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Performance of Common Treatments for Reinforced Concrete Highway Bridge Decks

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PERFORMANCE OF COMMON TREATMENTS FOR REINFORCED CONCRETE HIGHWAY BRIDGE DECKS

by

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Abstract

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Performance of Common Treatments for Reinforced Concrete Highway Bridge Decks

Thesis directed by Associate Professor George Hearn

This study gathers information on more than 15,000 bridges to examine time domain trends in condition of bridge decks in service that employ several common treatments. This study computes average improvement to deck condition due to these treatments and computes the mean intervals of changes in general condition ratings related to the deck's post-treatment condition and its approximate pre-treatment condition. In addition, this study performs a cost analysis to compare the average unit cost and the cost effectiveness of each treatment. The results show an average improvement to deck condition of 1.31 rating values due to treatment, mean intervals to maintain approximate post-treatment condition ranging from 6.6 years to 19.4 years, and mean intervals to deteriorate to approximate pre-treatment condition ranging from 13.2 years to 29.4 years. Average costs of treatments range from $0.34 per square foot to $14.68 per square foot. Cost effectiveness is computed as cost per duration in years of improved conditions. Cost effectiveness ranges from $0.06 per square foot per year to $0.99 per square foot per year.

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Abbreviations

The following abbreviations are used in this document:

CDF	Cumulative Distribution Function
CWCCIS	Civil Works Construction Cost Index System
DOT	Department of Transportation
FHWA	Federal Highway Administration
GCR	General Condition Rating
HBRRP	Highway Bridge Rehabilitation and Replacement Program
NBI	National Bridge Inventory
NBIP	National Bridge Inspection Program
NBIS	National Bridge Inspection Standards

Notations

The following notations are used in this document:

a	An adjustment parameter for the Weibull distribution, in years.
c_0, c_1, c_2	Coefficients of a curve in S, T space.
CDF	Cumulative distribution function.
E[x]	Expected value of the Weibull distribution.
f(x)	Weibull probability density function.
F(x)	Weibull cumulative distribution function.
GCR_{effect}	Change in deck general condition rating coincident with treatment.
GCR_{post}	First reported deck general condition rating after treatment.
GCR_{pre}	Last reported deck general condition rating before treatment.
m	An adjustment parameter for Weibull distribution, years.
n	The number of points in Weibull distribution.
N_c	The count of censored observations with time interval at least *t* years.
N_u	The count of uncensored observations with time interval not greater than *t* years.
S	A variable representing the abscissa of a Weibull distribution, unitless.
t	Time, in years.
T	A variable representing the ordinate of a Weibull distribution, unitless.
T_u	The total count of uncensored observations.
x	Independent variable for Weibull distribution, unitless.
γ	A parameter of the Weibull distribution, unitless.
Δ*GCR 0*	Time interval after treatment for no decline in deck general condition rating, in years.
Δ*GCR 1*	Time interval after treatment for decline in deck general condition rating by *1*, in years.

CHAPTER 1

OVERVIEW

Objective

The objective of this study is to investigate several common treatments of U.S. highway bridge decks in service. Specifically, this study computes the average improvements to deck condition due to treatment, computes the mean time interval in which a certain treatment stays at its post-treatment condition, computes the mean time interval in which it takes for a treatment to fall just below its post-treatment condition, and performs a cost analysis of treatments.

Method

The objective is met by collecting information on bridge decks in service. This is performed through a literature review of reports on treatments of bridge decks in service. In addition, four US state Departments of Transportation (DOTs) submitted datasets containing large amounts of information on treated bridge decks in service in their states.

Next, the information on the bridge decks and treatments is organized into a database created for this study. Key identifying information about each bridge deck is used to search the National Bridge Inventory (NBI) to find the bridge and condition information of the bridge deck before and since its treatment. The condition history of each deck is then organized into a second database created for this study.

A statistical analysis is performed, using condition histories, to compute the mean time intervals for changes to conditions of decks after treatment. The average improvement in deck condition due to treatment is computed. Average costs of treatments are computed. Using the mean time intervals and average costs, cost effectiveness of the common treatment types is also computed.

Highway Bridge Decks

This study examines the effectiveness of treatments performed on reinforced concrete bridge decks. Of 480,000+ bridge decks in service in the US, approximately 89% of them are made of reinforced concrete (USDOT 2016).

This study only examines the effectiveness of treatments performed on bridge decks in service. Laboratory studies of treatments of decks are not included.

Treatments

“Treatment” is defined in this study as a material applied to hardened concrete decks to improve its condition or to extend its service life. This section provides a description of common treatments for U.S. highway bridge decks in service and how these treatments are placed. This section describes other treatments and other actions for decks that were found in the literature review and the datasets submitted by state DOTs.

This study identifies two common types of treatments for decks in service. The two types are “wearing surfaces” and “overlays”. Both types of treatment include a variety of materials, and each material has its own performance.

Wearing Surfaces

In this study, the term “wearing surface” means non-structural additions to the concrete deck. Wearing surfaces are asphalt layers placed atop concrete bridge decks. Wearing surfaces protect decks against abrasion. Wearing surfaces are renewable; wearing surfaces can be removed, repaired, and replaced without disturbing the structural deck. A waterproofing membrane can be installed beneath a wearing surface. The membrane will resist water intrusion to the concrete deck.

The two types of wearing surfaces are an asphalt overlay and an asphalt overlay with a waterproofing membrane. Membranes fall under two categories: formed-on-site systems and preformed systems. Formed-on-site membranes are liquids that are sprayed or spread on the deck. The liquid hardens and creates a solid membrane. Preformed membranes are rolls or tiles that are delivered to a site, placed on the deck, bound together, and bound to the concrete deck.

Asphalt is non-structural and does not, alone, provide waterproofing to decks.

Overlays

The two types of overlays discussed in this study are Portland cement concrete overlays (here called "concrete overlays") and polymer overlays. The overlays are placed atop the bridge deck and can be structural, or provide waterproofing, or both. Additionally, overlays provide a new wearing surface to the bridge deck.

Concrete Overlays

Concrete overlays are Portland cement concrete mixes placed on top of hardened concrete bridge decks. Some DOTs have created special mixes of concrete to make the overlay more "dense" and resist water intrusion. Additions to the traditional concrete mix that resist water intrusion include latex, microsilica, silica fume, and fly ash. Fiber reinforcement (steel, polypropylene, etc.) is sometimes included in the mix to give the concrete higher strength and resist cracking. This population of overlays is referred to as "modified concrete overlays".

All concrete overlays are applied to the deck by similar methods. First, the existing bridge deck is milled to remove the top layer of concrete. Next, the concrete mix is combined into a slurry that is poured onto the bridge deck until the desired thickness is met. The riding surface is then textured as desired and finally cured until the overlay is hard enough to resume traffic.

Polymer Overlays

Polymer overlays are made with epoxy, methyl methacrylate, or polyester binder. Binders are delivered to the site as two components where they are mixed together and combined with sand or other aggregate for improved surface friction. The two methods of applying a polymer overlay to a concrete deck are the "broom and seed" method and the "slurry" method.

The broom and seed method entails applying the polymer evenly to the concrete deck first, and then spreading out the aggregate over the liquid polymer by hand or by some mechanical device. This can be done multiple times to create multiple layers of the overlay and reach a desired thickness. The slurry method is where the polymer binder and the aggregate are combined in a mixer before placement on the deck, similarly to concrete overlays. After being mixed, the slurry is placed evenly over the concrete deck to the desired thickness. Typically, additional aggregate is placed over the top of the slurry. In either method of placement, once the overlay polymerizes to its preferred hardness, traffic can resume on the bridge.

Other Treatments

This section discusses other deck treatments discovered in this study. They are categorized separately due to one of the following reasons:

- The treatment description may lack detail.
- The treatment may have appeared too infrequently to perform an independent statistical analysis of performance (the treatment may be included in populations of similar treatments).

Treatments Lacking Detail

Overlay: A treatment called "Overlay" appears in the California and Washington deck datasets submitted for this study. The material used is not identified. Due to this ambiguity, these decks are not included in analysis of performance of treatments.

Patch Repair: A treatment called "Patch Repair" appears in the California deck dataset submitted for this study. Patch material and patch depth are not identified. Patching is not evaluated as a deck treatment.

Polymer Overlay: The treatment "Polymer Overlay" appears in several sources on bridge deck treatments. The polymer material is not named. These decks are included with all polymer overlays in analysis of performance of treatments.

Resurface: An action called "Resurface" appears in the California deck dataset submitted for this study. The term is not defined. These decks are not included in the analysis of treatment performance.

Treatments Appearing Infrequently

Acrylic Modified Concrete Overlay: An acrylic modified Portland cement concrete overlay employs an acrylic resin as part of the concrete mix. Acrylic modified concrete is found on four bridge decks in this study. These decks are included in a population of all overlays with modified concretes for analysis of performance.

Cathodic Protection: Cathodic Protection systems are electrical systems put in place on a bridge to prevent the reinforcing steel from corroding. Cathodic protection prevents corrosion by supplying an electrical current to the reinforcing steel to convert anodic sites on the metal's surface into cathodic sites (Sharp 2007). Supplying current to the reinforcing steel can be done through either "active" or "passive" systems. An active system uses current from an electric utility, and a passive system uses a sacrificial galvanic anode which supplies current to the steel through a difference in electrical potential (Wenzlick 2010). Cathodic protection is found on nine bridge decks in this study. Cathodic protection is not included in analysis of treatment performance.

Microlite Modified Concrete Overlay: A microlite modified concrete overlay employs microlite, an expanded volcanic material, as part of the concrete mix. Microlite modified concrete is found on two bridge decks in this study. This treatment is included with modified concrete overlays in analysis of performance of treatments.

Pyrament Modified Concrete Overlay: A pyrament modified concrete overlay employs a proprietary pyrament-blended cement as part of the concrete mix. Pyrament modified concrete is found on one bridge deck in this study. This deck is included among all modified concrete overlays in analysis of performance of treatments.

Sealers: Sealers are intended to reduce water permeability of the concrete deck. Sealers do not provide a new wearing surface. Sealers are often low viscosity variants of polymer overlays, such as epoxy and methyl methacrylate. Sealers can also be inorganic materials like silane and siloxane, or organic sealers, like linseed oil. These materials are used because they are particularly good at penetrating into the concrete deck to seal cracks and create a water-resistant barrier. Eleven treatments called "Seal" appear in the California deck dataset submitted for this study. The material used for sealing is not named. There are two silane sealer treatments found in the literature review. Due to the limited presence of sealers, there is no analysis of performance of sealers as treatments.

Wax Modified Concrete Overlay: A wax modified concrete overlay employs a wax as part of the concrete mix. Wax modified concrete is found on one bridge deck in this study. This treatment is included among all modified concrete overlays for analysis of performance of treatments.

Other Actions for Decks

There were a few actions found particularly in the DOT submitted datasets that are not treatments as defined in this study. These actions are discussed in the following section.

Deck Rehabilitation: An action called "Deck Rehab" appears in the Wisconsin deck dataset submitted for this study. Deck rehabilitation entails partial depth demolition and reconstruction. Rehabilitation is not a deck treatment.

Deck Replacement: Deck replacement is the act removing the deck of the bridge and replacing it with a new one. This is not a treatment. Bridges with deck replacements are not analyzed for treatment performance.

