Protocols for Concrete Bridge Deck Protections and Treatments

Başak Bektaş
Ahmed Albughdadi
Katelyn Freeseman
Bahar Bazargani

Iowa State University
Minnesota State University, Mankato

WisDOT ID no. 0092-18-03

August 2020

RESEARCH & LIBRARY UNIT

WHRP

WISCONSIN HIGHWAY RESEARCH PROGRAM

WISCONSIN DOT
PUTTING RESEARCH TO WORK

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. WisDOT 0092-18-03	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Protocols for Concrete Bridge Deck Protections and Treatments		**5. Report Date** August 2020
		6. Performing Organization Code
7. Author(s) Başak Bektaş, Ahmed Albughdadi, Katelyn Freeseman, and Bahar Bazargani		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**10. Work Unit No.**
		11. Contract or Grant No. 0092-18-03
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation Research & Library Unit 4822 Madison Yards Way, Room 911 Madison, WI 53705		**13. Type of Report and Period Covered** Final Report October 2017–July 2020
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The main objective of this research project was to develop a cost-effective life-cycle treatment plan for the preservation of Wisconsin bridge decks. The research team identified a comprehensive list of strategies through a review of current practice and department of transportation (DOT) policies and provided data-driven estimates of the performance and ideal timing of treatments with respect to condition by analyzing historic bridge condition data from the Wisconsin DOT (WisDOT) and other state DOTs and by considering engineering economics principles.

The scope of work included, in part, a literature review and a survey of Midwest states on the selection, implementation, and performance of deck preservation treatments. Initial email surveys were followed up by phone interviews. Detailed findings from these efforts are presented in Appendix A of this report and earlier intermediary reports to WisDOT. The major task for this project was to gather an archive of deck overlay and sealant history for Wisconsin decks and analyze these data in conjunction with historic deck conditions. Similar but limited data sets from South Dakota and Minnesota were also analyzed for the same purpose. The most common deck treatment plans that were observed in the data set were contrasted both for performance and cost-effectiveness in order to identify the most cost-effective treatment options for different deck conditions and at different points throughout a deck's life cycle. To the authors' knowledge, the work presented is the most comprehensive data analysis on deck preservation treatment performance by a state agency.

Regardless of the treatment, treated decks have consistently lower life-cycle costs than untreated decks. Sealing and overlaying decks as early as possible in the life cycle lead to lower life-cycle costs. Multiple applications of deck seals are cost-effective, particularly on high-traffic corridors. The treatment plans with simulated life-cycle costs can be considered by state agencies as they develop deck preservation plans.

17. Key Words bridge deck treatments, bridge management, bridge preservation, deck overlay performance, deck treatment efficiency, life-cycle planning, penetrating sealers, sealer performance		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 117	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DISCLAIMER

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project 0092-18-03. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers' names appear in this report only because they are considered essential to the object of the document.

EXECUTIVE SUMMARY

Preservation of bridge decks has historically been achieved through various types of concrete overlays, asphalt concrete overlays, miscellaneous asphalt overlays, polymer overlays, deck replacement, deck sealers, and/or crack repairs. The selection of the appropriate maintenance technique varies widely, as does the timing of implementation. These methods are of critical importance in states with cold weather climates such as Wisconsin due to the regular use of deicing chemicals and their associated detrimental effect on deck reinforcement. The optimum method and corresponding timing of the installation, determined through a cost-benefit analysis of the resulting service life, are therefore important criteria to define.

The main objective of this research project was to develop a cost-effective life-cycle treatment plan for the preservation of Wisconsin bridge decks. The research team identified a comprehensive list of strategies through a review of current practice and department of transportation (DOT) policies and provided data-driven estimates of the performance and ideal timing of treatments with respect to condition by analyzing historic bridge condition data from the Wisconsin DOT (WisDOT) and other state DOTs and by considering engineering economics principles.

Another objective of the research was to validate current WisDOT practice and policies, whose effectiveness was confirmed by the findings, and recommend any necessary updates that will provide WisDOT with a cost-effective and long-term bridge preservation strategy. Data-driven findings on treatment efficiency and the life-cycle cost of deck treatments can help identify strategies that could be adopted by WisDOT and can validate other policies already in place.

