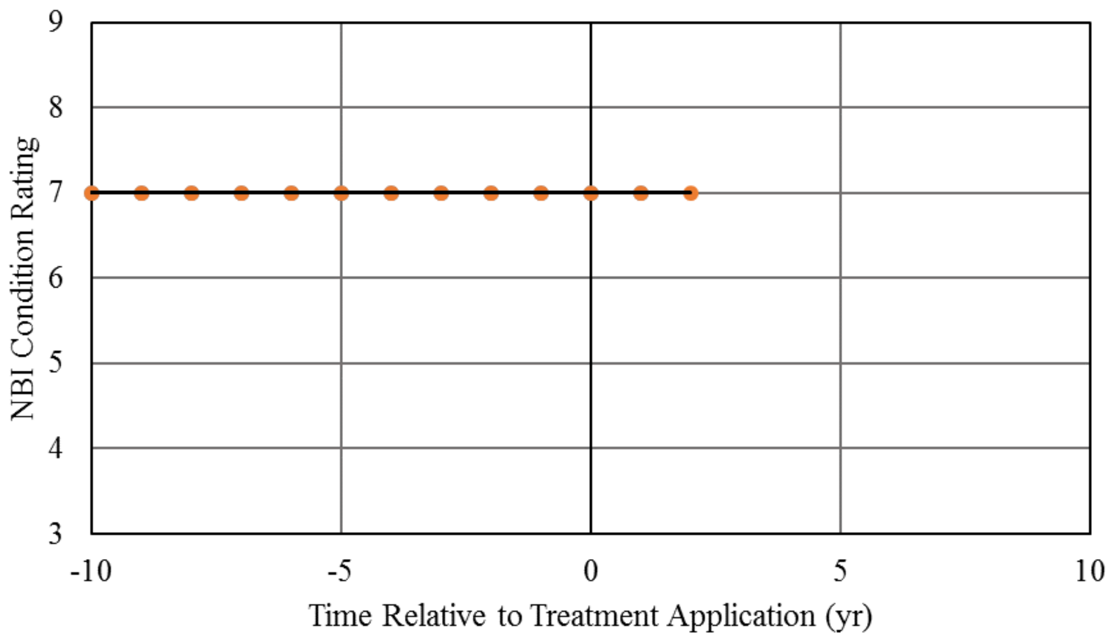


Figure C-9: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of an epoxy overlay in Region 2.