Epoxy Coated Reinforcement: This is not a treatment. Bridges employing epoxy coated reinforcement are not analyzed for treatment performance unless the deck was treated as well.

Untreated Decks: In addition to the treated decks, a collection of bridge decks labeled as "No treatment" appears in the Washington deck dataset submitted for this study. These decks are not included in analysis of performance of treatments.

Performance of Treatments of Bridge Decks

Performance of a treatment is the improvement to the condition of bridge decks due to the treatment as well as the time interval in which the deck persists with the improved condition. The decks in this study are decks on bridges in service on U.S. public roads. For these decks, general condition ratings (GCRs) are available from the United States Department of Transportation's (USDOT) National Bridge Inventory (NBI).

General condition ratings are numerical ratings assigned to decks by an inspector; typically every two years. The NBI does not present the histories of conditions in decks. Rather, the NBI is updated every year and each update file contains the most recently assigned GCRs. It is a task in this study to identify decks in the NBI, collect GCRs from multiple years of NBI update files, and assemble histories of condition ratings for decks.

From condition histories, improvements in condition due to treatment are obtained as well as time intervals for persistence of improved condition. For improvement to condition, average values are computed. For time intervals, mean values of Weibull distributions are computed. Various treatments are compared on the bases of improvement to condition and persistence of improved condition.

Organization of this Document

This document is organized in five chapters. Chapter 1 introduces the study and gives information on the treatments involved. Chapter 2 presents the findings of the literature review and the contents of the DOT datasets for bridge decks submitted. Chapter 3 describes the methods of organizing the information from the literature review, DOT datasets, and NBI update files. Chapter 4 demonstrates the methods in which the treatments are analyzed and presents the results of the analysis. Chapter 5 summarizes the findings and offers recommendations for future work. The appendix includes NBI coded information as well as more detailed results of the mean interval analysis.

CHAPTER 2

INFORMATION ON BRIDGE DECKS AND TREATMENTS

Overview

Information on treated bridge decks in service is collected from technical literature and from datasets provided by U.S. state DOTs. The study focuses on decks in service and does not include laboratory studies of materials or methods for treatment of bridge decks.

Literature Review

Information on bridge decks and their treatments are found in research documents posted on websites of U.S. state Departments of Transportation (DOTs). Most DOTs have conducted, and continue to conduct, field trials of treatments of decks. This study focuses on these trials because:

- These are real decks in service on US highways.
- The reports identify locations of bridges.
- The reports identify what treatment was used and when it was used.
- The reports often describe extent of the treatment and what repairs and preparations have been performed prior to treatment.
- The reports often include inspection reports and tests following the treatment.
- The reports often include cost of treatment.

Research reports are found using a standard search procedure on DOT websites. The search uses a single set of keywords for all DOT websites. The search uses keywords “deck overlay”, “deck membrane”, “deck seal”, and “polymer overlay”. These keywords yield 53 reports from 25 DOTs. These reports contain information on 788 treated bridge decks. The search is limited to a few pages of results for each keyword at each DOT site. This makes the search finite.

The following section contains a repetitive account of the results from the literature search. It has the format of: The state DOT searched, the title of the report, the number of bridge decks yielded, and the type of treatment(s) applied. A summary of the literature review can be found in Table 1.

Alabama:

- From the Alabama DOT website, Ramey and Oliver (1998) report six decks with the following treatment(s): Concrete overlay, Latex Modified concrete overlay, Polyester overlay, Deck replacement with Epoxy overlay.

Alaska:

- From the Alaska DOT website, Martinelli (1996) reports 31 decks with asphalt overlay, or asphalt overlay with membrane.

Colorado:

- From the Colorado DOT website, Liang (et al. 2014) report one deck with the following treatment(s): Methyl methacrylate overlay, Epoxy overlay, Silane seal.

Florida:

- From the Florida DOT website, Arockiasamy and Barbosa (2000) report on one deck with a latex modified concrete overlay and three decks with epoxy coated reinforcement.

Georgia:

- From the Georgia DOT website, Tatum (1993) reports one deck with the following treatment(s): Concrete overlay, Microsilica modified concrete overlay, Latex modified concrete overlay.

Illinois:

From the Illinois DOT website, two reports of field trials of deck treatments are found.

- Pfeifer and Kowlaski (1999) report two decks with epoxy overlays.

- Pfeifer (1999) reports 21 decks with microsilica modified concrete overlays.

Indiana:

- From the Indiana DOT website, Frosch (et al. 2013) report on eight decks with an asphalt overlay with membrane, two decks with a polymer overlay, one deck with a polymer overlay and epoxy coated reinforcement, and one deck with only epoxy coated reinforcement.

Iowa:

From the Iowa DOT website, six reports of field trials of deck treatments are found.

- Anderson (1990) reports 15 decks with the following treatment(s): Concrete overlay, Latex modified concrete overlay.
- Adam and Gansen (2001) report one deck with an epoxy overlay.
- Keierleber and Engle (2005) report two decks with concrete overlays.
- Engle (2007) reports two decks with fly ash modified concrete overlays.
- Phares (et al. 2016) report one deck with a concrete overlay.
- Dahlberg and Phares (2016) report two decks with epoxy overlays.

Kansas:

- From the Kansas DOT website, Meggers and Hobson (2007) report four decks with the following treatment(s): Concrete overlay, Silica fume modified concrete overlay.

Kentucky:

- From the Kentucky DOT website, Griffin (et al. 2006) report two decks with concrete overlays.

Louisiana:

- From the Louisiana DOTD website, Rasoulian and Rabalais (1991) report four decks with epoxy overlays.

Michigan:

From the Michigan DOT website, four reports of field trials of deck treatments are found.

- Laaninen (1978) reports three decks with concrete overlays.
- Simonsen (1988) reports 22 decks with concrete overlays.
- Beck (1999) reports three decks with concrete overlays.
- Alger (et al. 2003) report 98 decks with epoxy overlays.

Missouri:

From the Missouri DOT website, two reports of field trials of deck treatments are found.

- Harper (2007) reports 100 decks with epoxy overlays.
- Wenzlick (2010) reports one deck a cathodic protection.

Montana:

- From the Montana DOT website, Johnson and Stephens (1997) report 13 decks with the following treatment(s): Acrylic modified concrete overlay, Silica fume modified concrete overlay, Epoxy overlay, Methyl methacrylate overlay.

New Hampshire:

- From the New Hampshire DOT website, Real and Roberts (2004) report two decks with the following treatment(s): Epoxy overlay, Methyl methacrylate overlay.

New York:

From the New York DOT website, three reports of field trials of deck treatments are found.

- Picozzi and Frank (1990) report two decks with cathodic protection.
- Chamberlin (1990) reports 50 decks with concrete overlays.
- Doody and Morgan (1993) report 13 decks with the following treatment(s): Epoxy overlay, Polyester overlay.

Ohio:

From the Ohio DOT website, two reports of field trials of deck treatments are found.

- Gillum (et al. 1998) report 12 decks with the following treatment(s): Concrete overlay, Latex modified concrete overlay, Microsilica modified concrete overlay.
- Barnhart (2001) reports two decks with microlite modified concrete overlays.

Oregon:

From the Oregon DOT website, six reports of field trials of deck treatments are found.

- Petrak (1986) reports one deck with asphalt overlays with a membrane.
- Laylor and Petrak (1990) report five decks with an asphalt overlay with membrane and two decks with epoxy coated reinforcement.
- Miller (1990) reports five decks with microsilica modified concrete overlays.
- Houser and James (1993) report one deck with a latex modified concrete overlay.
- Brooks (1997) reports one deck with the following treatment(s): Latex modified and silica fume modified concrete overlay.
- Brooks (2000) reports one deck with the following treatment(s): Microsilica modified concrete overlay.

Pennsylvania:

- From the Pennsylvania DOT website, Harries (et al. 2013) report 158 decks with latex modified concrete overlays.

Rhode Island:

- From the Rhode Island DOT website, Sock (1996) reports 30 decks with the following treatment(s): Concrete overlay, Latex modified concrete overlay, Microsilica modified concrete overlay.

Utah:

- From the Utah DOT website, Guthrie (et al. 2005) reports three decks with the following treatment(s): Epoxy overlay, Methyl methacrylate overlay.

Vermont:

From the Vermont AOT website, two reports of field trials of deck treatments are found.

- Tremblay (2013a) reports one deck with an asphalt overlay with membrane.
- Tremblay (2013b) reports one deck with an epoxy overlay.

Virginia:

From the Virginia DOT website, six reports of field trials of deck treatments are found.

- Sprinkel (1986) reports 21 decks with the following treatment(s): Polyester overlay, Polymer overlay.
- Sprinkel (1987) reports 13 decks with the following treatment(s): Epoxy overlay, Methyl methacrylate overlay, Silane sealer.
- Ozyildirim (1993) reports one deck with a silica fume modified concrete overlay.
- Ozyildirim (1996) reports two decks with the following treatment(s): Microsilica modified concrete overlay, Pyrament modified concrete overlay.
- Sharp and Brown (2007) report 8 decks with the following treatment(s): Cathodic protection, Latex modified concrete overlay.
- Sprinkel and Apeagyei (2013) report two decks with the following treatment(s): Asphalt overlay, Asphalt overlay with epoxy membrane.

Washington:

From the Washington DOT website, five reports of field trials of deck treatments are found.

- Roper and Henley (1991a) report 33 decks with the following treatment(s): Epoxy overlay, Methyl methacrylate overlay.

- Roper and Henley (1991b) report one deck with a methyl methacrylate overlay.
- Roper and Henley (1992) report one deck with a latex modified concrete overlay.
- Wilson and Henley (1995) report 54 decks with the following treatment(s): Epoxy overlay, Methyl methacrylate overlay.
- Anderson (2014) reports one deck with an asphalt overlay with methacrylate membrane.

Wisconsin:

- From the Wisconsin DOT website, Battaglia (2012) reports 10 decks with the following treatment(s): Asphalt overlay with membrane, Concrete overlay.