The scope of work included, in part, a literature review and survey of Midwest states on the selection, implementation, and performance of deck preservation treatments. Initial email surveys were followed up by phone interviews. Detailed findings from these efforts are presented in Appendix A of this report and earlier intermediary reports to WisDOT. The major task for this project was to gather an archive of deck overlay and sealant history for Wisconsin decks and analyze these data in conjunction with historic deck condition. Similar but limited data sets from South Dakota and Minnesota were also analyzed for the same purpose. The most common deck treatment plans that were observed in the data set were contrasted both for performance and cost-effectiveness in order to identify the most cost-effective treatment options for different deck conditions and at different points throughout a deck’s life cycle.

The main findings from the study can be summarized as follows:

- The “do nothing” treatment plan (replace the deck at the end of its life) results in the highest overall equivalent uniform annual cost (EUAC). Any treated deck has a lower life-cycle cost and provides value to the agency and road users.
- Treating decks as early as possible in their life cycles leads to lower EUACs.
- The data set included a limited number of epoxy overlay applications at a National Bridge Inventory (NBI) General Condition Rating (GCR) of 8. It would be beneficial to revisit the time in state (TIS) data for thin polymer overlays applied at GCR 8 to properly contrast sealers and polymer overlays at GCR 8.

- For an average deck, sealing the deck early, at GCR 8, followed by another seal at GCR 7 results in a lower life-cycle cost. For decks that carry high volumes of traffic, bridge owners should consider applying sealers more frequently than for decks that carry lower volumes of traffic, since the findings indicate that sealers perform significantly differently at high traffic volumes than at low traffic volumes.
- Due to the limited number of cases with various frequencies of sealers at different traffic volumes, an ideal frequency of sealers cannot be recommended at this time. Additionally, comparing the EUACs of sealers at high and low traffic volumes is not meaningful, since maintenance decisions regarding decks in these two different environments are independent of each other. Therefore, we recommend that eligible concrete decks on bridges that carry an annual average daily traffic (AADT) of 15,000 or higher be sealed every three years. While current WisDOT policy recommends sealing decks every three to five years regardless of AADT, we recommend that this frequency be determined based on the AADT carried by the structure.
- Due to data limitations, it was not possible to properly contrast the cost-effectiveness of hot-mix asphalt (HMA) overlays with membrane and polymer-modified asphaltic (PMA) overlays with other treatment options.
- Some of the life-cycle profiles show decks that are in better condition overall throughout their life cycles. For example, thin polymer overlays are typically applied at GCR 8 or 7, while HMA overlays are typically considered for decks at lower GCRs. Therefore, the life-cycle cost findings presented here should be considered in conjunction with the asset performance measure targets of the agency. The treatment efficiency findings can be incorporated into agency bridge management systems to facilitate bridge-level decisions.
- Out of nine special treatment plan cases recommended by the WisDOT Bureau of Structures, Case 9 (sealing a deck at GCR 8, then at GCR 7, followed by two thin polymer overlays when the GCR drops to 7, a concrete overlay at GCR 6, and a seal at GCR 7) provides the most cost-effective option regardless of whether project or treatment costs are considered. We recommend the sequence of treatments in Case 9 as the deck preservation policy for Wisconsin decks, with more frequent seals at GCR 8 for high-AADT corridors when possible.
- Based on project costs, Case 8 (sealing a deck at GCR 8, then at GCR 7, followed by one thin polymer overlay when the GCR drops to 7, a concrete overlay at GCR 6, and a seal at GCR 7) is the second most cost-effective option. Therefore, if a second thin polymer overlay cannot be applied at GCR 7, we recommend a concrete overlay at GCR 6 followed by a seal at GCR 8 (frequency determined based on AADT). Based on treatments costs only, Case 5 (sealing a deck at GCR 8, then at GCR 7 and GCR 6, a concrete overlay at GCR 6, and a seal at GCR 7, followed by a second concrete overlay at GCR 5) is the second most cost-effective option. In cases where a thin polymer overlay cannot be applied, we recommend that decks be sealed at GCRs 8, 7, and 6, before applying a concrete overlay at GCR 6 and then a seal at GCR 8 (frequency determined based on AADT).

While limited data were available for some treatment options, the work described in this report yielded data-driven estimates of treatment efficiency for deck overlays and sealers. The simulated life-cycle costs for various life-cycle plans give insight into the most cost-effective strategies that could be adapted by WisDOT and potentially other Midwest agencies. The data analysis was enabled by the rich work history data collected by the WisDOT Bureau of

Structures and the individual regions. Continuation of this data collection effort at WisDOT is paramount for improving asset management practice and refining the bridge preservation policy further in future.