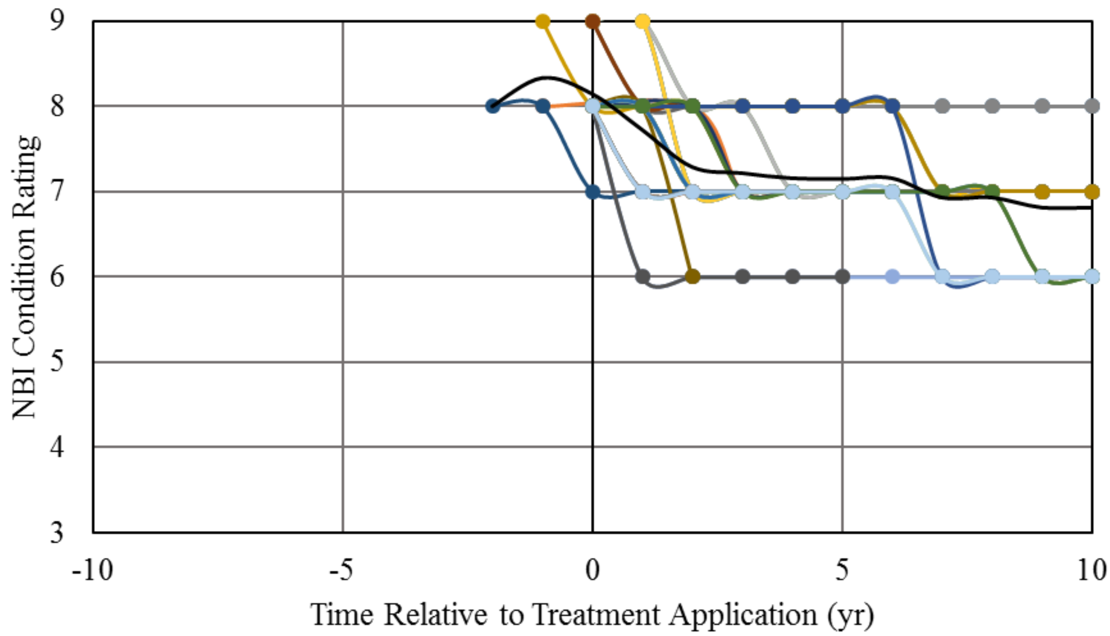


Figure C-10: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of latex-modified concrete in Region 2.

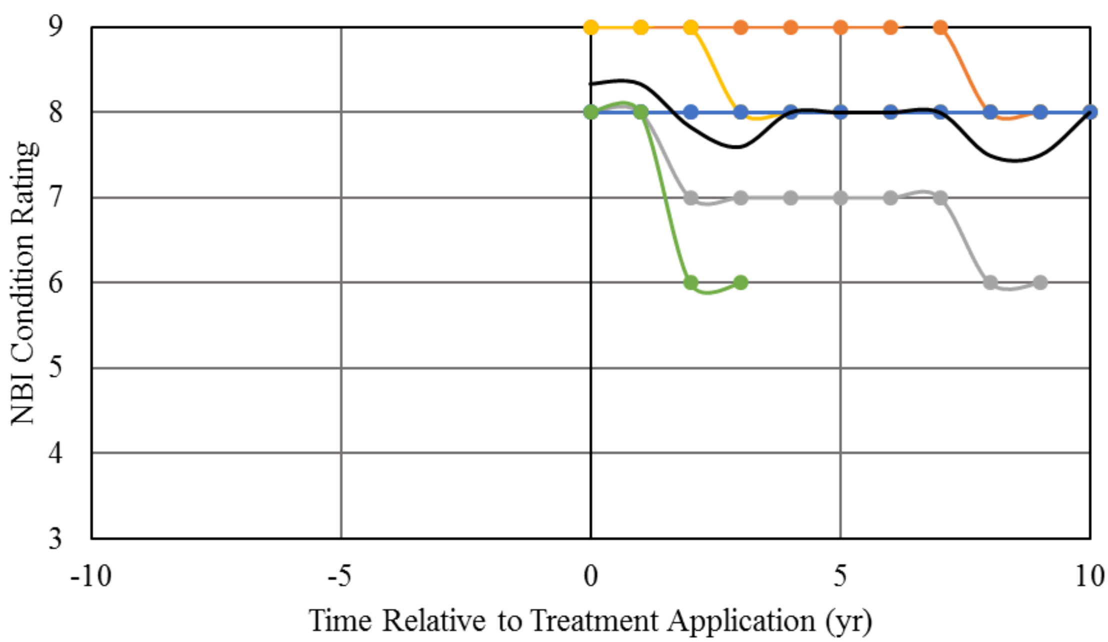


Figure C-11: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of a bituminous overlay in Region 3.