Table 1: Results of Literature Review

State DOT	Report	Number of Decks Reported	Treatment(s)
Alabama	Ramey and Oliver (1998)	6	Concrete overlay, Latex modified concrete overlay, Polyester overlay, Deck replacement with epoxy overlay
Alaska	Martinelli (1996)	31	Asphalt overlay, Asphalt overlay with membrane
Colorado	Liang (et al. 2014)	1	Methyl methacrylate overlay, Epoxy overlay, Silane overlay
Florida	Arockiasamy and Barbosa (2000)	4	Latex modified concrete overlay, Epoxy coated reinforcement
Georgia	Tatum (1993)	1	Concrete overlay, Microsilica modified concrete overlay, Latex modified concrete overlay
Illinois	Pfeifer and Kowlaski (1999)	2	Epoxy overlay
Illinois	Pfeifer (1999)	21	Microsilica modified concrete overlay
Indiana	Frosch (et al. 2013)	12	Asphalt overlay with membrane, Thin polymer overlay, Thin polymer overlay with Epoxy coated reinforcement, Epoxy coated reinforcement
Iowa	Anderson (1990)	15	Concrete overlay, Latex modified concrete overlay
Iowa	Adam and Gansen (2001)	1	Epoxy overlay
Iowa	Keierleber and Engle (2005)	2	Concrete overlay
Iowa	Engle (2007)	2	Fly ash modified concrete overlay
Iowa	Phares (et al. 2016)	1	Concrete overlay
Iowa	Dahlberg and Phares (2016)	2	Epoxy overlay

State DOT	Report	Number of Decks Reported	Treatment(s)
Kansas	Meggers and Hobson (2007)	4	Concrete overlay, Silica fume modified concrete overlay
Kentucky	Griffin (et al. 2006)	2	Concrete overlay
Louisiana	Rasoulian and Rabalais (1991)	4	Epoxy overlay
Michigan	Laaninen (1978)	3	Concrete overlay
Michigan	Simonsen (1988)	22	Concrete overlay
Michigan	Beck (1999)	3	Concrete overlay
Michigan	Alger (et al. 2003)	98	Epoxy overlay
Missouri	Harper (2007)	100	Epoxy overlay
Missouri	Wenzlick (2010)	1	Cathodic protection
Montana	Johnson and Stephens (1997)	13	Acrylic modified concrete overlay, Silica fume modified concrete overlay, Epoxy overlay, Methyl methacrylate overlay
New Hampshire	Real and Roberts (2004)	2	Epoxy overlay, Methyl methacrylate overlay
New York	Picozzi and Frank (1990)	2	Cathodic protection
New York	Chamberlin (1990)	50	Concrete overlay
New York	Doody and Morgan (1993)	13	Epoxy overlay, Polyester overlay
Ohio	Gillum (et al. 1998)	12	Concrete overlay, Latex modified concrete overlay, Microsilica modified concrete overlay
Ohio	Barnhart (2001)	2	Microlite modified concrete overlay
Oregon	Petrak (1986)	1	Asphalt overlay with membrane
Oregon	Laylor and Petrak (1990)	7	Asphalt overlay with membrane, Epoxy coated reinforcement
Oregon	Miller (1990)	5	Microsilica modified concrete overlay
Oregon	Houser and James (1993)	1	Latex modified, concrete overlay
Oregon	Brooks (1997)	1	Latex modified, silica fume modified, concrete overlay
Oregon	Brooks (2000)	1	Microsilica modified concrete overlay
Pennsylvania	Harries (et al. 2013)	158	Latex modified concrete overlay
Rhode Island	Sock (1996)	30	Concrete overlay, Latex modified concrete overlay, Microsilica modified concrete overlay
Utah	Guthrie (et al. 2005)	3	Epoxy overlay, Methyl methacrylate overlay
Vermont	Tremblay (2013a)	1	Asphalt overlay with membrane

State DOT	Report	Number of Decks Reported	Treatment(s)
Vermont	Tremblay (2013b)	1	Epoxy overlay
Virginia	Sprinkel (1986)	21	Polyester overlay, Thin polymer overlay
Virginia	Sprinkel (1987)	13	Epoxy overlay, Methyl methacrylate overlay, Silane Sealer
Virginia	Ozyildirim (1993)	1	Silica fume modified concrete overlay
Virginia	Ozyildirim (1996)	2	Microsilica modified concrete overlay, Pyrament modified concrete overlay
Virginia	Sharp and Brown (2007)	8	Cathodic protection, Latex modified concrete overlay
Virginia	Sprinkel and Apeagyei (2013)	2	Asphalt overlay, Asphalt overlay with epoxy membrane
Washington	Roper and Henley (1991a)	33	Epoxy overlay, Methyl methacrylate overlay
Washington	Roper and Henley (1991b)	1	Methyl methacrylate overlay
Washington	Roper and Henley (1992)	1	Latex modified concrete overlay
Washington	Wilson and Henley (1995)	54	Epoxy overlay, Methyl methacrylate overlay
Washington	Anderson (2014)	1	Asphalt overlay with methacrylate membrane
Wisconsin	Battaglia (2012)	10	Asphalt overlay with membrane, Concrete overlay
	Total:	788	

DOT Datasets for Bridge Decks

Another source that yields many decks for this study is from individual state DOTs submitting, through private communication, datasets of bridge decks. There are four DOTs (California, Illinois, Washington, and Wisconsin) that each submitted a dataset, providing information on 14,698 bridge decks. The information for decks in these datasets is:

- Where the bridge is located (or National Bridge Inventory (NBI) Structure Number (USDOT 1995))
- What treatment was applied
- When the treatment was applied
- Cost of the treatment (California and Wisconsin only)

The following section contains a repetitive account of deck treatments in DOT dataset. It has the format of: The state DOT, the number of bridge decks, and the type of treatments or other actions. A summary of treatments in DOT datasets can be found in Table 2.

California:

The California DOT dataset (California DOT 2016) has 8,084 decks with the following treatments and other actions:

Treatments:

- Asphalt Overlay
- Asphalt Overlay with Membrane
- Epoxy Overlay
- Methyl Methacrylate Overlay
- Overlay
- Patch Repair
- Polyester Overlay
- Seal

Other Actions:

- Deck Replacement
- Resurface

Illinois:

The Illinois DOT dataset (Illinois DOT 2016) has 303 decks with the following treatments:

- Concrete Overlay
- High Density Modified Concrete Overlay
- Latex Modified Concrete Overlay

- Microsilica Modified Concrete Overlay

Washington:

The Washington DOT dataset (Washington DOT 2016) has 2,528 decks with the following treatments and other actions:

Treatments

- Asphalt Overlay
- Asphalt Overlay with Membrane
- Concrete Overlay
- Epoxy Overlay
- Fly Ash Modified Concrete Overlay
- High Density Modified Concrete Overlay
- Latex Modified Concrete Overlay
- Methyl Methacrylate Overlay
- Microsilica Modified Concrete Overlay
- Overlay
- Polyester Overlay
- Silica Fume Modified Concrete Overlay
- Wax Modified Concrete Overlay

Other Actions:

- Deck Replacement
- Epoxy Coated Reinforcement

In addition, the Washington dataset includes information on 587 untreated decks, for a total of 3,115 decks.

Wisconsin:

The Wisconsin DOT dataset (Wisconsin DOT 2016) has 3,196 decks with the following treatments and other actions:

Treatments:

- Asphalt Overlay
- Asphalt Overlay with Membrane
- Concrete Overlay
- Epoxy Overlay
- Polymer Overlay

Other Actions:

- Deck Rehab
- Deck Replacement
- Epoxy Coated Reinforcement

Table 2: Contents of DOT Datasets for Decks

State DOT	**Department Contact**	**Number of Decks**	**Treatments and Actions**
California	Paul Cooley	8,084	• Asphalt Overlay • Asphalt Overlay with Membrane • Deck Replacement • Epoxy Overlay • Methyl Methacrylate Overlay • Overlay • Patch Repair • Polyester Overlay • Resurface • Seal
Illinois	Sarah Wilson	303	• Concrete Overlay • High Density Modified Concrete Overlay • Latex Modified Concrete Overlay • Microsilica Modified Concrete Overlay
Washington	DeWayne Wilson	3,115	• Asphalt Overlay • Asphalt Overlay with Membrane • Concrete Overlay • Deck Replacement • Epoxy Coated Reinforcement • Epoxy Overlay • Fly Ash Modified Concrete Overlay • High Density Modified Concrete Overlay • Latex Modified Concrete Overlay • Methyl Methacrylate Overlay • Microsilica Modified Concrete Overlay • No Treatment • Overlay • Polyester Overlay • Silica Fume Modified Concrete Overlay • Wax Modified Concrete Overlay
Wisconsin	Ryan Bowers	3,196	• Asphalt Overlay • Asphalt Overlay with Membrane • Concrete Overlay • Deck Rehab • Deck Replacement • Epoxy Coated Reinforcement • Epoxy Overlay • Polymer Overlay
	Total:	14,698	

CHAPTER 3

CONDITION HISTORIES OF TREATED BRIDGE DECKS

The performance of a treatment is evaluated as improvement to conditions of decks, and time intervals of persistence of improved condition. To analyze the performance of a treatment, first a database of the information found in the literature review and DOT datasets is produced. Research reports and DOT datasets provide various levels of information on bridge decks and their treatments. Therefore, it is necessary to produce a database containing available information pertaining to the decks and their treatments from the different sources. The information from this database of decks and their treatments is used to search the NBI update files for the same decks. Once the decks are found, an accompanying database is produced to contain values related to the treatment's performance.

Database of Decks and Treatments

Available information on decks and treatments in DOT reports and datasets are transferred into a standard data record. The standard data record captures information on the bridge deck, its condition, its treatment, and the treatment's cost. The database fields are listed in Table 3.

Table 3: Deck and Treatment Database and Data Fields

Database Field	**Description**
Source:	
Title	Report Title
Author(s)	Report Author(s)
Report No.	Report Number
Year	Report Year
Link	Link to Report Location (URL)

Bridge:	
State	State the Bridge is Located
Structure No.	NBI Structure Number
Route Carried	Route Carried by Bridge
Feature Crossed	Feature the Bridge Crosses
Milepoint	Milepoint Location of Bridge on Route Carried
Location	General Location Description (i.e. South Portland, County, etc)
Bridge Constructed (Year)	Year the Bridge was Constructed
Latest Deck Replacement (Year)	Year the Bridge had deck replacement (if applicable)
Dates:	
Treatment (Month/Year)	Month and Year of Deck Treatment
Follow Up Inspection (Month/Year)	Month and Year of Follow Up Inspection(s)
Final/Latest Inspection (Month/Year)	Month and Year of Final Inspection
Prior Wearing Surface:	
Generic/Descriptive	General Description of Prior Wearing Surface
Deck Thickness	Deck Thickness
Removal (Total/Partial)	Extent of Removal of the Prior Wearing Surface
Surface Condition:	
Defect Type	Defect Type of Prior Wearing Surface
Defect Extent	Extent of this Defect
Structural Condition:	
Defect Type	Defect Type of Structural Deck
Defect Extent	Extent of this Defect
Treatment Type:	
Generic/Descriptive	General Description of Treatment Used
Treatment Extent	Extent of this Treatment
Manufacturer	Manufacturer of this Treatment (if applicable)
Product Name	Product Name of this Treatment (if applicable)
Thickness	Thickness of Treatment
Construction:	
Demolition Method	Demolition Method of Prior Wearing Surface
Repairs Prior to Treatment:	
Repair Type	Repair Type Prior to Treatment of Deck
Repair Extent	Extent of this Repair
Treatment Material Usage (per SF, SY)	Treatment Material Usage
Previous Treatment:	Previous Treatments to this Deck Since Construction or Latest Deck Replacement

Traffic Control:	
Day/Night	Time of Day Traffic Control Was Implemented
Closures (Complete, Lane-by-Lane)	Extent of Lane Closure During Construction
Cost:	
Historical Material Cost	Cost of Treatment Material Listed in Report
Units	Units of Historical Material Cost
Historical In-Place Material Cost	Cost of Treatment Material and Implementation Listed in Report
Units	Units of Historical In-Place Material Cost
Historical Traffic Control Cost	Cost of Traffic Control During Construction
Units	Units of Historical Traffic Control Cost
Historical Total Cost	Cost of Entire Project Listed in Report
Units	Units of Historical Total Cost
Historical Material Cost ($/S.F.)	Cost of Treatment Material, Converted to $/S.F.
Historical In-Place Material Cost ($/S.F.)	Cost of In-Place Material, Converted to $/S.F.
Historical Traffic Control Cost ($/S.F.)	Cost of Traffic Control, Converted to $/S.F.
Historical Project Cost ($/S.F.)	Cost of Entire Project, Converted to $/S.F.
Historical Cost Index	CWCCIS Cost Index of Treatment Year
2015 Cost Index	CWCCIS Cost Index of 2015
2015 Material Cost ($/S.F.)	Cost of Treatment Material, Converted to 2015 $/S.F.
2015 In-Place Material Cost ($/S.F.)	Cost of In-Place Material, Converted to 2015 $/S.F.
2015 Traffic Control Cost ($/S.F.)	Cost of Traffic Control, Converted to 2015 $/S.F.
2015 Project Cost ($/S.F.)	Cost of Entire Project, Converted to 2015 $/S.F.