ACKNOWLEDGMENTS

The authors would like to thank the members of the project oversight committee (Ryan Bowers, Bill Oliva, Tim Borowski, Dominique Bechle, Philip Meinel, Anthony Stakston, and David Kiekbusch) for their insight and guidance throughout the project. The authors would also like to thank other Wisconsin Department of Transportation (WisDOT) and University of Wisconsin technical support personnel (Heidi Noble, Dante Fratta, Sabrina Bradshaw, and Jamie Valentine) for their input and efforts on the project. Many thanks are also due to WisDOT region engineers for communicating with the research team and sharing their data. Finally, the authors would like to thank Todd Thompson from the South Dakota Department of Transportation (SDDOT), David Hedeen, Sarah Sondag, and Paul Pilarski from the Minnesota Department of Transportation (MnDOT), and Danny X. Xiao from University of Wisconsin-Platteville for sharing their data.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Preservation of bridge decks has historically been achieved through various types of concrete overlays, asphalt concrete overlays, miscellaneous asphalt overlays, polymer overlays, deck replacement, deck sealers, and/or crack repairs. The selection of the appropriate maintenance technique varies widely, as does the timing of implementation. These methods are of critical importance in states with cold weather climates such as Wisconsin due to the regular use of deicing chemicals and their associated detrimental effect on deck reinforcement. The optimum method and corresponding timing of installation, determined through a cost-benefit analyses of the resulting service life, are therefore important criteria to define.

The main objective of this research project was to develop a cost-effective life-cycle treatment plan for the preservation of Wisconsin bridge decks. The research team identified a comprehensive list of strategies through a review of current practice and department of transportation (DOT) policies and provided data-driven estimates of the performance and ideal timing of treatments with respect to condition by analyzing historic bridge condition data from the Wisconsin DOT (WisDOT) and other state DOTs and by considering engineering economics principles.

Another objective of the research was to validate current WisDOT practice and policies, whose effectiveness was confirmed by the findings, and recommend any necessary updates that will provide WisDOT with a cost-effective and long-term bridge preservation strategy. Data-driven findings on treatment efficiency and the life-cycle cost of deck treatments can help identify strategies that could be adopted by WisDOT and can validate other policies already in place.

The scope of work included, in part, a literature review and survey of Midwest states on the selection, implementation, and performance of deck preservation treatments. Initial email surveys were followed up by phone interviews. Detailed findings from these efforts are presented in Appendix A of this report and earlier intermediary reports to WisDOT. The major task for this project was to gather an archive of deck overlay and sealant history for Wisconsin decks and analyze these data in conjunction with historic deck condition. Similar but limited data sets from South Dakota and Minnesota were also analyzed for the same purpose. The most common deck treatment plans that were observed in the data set were contrasted both for performance and cost-effectiveness in order to identify the most cost-effective treatment options for different deck conditions and at different points throughout a deck’s life cycle.

2. LITERATURE REVIEW

2.1 Background

With the extensive development of transportation infrastructure and the rapid growth in the use of automobiles in the late 1960s, the need for a systematic approach to maintenance and rehabilitation strategies for the transportation system was identified. This new perspective shifted the focus from design and construction to the maintenance and rehabilitation of existing facilities (Scherer and Glagola 1994). Bridges are an essential part of transportation infrastructure, making maintenance and rehabilitation of bridge decks an ongoing concern for DOTs throughout the United States (Krauss et al. 2009). Transportation agencies aim to extend the service lives of existing bridges through a combination of preventative maintenance and repair activities prior to replacement (Krauss et al. 2009).

During the last 10 years, research efforts have increasingly focused on maintenance planning optimization for deteriorating highway bridge systems. The goal of these efforts in academic research as well as research projects initiated by DOTs has been to improve the allocation of resources under severe financial constraints. As research focuses on minimizing life-cycle maintenance costs while maintaining bridges in a safe and serviceable condition, agencies continue to develop their own sets of guidelines based on agency practice and vision (Liu and Frangopol 2004, Krauss et al. 2009).

For this literature review, a number of studies related to the field of bridge deck maintenance were reviewed, and those that were applicable to this project are summarized herein. Because concrete bridge decks are by far the most commonly used deck type in the United States and are the focus of this research project, the review focuses on concrete decks (Krauss et al. 2009). Especially in northern states that get heavy snow during winter months and where deicing salt is used to provide safe travel to road users, concrete bridge decks deteriorate rapidly due to the penetration of corrosive chlorides into the deck. Therefore, for northern states such as Wisconsin, it is critical to identify and implement the most cost-effective treatment strategies as part of bridge preservation programs. This initial literature review looks at current practice by presenting the major findings from national-level studies. Because the following chapter focuses on the policies of Wisconsin and other states, agency policies are covered minimally in this chapter to avoid duplication.