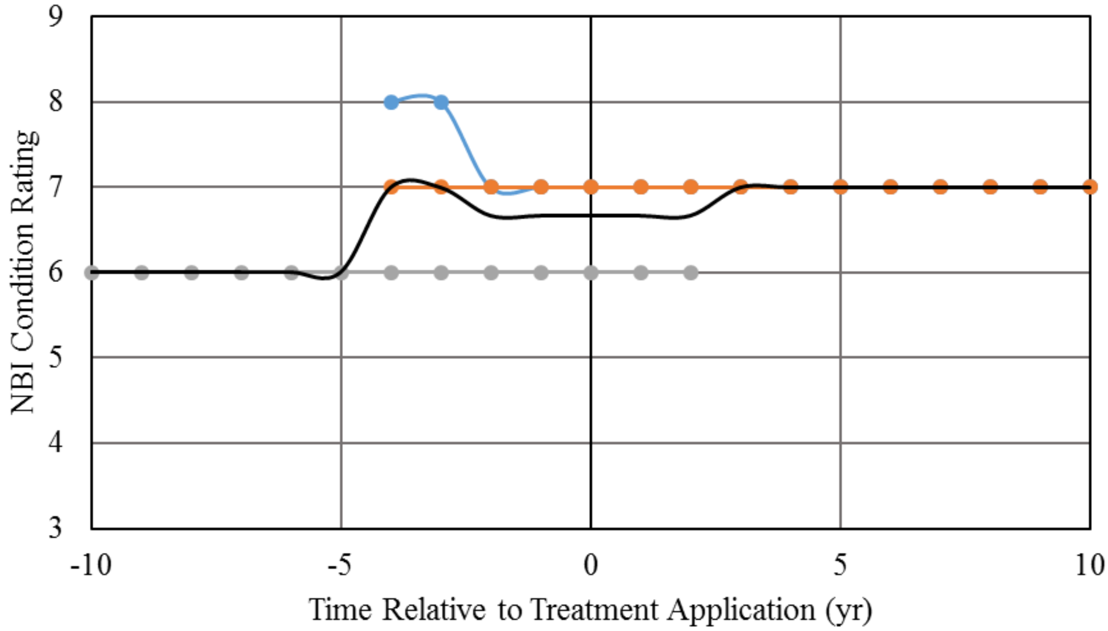


Figure C-12: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of a bituminous overlay in Region 3.

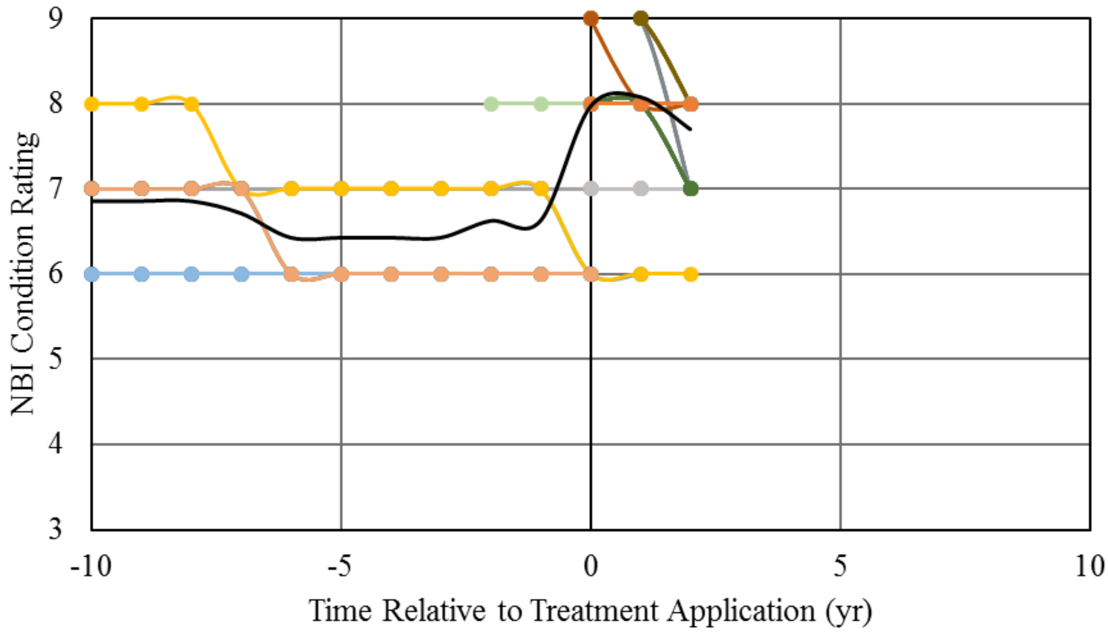


Figure C-13: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of an epoxy overlay in Region 3.