Source of Condition Ratings

To evaluate the condition improvement and the performance of different treatments over time, condition histories of decks are assembled. The condition histories are sets of general condition ratings.

Research reports about deck treatments offer some information on conditions before and after treatments. Some reports include follow-on conditions a few months or a few years after treatment. Datasets from DOTs on decks and treatments do not provide histories of conditions after treatment. Regardless, full condition histories are assembled from the NBI for decks from both sources.

General condition ratings are reported in the USDOT National Bridge Inventory (USDOT 2017). The National Bridge Inventory (NBI) is the source of condition ratings used in this study.

National Bridge Inventory

History of NBI

The development of national standards for bridge inspection has largely occurred from the observation of collapses and the response of the United States Congress. Following the Silver Bridge collapse in 1967, the Federal-Aid Highway Act of 1968 established the National Bridge Inspection Program (NBIP) (USDOT 2004). The NBIP established inspection procedures for federal-aid bridges. Later, Congress directed the Secretary of Transportation to develop regulations for inspection, reporting, and coding for bridges through the Federal-Aid Highway Act of 1970. This was performed by the Federal Highway Administration (FHWA) in which they developed the National Bridge Inspection Standards (NBIS). The NBIS established a uniform, national standard for inspection that specified inspection intervals, data collection requirements, qualifications of inspectors, and training programs necessary for bridge inspectors. The Surface Transportation Assistance Act of 1978 extended the scope of bridges being inspected to all bridges on public roads in excess of 6.1 meters span (20 feet), and established the Highway Bridge Rehabilitation and Replacement Program (HBRRP). The HBRRP distributed federal funding to rehabilitate or replace deficient bridges. The Mianus River Bridge failure, caused by instantaneous fracture of a pin and hanger detail, and the Schoharie Creek Bridge failure, initiated by flooding causing localized soil scour resulting in pier collapse, influenced the Surface Transportation and Uniform Relocation Assistance Act of 1987. This act required inspection of fracture-critical members, and underwater inspections of substructures.

The inspection of highway bridges in the US is regulated under Title 23 of the Code of Federal regulation (United States 2014). Inspectors are trained by the National Highway Institute using a standard reference manual (USDOT 2012), and findings of inspections are reported to the USDOT using a standard coding guide (USDOT 1995).

NBI Annual Update Files

NBI is an annually growing collection of publicly-accessible information on highway bridges established by the FHWA as part of the NBIP. NBI is a data collection rather than a database. The data collection is comprised of individual text files called update files. Each update file is composed of coded information on the inventory of bridges in one US state for one year. NBI update files contain the general condition ratings (GCR) for bridges. Since most bridges are inspected every two years, about one half of bridge condition ratings in a NBI update file are new ratings.

For example, if a bridge was inspected in 2000, but not again until 2002, the 2001 update file repeats the bridge condition ratings from the 2000 inspection.

Types of NBI Information

Types of information in NBI consists of: general information, structural information, bridge condition, bridge geometry, and traffic demand (USDOT 1995). For this study, an item that is extracted from NBI is the general condition rating (Item 58) of the deck from year to year. The structure number is a unique string assigned to the bridge by each state. The structure number is often found in research reports, and is recorded in bridge datasets submitted by US state DOTs. In addition to the deck GCRs, the NBI's general information section is used to help determine the structure number of a bridge if the structure number is not reported in the source information for a deck treatment. This is done by comparing the Route Carried, Feature Crossed, and Year Built (Item 7, Item 6, and Item 27 in the FHWA Bridge Coding Guide) to what is noted in source information. The Inspection Date (Item 90), is used in combination with the reported treatment date to find GCRs before and after the treatment. The NBI Inspection Dates after treatment are used to create a vector of (Inspection Date, GCR); the condition history of the deck since treatment. Table 18 in the Appendix lists NBI items used in this study.

Definition of a Highway Bridge

Conventional bridges have three components: deck, superstructure and substructure. Decks carry traffic. The superstructure carries the deck. The substructure supports the superstructure. Figure 1 is an illustration of the three main bridge components.

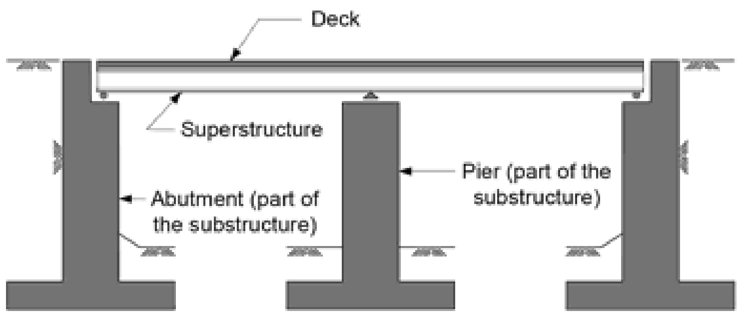

Figure 1: Major Components of a Bridge (USDOT 2012)

Each component, deck, superstructure, and substructure is assigned a general condition rating in each NBIS safety inspection.

General Condition Ratings

The FHWA Recording and Coding Guide (USDOT 1995) defines general condition ratings (GCRs) for bridge components (Table 4). GCRs are integers from 0 to 9 that indicate the overall condition of a bridge component. Individual GCRs are distinguished by extent and severity of deterioration. Localized deterioration, although an important consideration, is not the basis for overall condition of a component.

NBI Item 58 is the deck general condition rating. For concrete decks, inspectors are instructed to look for deterioration in the form of cracks, spalls, full depth failure, delaminating at the rebar, and chloride intrusion. When determining deck GCRs, the conditions of non-structural deck elements are noted, but do not influence the GCR. Non-structural elements include expansion devices, wearing surfaces, sidewalks, bridge rails, etc. (USDOT 1995)

Table 4: FHWA Bridge Component General Condition Rating (USDOT 1995)

Code	Description
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION - structural elements show some minor deterioration.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.
4	POOR CONDITION - advanced section loss, deterioration, spalling, or scour.
3	SERIOUS CONDITION - loss of section, deterioration, spalling, or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	"IMMINENT" FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	FAILED CONDITION - out of service - beyond corrective action.

Database of Performance Values of Treated Bridge Decks

To study the performance of deck treatments in service, a database of deck condition values is assembled. The database contains bridge structure number, type of treatment, month and year of treatment, and time intervals relevant to its condition history (e.g. time, in years, that the GCR maintained at its post-treatment GCR).

The objective of creating a treatment performance database is to compile performance values for each treated bridge deck. This begins by collecting the GCRs for each bridge related to a deck treatment. The first GCR recorded is from the safety inspection immediately before the deck treatment. The final recorded GCR for a given bridge is from one of the following:

1. the most recent NBI file, if the bridge is still in service.
2. the most recent inspection found in NBI; a bridge may be replaced or taken out of service.

3. the inspection before an observed increase in GCR. Increase in GCR is unexpected, and may indicate additional treatment of the deck.

Of the original 15,486 bridge decks listed in the literature review and state DOT dataset submittal combined, 10,512 have deck condition histories. There are circumstances that would prevent us from finding a deck condition history.

The first circumstance is if the structure number of the bridge is not found in a search of NBI update files. This occurs if the structure number is not reported in the source information *and* the structure number is not determined using route carried/feature crossed/year built. Without the structure number, the history of deck condition ratings cannot be assembled.

Another circumstance is if the structure number is known, but does not appear in NBI update files. Without a match on structure number, the history of deck condition ratings cannot be assembled.

Finally, a condition history cannot be assembled if the treatment occurred before the earliest NBI update file. The earliest update file is the year 1992 file.

After the condition history vector is collected for a deck from the multiple NBI update files, relevant information is transferred into a database containing information related to the bridge, the treatment, and the performance values. Database fields are shown in Table 5. For this study, the performance values notably include the GCR before treatment (GCR_{pre}), GCR after treatment (GCR_{post}), change in GCR due to treatment (GCR_{effect}), and the mean intervals of deck condition rating decline (ΔGCR 0 and ΔGCR 1). These performance values are defined in Chapter 4 of this study.

Table 5: Deck Performance Database and Data Fields

Database Field	**Description**
Treatment Generic	General Description of Treatment Used
Treatment Extent	Extent of this Treatment
Manufacturer	Manufacturer of this Treatment (if known)
Product Name	Product Name of this Treatment (if known)
Thickness	Thickness of Treatment
Treatment Key	Unique Key to Treatment Type
Report Key	Unique Key to Source Report or Dataset
Bridge State	State the Bridge is Located in
Treatment Month	Month of Treatment
Treatment Year	Year of Treatment
Treatment Fraction	Fractional Month/Year of Treatment
GCR_{pre}	GCR Before Treatment Date
GCR_{post}	GCR After Treatment Date
GCR_{effect}	GCR Change Before and After Treatment
ΔGCR 0, Uncensored	Time Interval of Uncensored Observation of ΔGCR 0, in years
ΔGCR 0, Censored	Time Interval of Censored Observation of ΔGCR 0, in years
ΔGCR 1, Uncensored	Time Interval of Uncensored Observation of ΔGCR 1, in years
ΔGCR 1, Censored	Time Interval of Censored Observation of ΔGCR 1, in years

Cost of Treatments

In addition to deck performance, it is appropriate to compare the cost of the different treatments. Once costs from the research reports and DOT datasets are transferred to the standard database format for deck and treatment information (Table 3), costs are adjusted to year 2015 using the U.S. Army Corps of Engineers' Civil Works Construction Cost Index System (CWCCIS) (US Army, 2017). For this study, the treatment cost obtained from research reports and DOT datasets is referred to as that treatment's historical cost.

Costs are adjusted as:

$$2015\ Cost = Historical\ Cost * \frac{2015\ Cost\ Index}{Historical\ Cost\ Index}$$

The historical costs from the research reports appear in various forms. Cost could be a total cost, or a form of cost per deck area. Cost could be the cost of the treatment material alone. Cost could be the “in-place” cost of the treatment, which includes the labor cost. Cost could be the total cost of a bridge rehabilitation project, which could include costs of other rehabilitation efforts. For this study, only “in-place” cost of the treatment is evaluated. Costs are evaluated in cost per square foot of deck area. Total costs are converted to unit costs using the area of bridge deck. Deck area is often stated in the research report. If it is not, deck area is computed from NBI Item 49 – Structure Length and NBI Item 52 – Deck Width.

The historical costs from the DOT datasets (California and Wisconsin only) appear as total costs, as opposed to unit costs. The California DOT dataset does not provide the deck area of each bridge, so deck areas are computed from the NBI. The Wisconsin DOT dataset does provide deck areas. Note that it is unknown whether the costs from California and Wisconsin are material costs, in-place treatment costs, or total project costs.