2.2 Bridge Deck Repair and Maintenance

As reported by a National Cooperative Highway Research Program (NCHRP) project that reviewed and surveyed agency practice in the United States, preservation actions are typically based on deck characterization (i.e., the condition of the existing deck and the deck material) while also taking into account the expected future performance of the deck. Several factors have an impact on the deck characterization process (Krauss et al. 2009):

- Percent Deck Deterioration and National Bridge Inventory (NBI) General Condition Rating (GCR) – Percent deck deterioration is the percent of non-overlapping areas on the deck that exhibit patches, spalls, delamination, and copper sulfate half-cell potentials lower than -0.35 V, and NBI condition rating is based on an examination of the top and bottom deck surfaces.

- Estimated Time to Corrosion – This is expressed as the estimated time until sufficient chloride penetration occurs to initiate corrosion in a given percentage of the reinforcing steel.
- Deck Surface Condition – This indicates whether the deck surface is exhibiting poor drainage, surface scaling, abrasion loss, or skid resistance problems.
- Concrete Quality – This is related to concrete durability (in terms of alkali silica reaction [ASR], delayed ettringite formation [DEF], and freeze-thaw resistance) and strength issues.

Other factors are also influential when selecting the repair material and technique. Site conditions such as traffic constraints, dead load or overhead limitations, anticipated service life, general exposure conditions, application constraints, previous repairs, skid resistance, concrete cover, reinforcement type, contractor experience, planned future work, special conditions, and costs influence the repair decision (Krauss et al. 2009).

In addition to all the characteristics noted above, a possible future deck replacement should also be taken into consideration. Even though the general objective of a maintenance program is to keep the bridge deck in service for as long as reasonably possible at the lowest annual cost, sometimes it is best to perform minimal repair and maintenance. For instance, if a deck is to be replaced within approximately 10 years, the most economic decision could be to only plan for the minimum maintenance. Therefore, during the decision-making process it is important to consider the plan for the deck over the next 10 to 15 years. If a deck replacement is planned, then minimally maintaining the deck until replacement is sufficient (Krauss et al. 2009).

After quantifying the state of the deck and considering other factors, a primary repair decision must be made. Possible decisions are generalized as follows (Krauss et al. 2009):

1. Do nothing
2. Perform maintenance, which may include the following:
   a. Patching
   b. Crack repairs
   c. Concrete sealer application
3. Apply a protective overlay
4. Perform structural rehabilitation, which may include the following:
   a. Partial deck replacement
   b. Full-depth deck replacement

One common manifestation of damage in bridges is transverse cracking. Transverse cracks start to develop on concrete bridge decks shortly after construction. These cracks increase the speed of corrosion in the reinforcing steel and thereby cause deterioration in the concrete, which leads to damaged components beneath the deck and an unsightly appearance (Krauss and Rogalla 1996). This deterioration is particularly severe when black reinforcing bars are used (FHWA 2018). This damage caused by transverse cracking results in decreased service life and increased maintenance costs (Krauss and Rogalla 1996). In addition, transverse cracking can lead to concrete spalling at intersections with non-transverse cracks (FHWA 2018). In a survey of US transportation agencies by Krauss and Rogalla (1996), 52 US DOTs and other transportation agencies reported the status of a total of 225,000 bridges. The responses indicate that an average of 52% of decks suffer from transverse deck cracking (Krauss and Rogalla 1996). Moreover, 15% of all agencies also reported that 100% of their decks are experiencing transverse deck cracking. Deck cracking grows more aggressive over time and is not confined to one geographic or climatic location (Krauss and Rogalla 1996).

Sealers and overlays are two methods to treat bridge deck deficiencies. By sealing the deck surface from aggressive chloride solutions and reducing the impact of aging and weathering, overlays significantly increase the life of the deck (FHWA 2018). The guideline in the most recent NCHRP study for selection of bridge deck overlays, sealers, and treatments (Krauss and Rogalla 1996) suggests installation of an overlay for decks with little to moderate deterioration that are likely to have more deterioration in future. As such, overlays are used when the deck is not in need of immediate replacement. It can also be advantageous to use overlays when the traffic on the bridge is very high, because in such cases it is expensive and very disruptive to replace the deck using typical staged construction. On the other hand, for bridges in rural areas that experience low traffic volumes, the cost and disruption resulting from deck replacement should be compared to the value gained by installing an overlay.