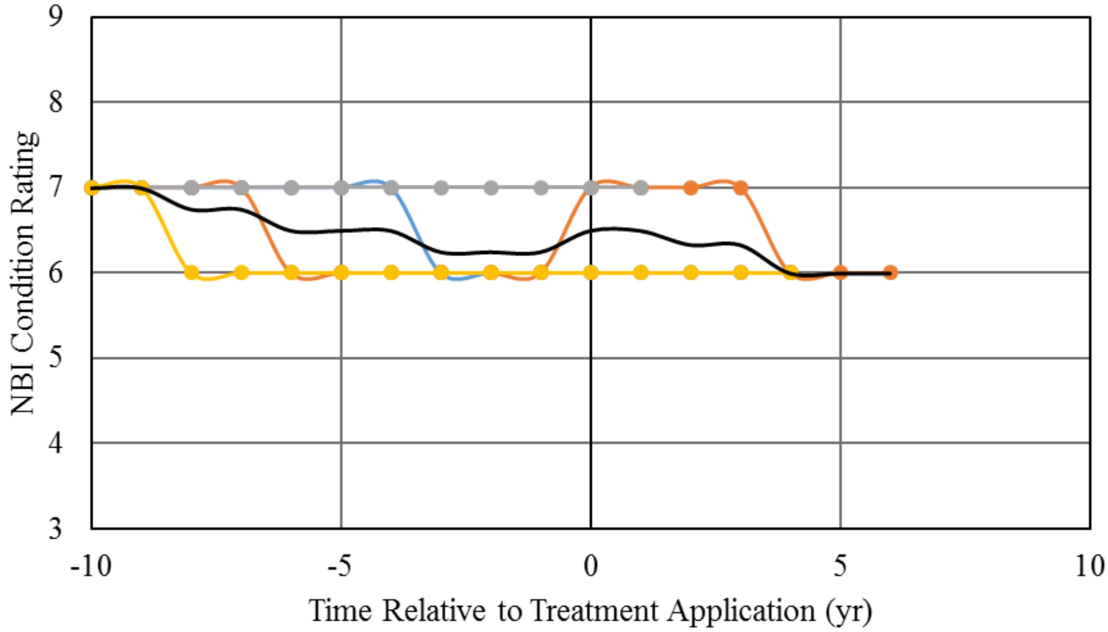


Figure C-14: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of an epoxy overlay in Region 3.