CHAPTER 4

PERFORMANCE OF HIGHWAY BRIDGE DECKS AND TREATMENTS

Treatment of bridge decks improves general condition and preserves improved condition for a period of years. The improvement to general condition and persistence of improved condition are adopted as performance values of treatments. Values related to treatment performance are listed in Table 6.

Table 6: Deck Treatment Performance Values

Measure	Meaning	Unit
GCR_{pre}	Last reported deck general condition rating before treatment.	rating
GCR_{post}	First reported deck general condition rating after treatment.	rating
GCR_{effect}	Change in deck general condition rating coincident with treatment. $GCR_{effect} = GCR_{post} - GCR_{pre}$	rating
$\Delta GCR\ 0$	Time interval after treatment for no decline in deck general condition rating. Time t such that $0 = GCR(t) - GCR_{post}$	years
$\Delta GCR\ 1$	Time interval after treatment for decline in deck general condition rating by 1. Time t such that $1 = GCR(t) - GCR_{post}$	years

The values for GCR_{pre}, GCR_{post}, and GCR_{effect} are straightforward. The GCR_{pre} and GCR_{post} are collected from the corresponding NBI update file. GCR_{effect} is the difference between GCR_{pre} and GCR_{post}. Time intervals ΔGCR 0 and ΔGCR 1 quantify the ability of a treatment to resist deck deterioration. Although it is possible to calculate time intervals ΔGCR 2, ΔGCR 3, etc., relatively few instances are found in condition histories. In addition, the average GCR_{effect} for all treatments is 1.31. Considering that GCRs are integers, the time interval ΔGCR 1 is close to the time it takes for a deck to return to its condition prior to treatment.

Limitations to Performance Values of Treatments

NBI update files are available between years 1992 and 2016. Performance values for treatments that occurred near either end of this 25-year range are constrained in the following ways.

GCR_{effect} can be computed when both GCR_{pre} and GCR_{post} are found. Most treatments applied between years 1993 and 2015 can be computed for GCR_{effect}. For treatments in earlier or later years, GCR_{effect} cannot be computed.

Intervals for persistence of condition, ΔGCR 0 and ΔGCR 1, can only be evaluated if GCR_{post} is found. Treatments applied in year 1992 or later may be evaluated.

Censored Data vs. Uncensored Data

The performance values measured as time interval, ΔGCR 0 and ΔGCR 1, include what is referred to as "censored" and "uncensored" time intervals. A time interval is uncensored if the date of beginning of time interval and the date of ending of time interval are both observed. For example, a treatment performed in 1995 has a GCR_{post} of 7, and the GCR stays 7 until, in 2015, a GCR of 6 is observed. This is an uncensored observation of ΔGCR 0 equal to 20 years for that deck and treatment. An uncensored observation is:

"time interval equals *t* years".

A time interval is censored if the date of ending is not observed. An example of this is a treatment performed in 2000 has a GCR_{post} of 7, and the GCR stays 7 until 2016, the last available NBI update file. This is a censored observation that ΔGCR 0 is 16 years for that deck and treatment. A censored observation is:

"time interval is at least *t* years".

Cumulative Distribution Function

For measures of time interval at ΔGCR 0 and ΔGCR 1, cumulative distribution functions (CDF) are formed. To form CDFs, first collect the count of all uncensored observations, T_u. Next, at each value of time interval, *t* years, there are $N_c(t)$ censored observations that are at least *t* years, and $N_u(t)$ uncensored observations not greater than *t* years. The CDF is computed as:

$$CDF(t) = \frac{N_u(t)}{T_u + N_c(t)} \qquad \text{Eq 1}$$

At t equals zero, $N_u(t)$ is equal to 0, and $N_c(t)$ is equal to the count of all censored observations. As time increases, the count of uncensored observations, $N_u(t)$, approaches the total count of uncensored observations, T_u, and the count of censored observations, $N_c(t)$, approaches zero. CDFs begin at zero and approach one.

Weibull Probability Distribution

To compute the mean intervals ΔGCR 0 and ΔGCR 1, Weibull probability distributions are used. A Weibull probability distribution is selected because it is a generally applicable probability distribution. Weibull distributions have a property that the independent variable must be non-negative. Time intervals ΔGCR 0 and ΔGCR 1 are non-negative.

The Weibull cumulative distribution function is:

$$F(x) = 1 - e^{-x^{\gamma}} \qquad \text{Eq 2}$$

Note, x is the independent variable and γ is a parameter of the probability distribution.

The Weibull probability density function is:

$$f(x) = \gamma x^{\gamma-1} e^{-x^{\gamma}} \qquad \text{Eq 3}$$

x is related to time interval, t, in years.

$$x = \frac{t - a}{m} \qquad \text{Eq 4}$$

In Eq 4, a and m are also parameters of the distribution.

The task in fitting a Weibull probability distribution to an empirical CDF, is a task in selecting parameters γ, a and m so that Eq 2 matches values of CDFs.

Method to Compute Parameters of Weibull Distribution

A Weibull cumulative distribution function yields a linear plot in a particular space. Begin with Eq 2 and re-arrange as:

$$1 - F(x) = e^{-x^{\gamma}} \qquad \text{Eq 5}$$

Take the natural log:

$$ln\big(1 - F(x)\big) = -x^{\gamma} \qquad \text{Eq 6}$$

Move the negative sign:

$$-ln\big(1 - F(x)\big) = x^{\gamma} \qquad \text{Eq 7}$$

Take natural log (again):

$$ln\Big(-ln\big(1 - F(x)\big)\Big) = \gamma \; ln(x) \qquad \text{Eq 8}$$

Eq 8 is a line in a space with $ln(x)$ as the abscissa and $ln\Big(-ln\big(1 - F(x)\big)\Big)$ as the ordinate. The slope of this trace equals γ. The trace passes through the origin of the space when x equals one.

Using the Empirical CDF to Get γ, *m*, and *a*

The fit of a Weibull distribution to empirical CDF is an iterative process.

Procedure:

Translate time t and values of $CDF(t)$ into $ln\left(\frac{t-a}{m}\right)$ and $ln\left(-ln\left(1-CDF(t)\right)\right)$. Note that values of a and m are needed right at the start. For the first iteration, use a equal to zero and m equal to one.

Table 7 is the CDF for all Portland cement concrete overlays in this study, both modified and unmodified. This CDF is used as an example to show a search for parameters of a Weibull distribution. Here are values of $N_u(t)$, $N_c(t)$, and $CDF(t)$.

Table 7: Example of Empirical CDF

$$T_u = 600$$

t, years	$N_u(t)$	$N_c(t)$	$CDF(t)$
0	0	559	0.00
1	8	549	0.01
2	111	511	0.10
3	207	441	0.20
4	262	375	0.27
5	351	325	0.38
6	393	290	0.44
7	437	244	0.52
8	471	220	0.57
9	492	206	0.61
10	512	193	0.65
11	533	172	0.69
12	544	163	0.71
13	560	147	0.75
14	566	137	0.77
15	574	122	0.80
16	580	110	0.82
17	591	108	0.83
18	595	102	0.85
19	598	97	0.86
20	598	85	0.87
21	599	73	0.89
22	599	66	0.90
23	600	53	0.92

t, years	$N_u(t)$	$N_c(t)$	$CDF(t)$
24	600	39	0.94
25	600	28	0.96
26	600	15	0.98
27	600	2	1.00
28	600	1	1.00
29	600	0	1.00
30	600	0	1.00

There is a total of 600 uncensored observations and 599 censored observations for ΔGCR 0. The first change to $N_u(t)$ occurs at year one, therefore parameter a must be less than one year to keep values of x positive. Next the CDF is translated into the space for the Weibull distribution (See Table 8). The translated values are labeled S for ordinate and T for abscissa.

Table 8: CDF-Weibull Conversion

t, years	$CDF(t)$	$x = \frac{t-a}{m}$	$S = ln(x)$	$T = ln\left(-ln\left(1 - CDF(t)\right)\right)$
0	0.00	0.00		
1	0.01	1.00	0.00	-4.96
2	0.10	2.00	0.69	-2.25
3	0.20	3.00	1.10	-1.51
4	0.27	4.00	1.39	-1.16
5	0.38	5.00	1.61	-0.74
6	0.44	6.00	1.79	-0.54
7	0.52	7.00	1.95	-0.32
8	0.57	8.00	2.08	-0.16
9	0.61	9.00	2.20	-0.06
10	0.65	10.00	2.30	0.04
11	0.69	11.00	2.40	0.16
12	0.71	12.00	2.48	0.22
13	0.75	13.00	2.56	0.33
14	0.77	14.00	2.64	0.38
15	0.80	15.00	2.71	0.46
16	0.82	16.00	2.77	0.53
17	0.83	17.00	2.83	0.59
18	0.85	18.00	2.89	0.63
19	0.86	19.00	2.94	0.67
20	0.87	20.00	3.00	0.72
21	0.89	21.00	3.04	0.79

t, years	$CDF(t)$	$x = \frac{t-a}{m}$	$S = ln(x)$	$T = ln\left(-ln\left(1 - CDF(t)\right)\right)$
22	0.90	22.00	3.09	0.83
23	0.92	23.00	3.14	0.92
24	0.94	24.00	3.18	1.03
25	0.96	25.00	3.22	1.13
26	0.98	26.00	3.26	1.31
27	1.00	27.00	3.30	1.74
28	1.00	28.00	3.33	1.86
29	1.00	29.00	3.37	
30	1.00	30.00	3.40	

For the translated values, fit a curve in (S, T) space. The general form of this curve is:

$$T = c_0 + c_1 S + c_2 S^2 \qquad \text{Eq 9}$$

Where c_0, c_1, and c_2 are the coefficients of the curve. Coefficients are calculated using a least squares approach to error.

$$\begin{gathered} Error = \sum (T(S_i) - T_i)^2 \\ \frac{\delta}{\delta c_0} Error = 0 \\ \frac{\delta}{\delta c_1} Error = 0 \\ \frac{\delta}{\delta c_2} Error = 0 \end{gathered} \qquad \text{Eq 5}$$

Eq 10 yields the system of equations.

$$\begin{bmatrix} n & \sum S_i & \sum S_i^2 \\ \sum S_i & \sum S_i^2 & \sum S_i^3 \\ \sum S_i^2 & \sum S_i^3 & \sum S_i^4 \end{bmatrix} \begin{Bmatrix} c_0 \\ c_1 \\ c_2 \end{Bmatrix} - \begin{Bmatrix} \sum T_i \\ \sum S_i T_i \\ \sum S_i^2 T_i \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} \qquad \text{Eq 6}$$

The values for the example are listed in Table 9.