Bonded overlays improve deck surface features such as cross-slope and grade, joint transitions, drainage, abrasion resistance, skid resistance, or scaling by providing the deck with a new wearing surface. Existing cracks in the bridge deck rarely reflect directly through a new bonded overlay. Since the deck is thickened with the addition of the overlay, structural capacity is also improved as a result. In order to prevent additional dead load, thin overlays can also be used, or a portion of the concrete cover can be milled prior to placing the overlay (Krauss and Rogalla 1996).

Because the use of an overlay may result in the longest service life for the least cost, new decks may also be candidates for overlays. Another benefit of overlays is that decks can be overlaid several times, as long as the base deck remains in generally good condition and there is sufficient concrete cover to avoid damaging the top mat of reinforcement during the removal of the overlay by milling of the deck surface (Krauss and Rogalla 1996).

The WisDOT *Structures Inspection Field Manual* currently lists the following bridge deck overlays in the inventory: asphaltic concrete (AC) overlays, AC overlays with membrane, thin polymer overlays, concrete (rigid) overlays, and polyester concrete overlays (Wisconsin DOT 2020). A low-slump concrete overlay, also referred to as a concrete overlay, is comprised of low-slump Grade E concrete and has a 1½-inch minimum thickness (Wisconsin DOT 2020). An AC overlay is used when the existing pavement is still structurally sound but needs better skid resistance, drainage, or other functional improvements (Habbouche et al. 2016). A thin polymer overlay, while it has a lower life expectancy than a rigid overlay, imposes less deadweight than a concrete overlay and can be more rapidly applied (Tabatabai et al. 2016). A polyester concrete overlay varies from ¾ to 12 in. in thickness, has a sealer primer that fills cracks, and is expected to last for 30 years (KwikBond Polymers 2020). These overlay options vary in expected life, the time required for installation, and expected benefits. The differences among these overlay options bring variability in their costs and benefits from a bridge preservation perspective. As new technologies are introduced into the bridge preservation field, it becomes critical for agencies to assess the performance of different options on their networks to make well-informed decisions.

Penetrating sealers, such as silane, are also commonly used on bridge decks. Based on the responses to the survey of US transportation agencies by Krauss and Rogalla (1996), the estimated mean service life of sealers varies from 4 to 10 years. Sealers minimize the deterioration of superstructure and substructure elements beneath the joints (FHWA 2018). They also reduce the permeability of concrete to deicer chemicals (Krauss and Rogalla 1996). Therefore, it is advised that sealers be used when the level of chloride at the bar depth is below or not greatly in excess of the threshold for corrosion (about 0.03% by weight of concrete or 0.2% by weight of cementitious content for black steel) and the concrete has high to moderate permeability, such that the sealer will substantially improve the resistance of the concrete to chloride ingress. The chloride diffusion coefficient is a factor that helps determine sealer applicability and can be found through core samples and chloride profile tests. A sealer is recommended if the chloride diffusion coefficient of the concrete is greater than about 0.1 in.^{2}/year ($2.0\text{x}10^{-12}$ m^2/s) and the chloride exposure is more than minor.

Even if the abovementioned criteria for sealers are met, it might be reasonable to use overlays instead of sealers in certain situations. For example, if the concrete has a high chloride content just above the level of the steel and corrosion is expected within the next 10 years, removing the chloride-contaminated concrete and placing an overlay may be a better option to greatly extend the deck's service life. An overlay may also be more appropriate than a sealer for a concrete deck having very low permeability because the sealer will have minimal effect (Krauss and Rogalla 1996).

The WisDOT *Bridge Preservation Policy Guide* gives a detailed account of the preservation activities currently used by the agency (Wisconsin DOT 2016). The deck preservation guidelines are summarized in Table 2-1.

Table 2-1: WisDOT bridge deck preservation guidelines

Bridge Preservation Type	Activity Description	Preventive Maintenance Type	Action Frequency (Years)
Preventive Maintenance	Deck Sealing/Crack Sealing	Cyclical	4–5
	Thin Polymer (Epoxy) Overlay		10
	Asphalt Overlay with Membrane	Condition Based	12–15
	Polymer-Modified Asphalt Overlay		6–12
Repair or Rehabilitate Element	Rigid Concrete Overlay	Condition Based	As needed
	Structural Reinforced Concrete Overlay		

2.3 Bridge Preservation Program

Maximizing the useful life of bridges in a cost-effective way is generally the main goal of any bridge preservation program. The Moving Ahead for Progress in the 21st Century Act (MAP-21) advocates the goal of maintaining or preserving infrastructure assets "in a state of good repair." The Federal Highway Administration (FHWA) defines "state of good repair" as when bridges are functioning as designed and are sustained through regular maintenance, preservation, and replacement programs. Preserving an asset also meets the requirements of a cost-effective transportation investment strategy. WisDOT has developed asset management goals that not only are in line with MAP-21 legislation but also address the priorities of the agency and its stakeholders (Wisconsin DOT 2016).