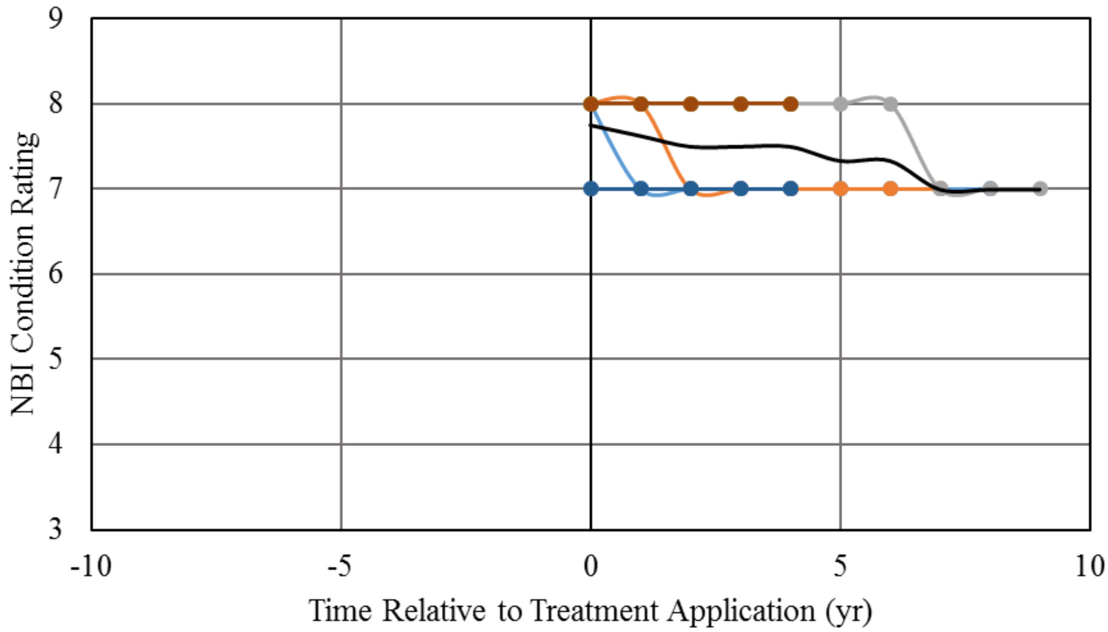


Figure C-15: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of latex-modified concrete in Region 3.

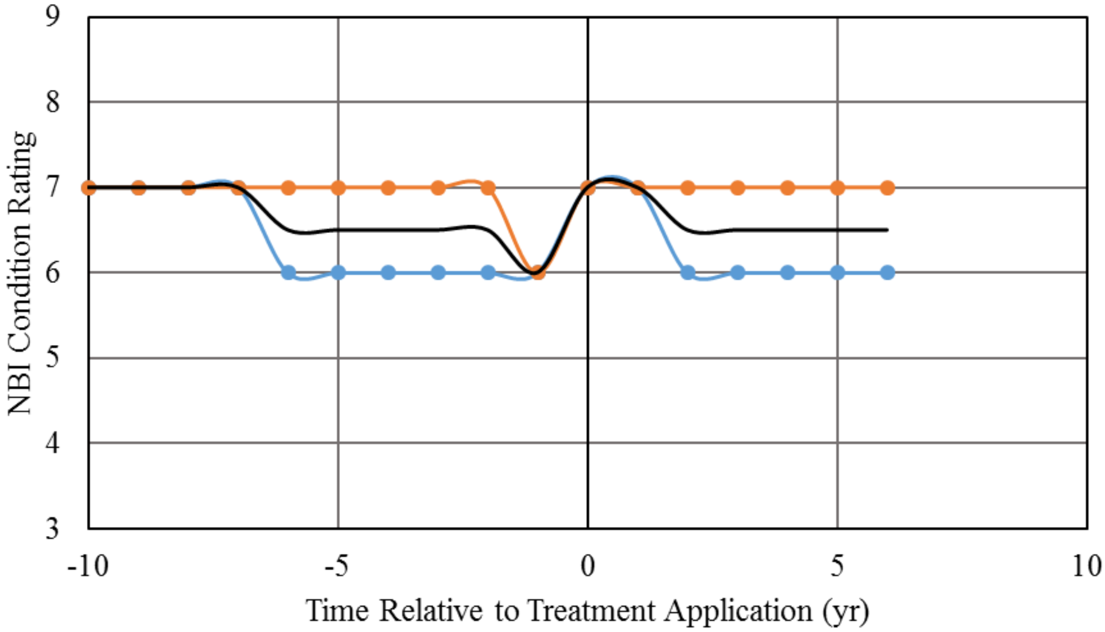


Figure C-16: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of latex-modified concrete in Region 3.