Table 9: System of Equations

	x	S	T	S^2	$S*T$	S^3	S^4	S^2*T
	0.00							
	1.00	0.00	-4.96	0.00	0.00	0.00	0.00	0.00
	2.00	0.69	-2.25	0.48	-1.56	0.33	0.23	-1.08
	3.00	1.10	-1.51	1.21	-1.65	1.33	1.46	-1.82
	4.00	1.39	-1.16	1.92	-1.61	2.66	3.69	-2.23
	5.00	1.61	-0.74	2.59	-1.19	4.17	6.71	-1.92
	6.00	1.79	-0.54	3.21	-0.97	5.75	10.31	-1.73
	7.00	1.95	-0.32	3.79	-0.61	7.37	14.34	-1.20
	8.00	2.08	-0.16	4.32	-0.33	8.99	18.70	-0.68
	9.00	2.20	-0.06	4.83	-0.13	10.61	23.31	-0.28
	10.00	2.30	0.04	5.30	0.08	12.21	28.11	0.20
	11.00	2.40	0.16	5.75	0.38	13.79	33.06	0.92
	12.00	2.48	0.22	6.17	0.55	15.34	38.13	1.37
	13.00	2.56	0.33	6.58	0.84	16.87	43.28	2.14
	14.00	2.64	0.38	6.96	1.00	18.38	48.51	2.64
	15.00	2.71	0.46	7.33	1.25	19.86	53.78	3.38
	16.00	2.77	0.53	7.69	1.47	21.31	59.09	4.07
	17.00	2.83	0.59	8.03	1.67	22.74	64.43	4.72
	18.00	2.89	0.63	8.35	1.83	24.15	69.79	5.28
	19.00	2.94	0.67	8.67	1.97	25.53	75.16	5.80
	20.00	3.00	0.72	8.97	2.17	26.88	80.54	6.50
	21.00	3.04	0.79	9.27	2.41	28.22	85.92	7.34
	22.00	3.09	0.83	9.55	2.57	29.53	91.29	7.94
	23.00	3.14	0.92	9.83	2.89	30.83	96.65	9.05
	24.00	3.18	1.03	10.10	3.27	32.10	102.01	10.39
	25.00	3.22	1.13	10.36	3.65	33.35	107.35	11.76
	26.00	3.26	1.31	10.62	4.27	34.59	112.68	13.93
	27.00	3.30	1.74	10.86	5.74	35.80	117.99	18.92
	28.00	3.33	1.86	11.10	6.18	37.00	123.29	20.61
	29.00	3.37		11.34		38.18	128.57	
	30.00	3.40		11.57		39.35	133.82	
$\sum$	28.0	67.9	2.65	184	36.1	520	1510	126

The system of equations for this example is:

$$\begin{bmatrix} 28.0 & 67.9 & 184 \\ 67.9 & 184 & 520 \\ 184 & 520 & 1510 \end{bmatrix} \begin{Bmatrix} c_0 \\ c_1 \\ c_2 \end{Bmatrix} - \begin{Bmatrix} 2.65 \\ 36.13 \\ 126 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} \qquad \text{Eq 7}$$

Once this system of equations is solved, the corresponding values for c_0, c_1, and c_2 are:

$$\begin{Bmatrix} c_0 \\ c_1 \\ c_2 \end{Bmatrix} = \begin{Bmatrix} -4.43 \\ 2.65 \\ -0.29 \end{Bmatrix} \qquad \text{Eq 8}$$

If parameters a and m are correct, this curve will pass through the origin, so c_0 should be zero. The curve will also be a straight line if correct, so c_2 should be zero. The initial guesses for parameters a and m yield a curve that does not meet either expectation. Parameters a and m are then adjusted until the curve is a straight line with zero intercept. Points (S_i, T_i) and the curve $T(S_i)$ are shown in Figure 2.

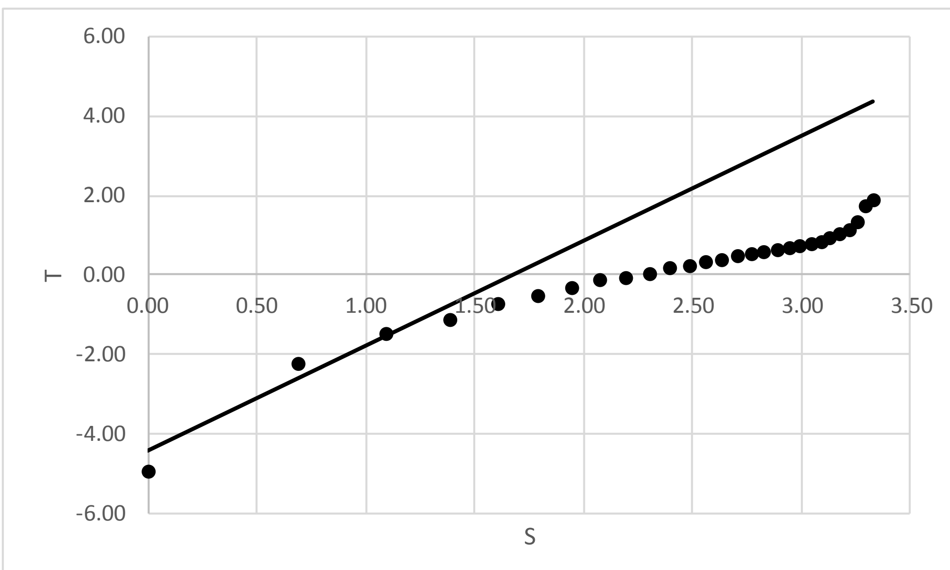

Figure 2: Example Weibull Distribution and Fit

An adjustment, Δm, is computed to shift the trace so that it intersects the origin in S,T space. The current trace is:

$$-c_0 = c_1 S + c_2 S^2 \qquad \text{Eq 9}$$

Expand S:

$$-c_0 = c_1 ln\left(\frac{t-a}{m}\right) + 2c_2 ln\left(\frac{t-a}{m}\right)$$ Eq 10

$$-c_0 = c_1 ln(t-a) - c_1 ln(m) + 2c_2 ln(t-a) - 2c_2 ln(m)$$

An adjustment Δm moves the trace to intersection with the origin as follows:

$$0 = c_1 ln(t-a) - c_1 ln(m+\Delta m) + 2c_2 ln(t-a) - 2c_2 ln(m+\Delta m)$$ Eq 16

Subtract Eq 16 from Eq 15.

$$-c_0 = c_1 ln(m+\Delta m) + 2c_2 ln(m+\Delta m) - c_1 ln(m) - 2c_2 ln(m)$$ Eq 17

$$-c_0 = [c_1 + 2c_2] ln\left(\frac{m+\Delta m}{m}\right)$$

This can be re-arranged as follows:

$$m + \Delta m = m\, e^{-\frac{c_0}{c_1+2c_2}}$$ Eq 17

Update m:

$$m + \Delta m \ \rightarrow m$$ Eq 17

This change in m requires update to Table 9, which, in turn, yields new values of c_0, c_1, and c_2. Next adjust m again, if needed. Once all iterations are completed, the new value of m, after adjustment, is 8.69. The final update to Table 9 is shown in Table 10.

Table 10: Updated System of Equations for Example

	x	S	T	S^2	$S*T$	S^3	S^4	S^2*T
	-0.10							
	0.01	-4.47	-4.96	19.94	22.16	-89.03	397.54	-98.97
	0.13	-2.07	-2.25	4.27	4.65	-8.84	18.27	-9.62
	0.24	-1.42	-1.51	2.02	2.14	-2.87	4.07	-3.04
	0.36	-1.03	-1.16	1.06	1.20	-1.10	1.13	-1.24
	0.47	-0.75	-0.74	0.56	0.56	-0.42	0.32	-0.42
	0.59	-0.53	-0.54	0.28	0.29	-0.15	0.08	-0.15
	0.70	-0.35	-0.32	0.13	0.11	-0.04	0.02	-0.04
	0.82	-0.20	-0.16	0.04	0.03	-0.01	0.00	-0.01
	0.93	-0.07	-0.06	0.01	0.00	0.00	0.00	0.00
	1.05	0.05	0.04	0.00	0.00	0.00	0.00	0.00

	x	S	T	S^2	$S*T$	S^3	S^4	S^2*T
	1.16	0.15	0.16	0.02	0.02	0.00	0.00	0.00
	1.28	0.24	0.22	0.06	0.05	0.01	0.00	0.01
	1.39	0.33	0.33	0.11	0.11	0.04	0.01	0.04
	1.51	0.41	0.38	0.17	0.16	0.07	0.03	0.06
	1.62	0.48	0.46	0.23	0.22	0.11	0.05	0.11
	1.74	0.55	0.53	0.30	0.29	0.17	0.09	0.16
	1.85	0.62	0.59	0.38	0.36	0.23	0.14	0.22
	1.97	0.68	0.63	0.46	0.43	0.31	0.21	0.29
	2.08	0.73	0.67	0.54	0.49	0.39	0.29	0.36
	2.20	0.79	0.72	0.62	0.57	0.49	0.38	0.45
	2.31	0.84	0.79	0.70	0.66	0.59	0.49	0.56
	2.43	0.89	0.83	0.79	0.74	0.70	0.62	0.65
	2.54	0.93	0.92	0.87	0.86	0.81	0.76	0.80
	2.66	0.98	1.03	0.95	1.00	0.93	0.91	0.98
	2.77	1.02	1.13	1.04	1.16	1.06	1.08	1.18
	2.89	1.06	1.31	1.12	1.39	1.19	1.26	1.47
	3.00	1.10	1.74	1.21	1.91	1.33	1.46	2.10
	3.12	1.14	1.86	1.29	2.11	1.47	1.67	2.40
	3.23	1.17		1.38		1.61	1.89	
	3.35	1.21		1.46		1.76	2.13	
$\sum$	28.0	2.08	2.65	39.2	43.7	-92.5	431	-102

The corresponding new values for c_0, c_1, and c_2 are:

$$\begin{Bmatrix} c_0 \\ c_1 \\ c_2 \end{Bmatrix} = \begin{Bmatrix} 0.00 \\ 1.13 \\ 0.01 \end{Bmatrix} \quad \text{Eq 11}$$

Use parameter a to adjust c_2 equal to zero. However, there are limits on a. a should be non-negative and a should be less than time t for the first, earliest transition. For this example

$$\begin{matrix} a \geq 0 \\ a < 1 \end{matrix} \quad \text{Eq 12}$$

The resulting plot of these updated parameters is displayed in Figure 3. Some noticeable differences between Figure 2 and Figure 3 is that Eq 9 intercepts with the origin and plots as a straight line. These two conditions satisfy the properties of a completed Weibull distribution. Additionally, the plotted points of the Weibull distribution are much closer to Eq 9, suggesting that the a and m values are now correct.