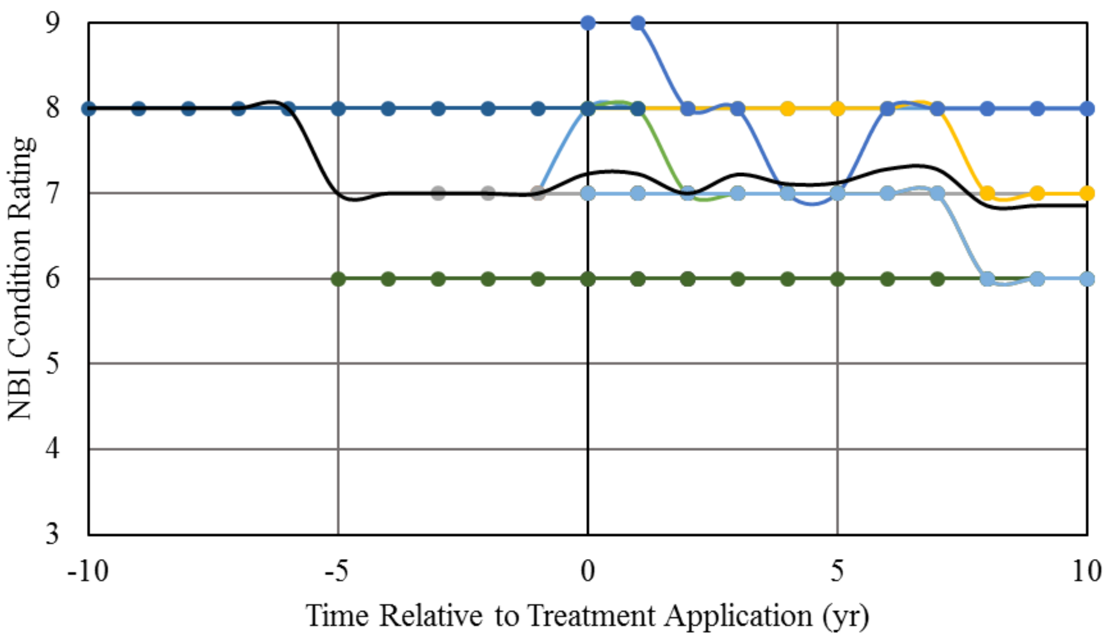


Figure C-17: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of a bituminous overlay in Region 4.

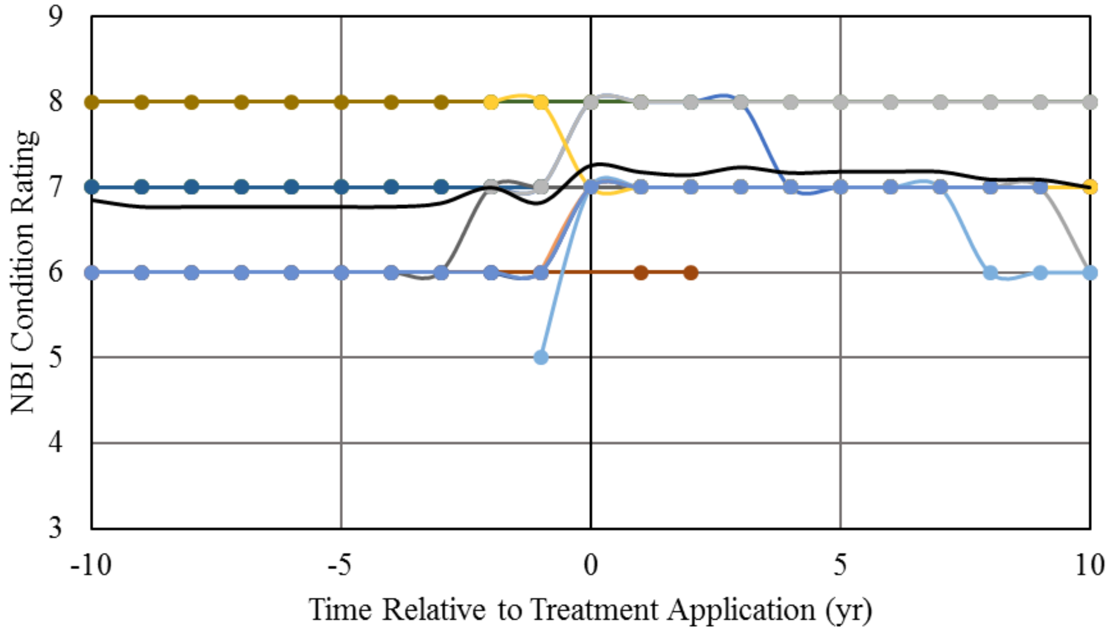


Figure C-18: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of a bituminous overlay in Region 4.

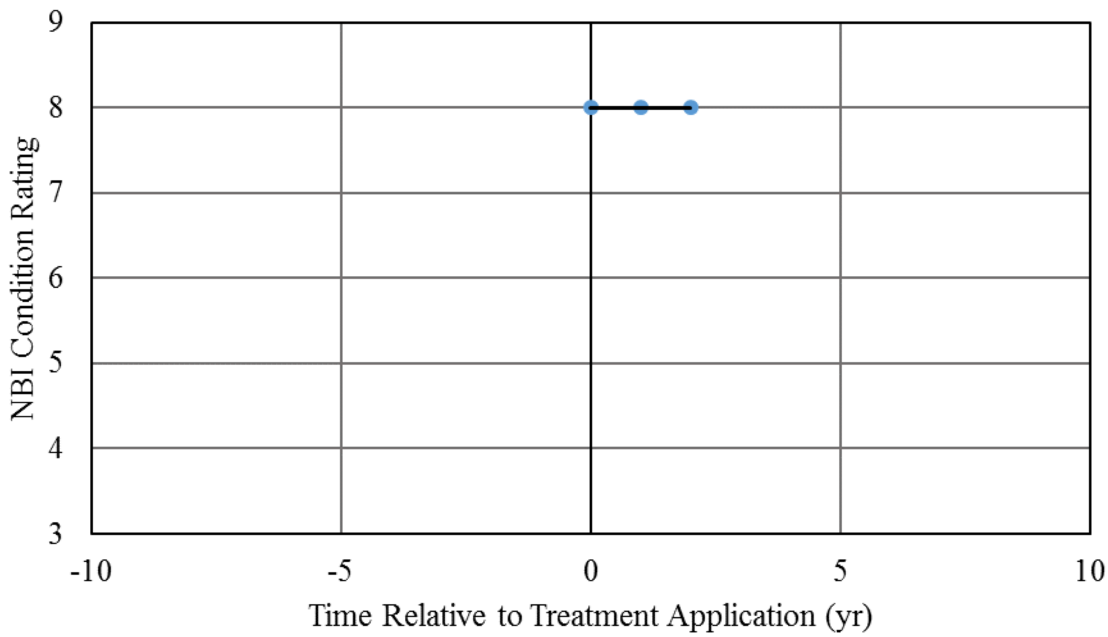


Figure C-19: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of an epoxy overlay in Region 4.