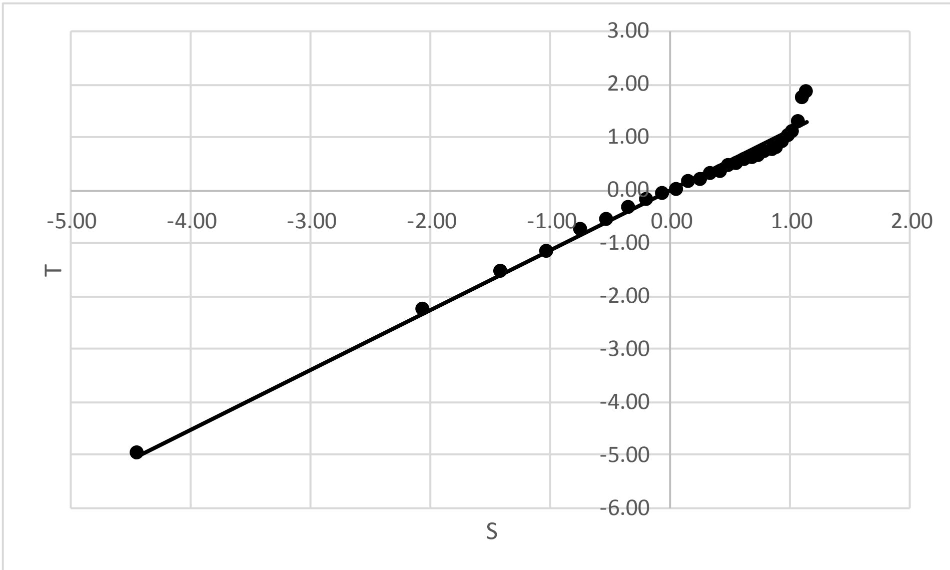

Figure 3: Updated Weibull Distribution and Fit

Iterative Process for Parameter 'a'

1. Select a value of a; Use intervals of 0.1.
2. Update S_i and T_i.
3. Compute c_0, c_1, and c_2. Note that update to m may be needed as a is changed.
4. Examine c_0 and c_2; both should be close to zero.
5. Adjust a as necessary.
6. Repeat steps 2-5 until c_0 and c_2 are as close to zero as possible.

Table 11 displays values of c_2 based on values of a between zero and one.

Table 11: Possible c_2 Solutions

a	m	c_2
0	9.05	-0.29
0.1	8.96	-0.26
0.2	8.88	-0.23
0.3	8.80	-0.20
0.4	8.73	-0.17
0.5	8.68	-0.14
0.6	8.63	-0.11
0.7	8.62	-0.08
0.8	8.63	-0.04
0.9	8.69	0.01

The 'best' choice is a equal to 0.9. The corresponding Weibull distribution parameters are:

$$\begin{Bmatrix} a \\ m \\ \gamma \end{Bmatrix} = \begin{Bmatrix} 0.90 \\ 8.69 \\ 1.13 \end{Bmatrix} \qquad \text{Eq 20}$$

The mean value of this distribution is calculated:

$$E[x] = \Gamma\left(\frac{\gamma + 1}{\gamma}\right) \qquad \text{Eq 13}$$

Where Γ represents the gamma function. For this example, the mean value is:

$$E[x] = 0.96 \qquad \text{Eq 14}$$

Using Eq 4, this mean can be expressed in years, t:

$$E[t] = 9.2 \text{ yrs} \qquad \text{Eq 15}$$

This final value of 9.2 years is the mean interval of ΔGCR 0 for the example set of data.

Populations of Treatments

The following treatments are analyzed for average GCR_{effect}, mean intervals of ΔGCR 0 and ΔGCR 1, and for cost analysis:

- Unmodified Portland cement concrete overlays.
- Portland cement concrete overlays with fly ash.

- Latex-modified Portland cement concrete overlays.
- Portland cement concrete overlays with microsilica.
- Asphalt wearing surfaces with no waterproofing membrane.
- Asphalt wearing surfaces with a waterproofing membrane.
- Epoxy overlays.
- Methyl methacrylate overlays.
- Polyester overlays.

Performance values are computed for populations of these treatments. The populations are: All Concrete Overlays, All Modified Concrete Overlays, All Asphalt Wearing Surfaces, and All Polymer Overlays.

- *All Concrete Overlays* is a population of all the Portland cement concrete overlays; modified and unmodified.
- *All Modified Concrete Overlays* is a population of Portland cement concrete overlays with addition of fly ash or latex or microsilica.
- *All Asphalt Wearing Surfaces* is a population of asphalt wearing surfaces with a membrane and asphalt wearing surfaces without a membrane.
- *All Polymer Overlays* is a population of epoxy overlays, methyl methacrylate overlays, polyester overlays, and 31 polymer overlays with unknown polymer type.

Results for Average GCR_{effect}

The following section reports the results of the average GCR_{effect} for each treatment and treatment population. The GCR_{effect} is the change in GCR before and after the treatment. A summary of these findings is found in Table 12.

For all Portland cement concrete overlays, the average GCR_{effect} due to treatment is 1.48. Within that population, the unmodified concrete overlays have an average GCR_{effect} of 1.40 and the all modified concrete overlays population average GCR_{effect} is 1.68. Within all modified concrete overlays, concrete overlays with fly ash have the highest average GCR_{effect} with 1.90, next is latex modified concrete overlays with 1.75, and finally concrete overlays with microsilica with 1.57.

For all asphalt wearing surfaces, the average GCR_{effect} due to treatment is 0.20. Asphalt wearing surfaces without a waterproofing membrane reports an average GCR_{effect} of 0.26 and asphalt wearing surfaces with a waterproofing membrane report 0.11.

For all polymer overlays, the average GCR_{effect} due to treatment is 1.59. The greatest average GCR_{effect} of the population is for methyl methacrylate overlays with 1.73, next is polyester overlays with 1.46, and finally epoxy overlays with 0.23.

Table 12: Summary of Average GCR_{effect} Results

Treatment	Average GCR_{effect}
All Concrete Overlays	1.48
Concrete Overlays, unmodified	1.40
All Modified Concrete Overlays	1.68
Concrete Overlays, Fly Ash	1.90
Concrete Overlays, Latex modified	1.75
Concrete Overlays, with Microsilica	1.57
All Asphalt Wearing Surfaces	0.20
Asphalt Wearing Surface, No Waterproofing Membrane	0.26
Asphalt Wearing Surface, with Waterproofing Membrane	0.11
All Polymer Overlays	1.59
Epoxy Overlays	0.23
Methyl Methacrylate Overlays	1.73
Polyester Overlays	1.46

Results for Time Intervals ΔGCR 0 and ΔGCR 1

The following section reports the results for the mean intervals of ΔGCR 0 and ΔGCR 1 for each treatment and treatment population. Summaries of these results are found in Table 13 and Table 14.

Additionally, a summary count of uncensored and censored observations for each treatment is found in Table 15.

ΔGCR 0

For Portland cement concrete overlays, there are 600 uncensored observations and 559 censored observations of ΔGCR 0. Modified Portland cement concrete overlays have longer mean interval ΔGCR 0 than unmodified Portland cement concrete overlays. The mean interval ΔGCR 0 for modified Portland cement concrete overlays is equal to 16.2 years. The mean interval ΔGCR 0 for unmodified Portland cement concrete overlays is equal to 6.6 years. Individually, the mean intervals of ΔGCR 0 for the modified Portland cement concrete overlays are 16.2 years for concrete with fly ash, 19.4 years for concrete with latex, and 15.2 years for concrete with microsilica.

For asphalt wearing surfaces, there are 365 uncensored observations and 985 censored observations of ΔGCR 0. The asphalt wearing surfaces with a waterproofing membrane have a mean interval ΔGCR 0 equal to 16.9 years and asphalt wearing surfaces without a waterproofing membrane have a mean interval ΔGCR 0 equal to 12.1 years.

For polymer overlays, there are 325 uncensored observations and 4,123 censored observations of ΔGCR 0. The mean interval ΔGCR 0 is 11.6 years for polyester overlays, 10.3 years for methyl methacrylate overlays, and 8.9 years for epoxy overlays. All polymer overlays have shorter mean intervals ΔGCR 0 than the modified concrete overlays.

Table 13: ΔGCR 0 Mean Interval

ΔGCR 0	Mean Interval (years)
All Concrete Overlays	9.2
Concrete Overlay, unmodified	6.6
All Modified Concrete Overlays	16.2
Concrete Overlay, with Fly Ash	16.2
Concrete Overlay, Latex modified	19.4
Concrete Overlay, with Microsilica	15.2
All Asphalt Wearing Surfaces	13.4
Asphalt Wearing Surface, No Waterproofing Membrane	12.1
Asphalt Wearing Surface, with Waterproofing Membrane	16.9
All Polymer Overlays	10.3
Epoxy Overlay	8.9
Methyl Methacrylate Overlay	10.3
Polyester Overlay	11.6

ΔGCR 1

For the Portland cement concrete overlays, there are 203 uncensored observations and 332 censored observations of ΔGCR 1. The modified Portland cement concrete overlays result in a longer mean interval ΔGCR 1 than the unmodified Portland cement concrete overlays. The mean interval ΔGCR 1 for modified Portland cement concrete overlays is 23.3 years. The mean interval ΔGCR 1 for unmodified Portland cement concrete overlays is 13.4 years. Among modified Portland cement concrete overlays, the mean intervals are 29.4 years for concrete with latex and 23.1 years for concrete with microsilica. There are too few observations of ΔGCR 1 for modified Portland cement concrete overlays with fly ash to compute a mean interval.

For asphalt wearing surfaces, there are 75 uncensored observations and 254 censored observations of ΔGCR 1. The asphalt wearing surfaces with a waterproofing membrane have a mean interval ΔGCR 1 equal to 21.3 years and asphalt wearing surfaces without a waterproofing membrane have a mean interval ΔGCR 1 equal to 17.3 years.

For polymer overlays, there are 29 uncensored observations and 219 censored observations of ΔGCR 1. The mean intervals ΔGCR 1 are 14.6 years for epoxy overlays and 13.2 years for methyl methacrylate overlays. There are too few observations of ΔGCR 1 for polyester overlays to compute a mean interval.

More detailed results for ΔGCR 0 and ΔGCR 1, including parameters of Weibull distributions, are found in the Appendix (Table 19 and Table 20).

Table 14: ΔGCR 1 Mean Interval

ΔGCR 1	Mean Interval (years)
All Concrete Overlays	14.7
Concrete Overlay, unmodified	13.4
All Modified Concrete Overlays	23.3
Concrete Overlay, with Fly Ash[1]	-
Concrete Overlay, Latex modified	29.4
Concrete Overlay, with Microsilica	23.1
All Asphalt Wearing Surfaces	17.4
Asphalt Wearing Surface, No Waterproofing Membrane	17.3
Asphalt Wearing Surface, with Waterproofing Membrane	21.3
All Polymer Overlays	13.7
Epoxy Overlay	14.6
Methyl Methacrylate Overlay	13.2
Polyester Overlay[1]	-

[1] Too few observations to compute parameters for Weibull distribution.

Table 15: Counts of Observations of Deck Treatments

	ΔGCR 0		ΔGCR 1	
Treatment	*Uncensored*	*Censored*	*Uncensored*	*Censored*
All Concrete Overlays	600	559	203	332
Concrete Overlay, unmodified	488	321	183	246
All Modified Concrete Overlays	112	238	20	86
Concrete Overlay, with Fly Ash	6	25	1	4
Concrete Overlay, Latex modified	54	129	9	43
Concrete Overlay, with Microsilica	51	81	10	38
All Asphalt Wearing Surfaces	365	985	75	254
Asphalt Wearing Surface, No Waterproofing Membrane	290	565	64	199
Asphalt Wearing Surface, with Waterproofing Membrane	75	420	11	55
All Polymer Overlays	325	4,123	29	219
Epoxy Overlay	89	219	10	69
Methyl Methacrylate Overlay	215	3,405	19	133
Polyester Overlay	21	468	0	15

Results of Cost Analysis

There are 9,700 values for cost, in dollars per square foot, available for this study from all sources. Of these, 6,984 cost values pertain to treatments analyzed for performance in this study. A summary of treatment costs and counts of cost values obtained for each treatment is found in Table 16.