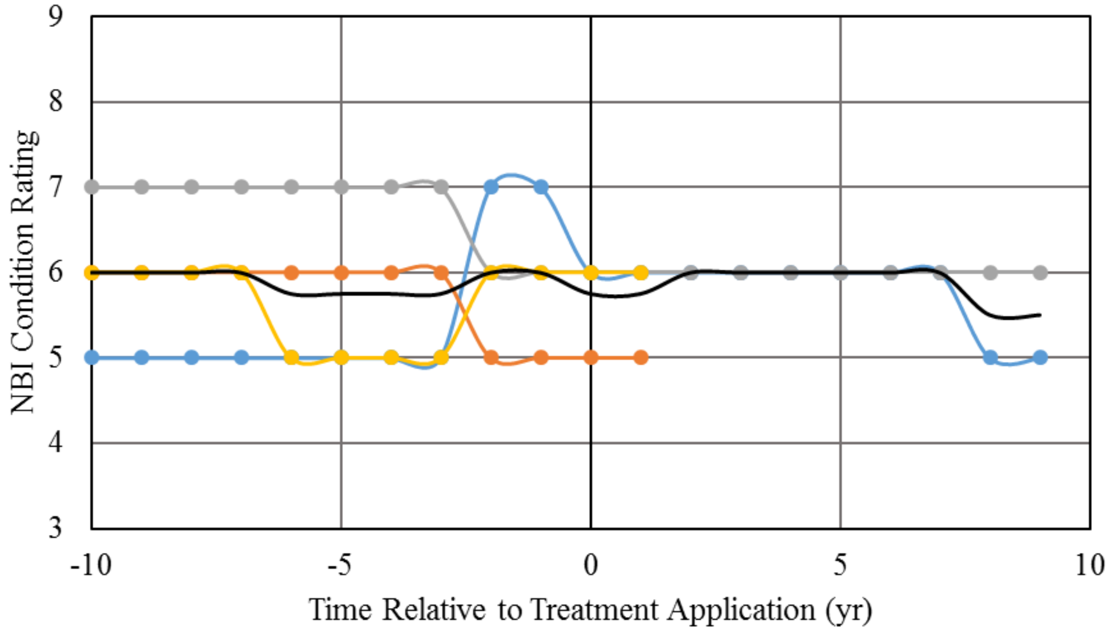


Figure C-20: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with late application of an epoxy overlay in Region 4.

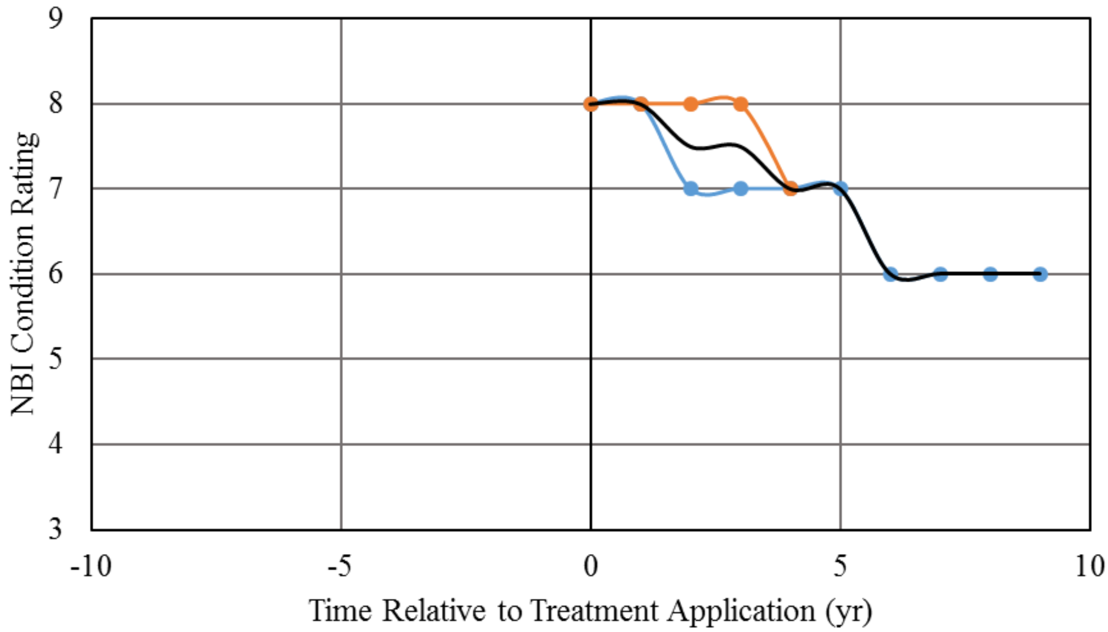


Figure C-21: Individual deterioration curves and average curve aligned by deck treatment time for bridge decks with early application of latex-modified concrete in Region 4.