For Portland cement concrete overlays, there are 33 costs available for modified Portland cement concrete overlays and 1,303 costs available for unmodified Portland cement concrete overlays. The average cost of modified Portland cement concrete overlays $7.86/S.F. is less than the average cost of unmodified Portland cement concrete overlays $14.68/S.F. Note that all but one cost for unmodified Portland cement concrete overlays is obtained from a single source, the Wisconsin DOT dataset.

For asphalt wearing surfaces, there are 349 costs available for asphalt wearing surfaces without a membrane and 15 costs available for asphalt wearing surfaces with waterproofing membranes. The average cost of asphalt wearing surfaces without a waterproofing membrane $8.35/S.F. is more than asphalt wearing surfaces with a waterproofing membrane $5.73/S.F. Note that 92% of the costs for all asphalt wearing surfaces is obtained from a single source, the Wisconsin DOT dataset. The remaining 8% is obtained from the California DOT dataset.

For polymer overlays, there are 63 costs available for epoxy overlays, 4,530 costs available for methyl methacrylate overlays, and 656 costs available for polyester overlays. The average cost of methyl methacrylate overlays is the least of these three with an average cost of $0.34/S.F. Next is polyester overlays with an average cost of $1.21/S.F. And finally, epoxy overlays has an average cost of $7.14/S.F. 98% of costs available for all polymer overlays are obtained from a single source, the California DOT dataset.

Table 16: Summary of Costs of Treatments

Treatment	**2015-Adjusted Average Unit Cost ($/S.F.)**	**Count**
All Concrete Overlays	$14.51	1,336
Concrete Overlays, unmodified	$14.68	1,303
All Modified Concrete Overlays	$7.86	33
Concrete Overlays, with Fly Ash	-	0
Concrete Overlays, Latex modified	$6.02	2
Concrete Overlays, with Microsilica	$7.98	31
All Asphalt Wearing Surfaces	$8.24	364
Asphalt Wearing Surface, No Waterproofing Membrane	$8.35	349
Asphalt Wearing Surface, with Waterproofing Membrane	$5.73	15
All Polymer Overlays	$0.59	5,284
Epoxy Overlays	$7.14	63
Methyl Methacrylate Overlays	$0.34	4,530
Polyester Overlays	$1.21	656

Using average costs, it is possible to determine cost effectiveness of the different treatments. The cost effectiveness of a treatment is calculated as:

$$Cost\ Effectiveness = \frac{2015\ Adjusted\ Average\ Unit\ Cost}{\Delta \mathrm{GCR}\ 1}$$

The cost effectiveness is calculated with the mean interval of ΔGCR 1 because this is the approximate time before the deck deteriorates to the condition before the treatment.

The cost effectiveness is calculated for the three main populations of treatments: All Concrete Overlays, All Asphalt Wearing Surfaces, and All Polymer Overlays and is summarized in Table 17. The lowest value is the most cost effective treatment.

All Polymer Overlays is most cost effective treatment population with a value of \$0.06/(S.F.*Year). All Asphalt Wearing Surfaces is the next most cost effective treatment population with a value of \$0.61/(S.F.*Year). Finally, All Concrete Overlays is the least cost effective treatment population with a value of \$0.99/(S.F.*Year).

Table 17: Cost Effectiveness of Treatments

Treatment	**Cost Effectiveness**	**Units**
All Concrete Overlays	0.99	$\frac{\$}{S.F.* Year}$
All Asphalt Wearing Surfaces	0.61	$\frac{\$}{S.F.* Year}$
All Polymer Overlays	0.06	$\frac{\$}{S.F.* Year}$

CHAPTER 5

CONCLUSIONS

An analysis of several common treatments to reinforced concrete bridge decks in service on U.S. highways is performed to investigate their deterioration over time. The objective of this study is to present and compare the average improvement to condition, mean time intervals of persistence of improved condition, average costs, and cost effectiveness of the common treatments.

The method by which these objectives is accomplished is: collection of data, assembly of condition histories, computation of performance values, and analysis of costs. Methods of cost analysis involves collecting historical cost data from DOT research reports and datasets, converting costs into unit costs using deck area, converting this historical unit cost to 2015 unit cost, and using the mean time interval, ΔGCR 1, to compute cost effectiveness of each treatment.

Summary of Findings for Performance Values of Treatments

Through an evaluation of the average GCR_{effect} results, certain trends are identified concerning the three main categories of treatment. Asphalt wearing surfaces have the lowest average GCR_{effect}, then concrete overlays, and finally polymer overlays have the largest average initial improvement to GCR with 0.20, 1.48, and 1.59 respectively. The modified concrete overlays were the treatment population with the largest average deck condition improvement of 1.68.

Through an evaluation of the mean intervals of ΔGCR 0, it is shown that concrete overlays, as a treatment population, have the weakest ability to resist deck deterioration with a mean interval of 9.2 years. This is due to the unmodified concrete overlays within this population with a mean interval of 6.6 years. The modified concrete overlays population has the greatest ability to resist deck deterioration with a mean interval of 16.2 years. This strongly suggests that modifying the concrete mix significantly improves the overlay's ability resist deck deterioration. Among materials that modify concrete overlays, fly ash, latex, and microsilica have mean intervals of 16.2 years, 19.4 years, and 15.2 years respectively. The next closest treatment population is the asphalt wearing surfaces with a mean interval of 13.4 years. Within this population, the asphalt surfaces without a waterproofing membrane have a mean interval of 12.1 and the asphalt surfaces with a waterproofing membrane have a mean interval of 16.9 years. This indicates that the membrane has a positive impact on resisting deck deterioration. All polymer overlays have a ΔGCR 0 of 10.3 years. Within this population, epoxy overlays, methyl methacrylate overlays, and polyester overlays have mean intervals of 8.9 years, 10.3 years, and 11.6 years respectively.

Through an evaluation of mean intervals of ΔGCR 1, a similar trend appears. Concrete overlays, as a population, have a mean interval of 14.7 years. Unmodified concrete overlays have a mean interval of 13.4 years, whereas the modified concrete overlays have a mean interval of 23.3 years. This again demonstrates that a modified concrete mix is superior to an unmodified mix at resisting deck deterioration. Among materials that modify concrete overlays, latex and microsilica have mean intervals of 29.4 years and 23.1 years respectively. Asphalt wearing surfaces as a population have a mean interval of 17.4 years. The asphalt surfaces without a membrane have a mean interval of 17.3 years, while the asphalt surfaces with a membrane have a mean interval of 21.3 years. This again shows that the membrane has a positive effect on resisting deck deterioration. Polymer overlays as a population, have a mean interval of 13.7 years. Within this population, epoxy overlays and methyl methacrylate overlays have mean intervals of 14.6 years and 13.2 years respectively. There are not enough observations of ΔGCR 1 to calculate mean intervals for either polyester overlays nor concrete overlays with fly ash.

Summary of Findings for Cost Analysis of Treatments

Through an evaluation of average costs of the common treatments, concrete overlays are the most expensive treatment per square foot with an average 2015-adjusted cost of $14.51 per square foot. The next most expensive treatment population is asphalt overlays with an average 2015-adjusted cost of $8.24 per square foot. Polymer overlays are the least expensive treatment population with an average 2015-adjusted cost of $0.59 per square foot. Cost effectiveness of concrete overlays, asphalt wearing surfaces, and polymer overlays are $0.99 per square foot per year, $0.61 per square foot per year, and $0.06 per square foot per year respectively.

It is important to note that much of the cost data used for these analyses came from few sources. It is possible that the costs depend on region. Additionally, in the case of cost data from state DOT datasets, it is not clear if the cost data reported is material cost, “in-place” treatment cost, or project costs.

Future Work

Recommendations for future work include investigations with current information and investigations that could be performed with more information collected.

An investigation that could be performed with current information includes analyzing the effect of deck condition before treatment (GCR_{pre}).

In addition, with more information collected, future work recommendations include evaluating confidence intervals with respect to the computed mean intervals. This would require information on the consistency of GCR reporting from inspectors. Future work could also include collecting even more treatments to allow for a more diverse selection of analyzed treatments acquired from more diverse sources. Examination into the effect of different treatment application methods, for example comparing the polymer overlay broom and seed method and the slurry method, could be performed. This would require information of how each treatment was applied to the deck.

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Appendix

Table 18: NBI Item List

Item Code	Description
6	Features Intersected
7	Facility Carried by Structure
8	Structure Number
27	Year Built
49	Structure Length
52	Deck Width, Out-to-Out
58	Deck Condition Rating
90	Inspection Date

Table 19: ΔGCR 0 Weibull Parameters

ΔGCR 0	Mean Life Span (years)	a (years)	m (years)	γ	c0	c1	c2
All Concrete	9.2	0.9	8.69	1.13	0.00	1.13	0.01
Concrete, unmodified	6.6	0.9	6.13	1.28	0.00	1.28	-0.08
All Modified Concrete	16.2	0.0	17.72	1.36	0.00	1.36	0.05
Concrete, with Fly Ash	16.2	0.9	16.42	1.25	0.00	1.25	0.13
Concrete, Latex modified	19.4	0.8	19.48	1.14	0.00	1.14	0.01
Concrete, with Microsilica	15.2	0.9	15.21	1.21	0.00	1.21	0.13
All Asphalt Wearing Surfaces	13.4	0.9	14.07	1.92	0.00	1.92	0.20
Asphalt Wearing Surface, No Waterproofing Membrane	12.1	0.9	12.57	1.80	0.00	1.80	0.19
Asphalt Wearing Surface, with Waterproofing Membrane	16.9	0.0	19.10	2.29	0.00	2.29	0.17
All Polymer Overlays	10.3	0.5	11.11	2.07	0.00	2.07	0.00
Epoxy Overlay	8.9	0.8	8.92	1.40	0.00	1.40	0.01
Methyl Methacrylate Overlay	10.3	0.2	11.36	2.51	0.00	2.51	0.00
Polyester Overlay	11.6	0.8	12.00	1.54	0.00	1.54	0.00

Table 20: ΔGCR 1 Weibull Parameters

ΔGCR 1	Mean Life Span (years)	a (years)	m (years)	γ	c0	c1	c2
All Concrete	14.7	2.4	13.86	1.94	0.00	1.94	0.01
Concrete, unmodified	13.4	1.4	13.58	2.21	0.00	2.21	0.01
All Modified Concrete	23.3	2.9	23.03	2.14	0.00	2.14	0.24
Concrete, with Fly Ash	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Concrete, Latex modified	29.4	5.9	26.46	1.84	0.00	1.84	0.21
Concrete, with Microsilica	23.1	2.9	22.61	1.70	0.00	1.70	0.18
All Asphalt Wearing Surfaces	17.4	0.5	19.06	2.64	0.00	2.64	0.00
Asphalt Wearing Surface, No Waterproofing Membrane	17.3	0.4	19.01	2.64	0.00	2.64	0.00
Asphalt Wearing Surface, with Waterproofing Membrane	21.3	1.4	22.45	2.04	0.00	2.04	0.00
All Polymer Overlays	13.7	1.5	13.72	2.46	0.00	2.46	0.00
Epoxy Overlay	14.6	4.8	10.88	1.53	0.00	1.53	0.01
Methyl Methacrylate Overlay	13.2	0.0	14.80	3.02	0.00	3.02	0.19
Polyester Overlay	N/A	N/A	N/A	N/A	N/A	N/A	N/A