The goals of the WisDOT Bridge Preservation Program are as follows:

- Maintain bridges in a "state of good repair" using low-cost, effective strategies
- Implement timely preservation treatments on structurally sound bridges to promote optimal life-cycle costs and extend service life, thereby reducing the need for major rehabilitation and replacement
- Limit the adverse impacts that deteriorating bridges might have on traffic operations and various stakeholders
- Promote and support budgeting of preventive maintenance activities
- Establish performance goals and monitor progress related to the preservation of bridges
- Optimize the benefits and effectiveness of long-term maintenance investment in achieving bridges in good condition

The FHWA defines preservation/preventive maintenance activities in its *Bridge Preservation Guide* (FHWA 2018) as "actions or strategies that prevent, delay, or reduce deterioration of bridges or bridge elements; restore the function of existing bridges; keep bridges in good or fair condition; and extend their service life." As a result of preservation activities, deterioration is delayed but the bridge elements or components are not necessarily improved. Agency rules that specify preservation actions may be cyclical (e.g., seal decks every three to five years) or condition based (e.g., apply an epoxy overlay when a deck's GCR is at least 7).

The literature suggests epoxy overlays for the treatment of deteriorating bridge decks in Midwestern and Northeastern states. A 1½ in. thick Type E overlay is placed on top of concrete bridges decks to address cracking and debonding in Wisconsin (Tabatabai et al. 2010). The Michigan Department of Transportation (MDOT) uses epoxy-based sealers and overlays as a fast, cost-effective, and long-lasting treatment that has extended the life of Michigan's structures (DeRuyver and Schiefer 2016). The Illinois Department of Transportation (IDOT) uses the desired overlay lifespan, average daily traffic (ADT) levels, stopping condition, and construction duration as parameters to select the overlay type (Illinois DOT 2011). The guidelines for Illinois are shown in Table 2-2.

Table 2-2: Bridge deck overlay selection guidelines in Illinois

Lifespan < 12 years ADT < 10,000	Lifespan < 12 years ADT ≥ 10,000	Lifespan ≥ 12 years ADT < 3,000	Lifespan ≥ 12 years ADT ≥ 3,000
• HMA w/coal tar membrane • HMA w/sheet membrane	• Fly ash GGBFS CO • Microsilica CO • HRM CO • Latex CO • Thin Polymer Overlay	• HMA w/coal tar membrane • HMA w/sheet membrane	• Fly ash GGBFS CO • Microsilica CO • HRM CO • Latex CO • Thin polymer overlay

The Minnesota Department of Transportation (MnDOT) states that if more than 15% of concrete deck or slab elements are in condition states 3 or 4, the appropriate preservation activity should be selected based on bridge deck age, traffic volume, and condition. These categories are shown in Table 2-3.

Table 2-3: Preservation activity selection guidelines in Minnesota

Condition Category	Percent of Unsound Deck Area	ADT less than 2,000	ADT between 2,000 and 10,000	ADT greater than 10,000 and Interstates
Moderate Deterioration	2% to 10% SIMS* Deck Condition State 3	Mill and Patch	Mill and Patch	Mill and Patch or Re-Overlay
Severe Deterioration	10% to 25% SIMS Deck Condition State 4	Deck Repairs, 100% Scarify and Add Overlay	Deck Repairs, 100% Scarify and Add Overlay	Deck Repairs, 100% Scarify and Add Overlay
Critical Deterioration	> 25% SIMS Deck Condition State 5	Deck Repairs, 100% Scarify and Add Overlay	Schedule New Deck	Schedule New Deck

Source: MnDOT 2015

*SIMS: Structure Information Management System

2.4 Summary

As gathered from the literature review, sealers are typically advised to be applied every three to five years, while overlays are typically advised to be used at varying frequencies depending on the material or based on condition. Different types of each can be used, and guidelines for their selection and application vary by agency. Common criteria used in selecting the overlay type are ADT, expected life, and current condition of the bridge deck (or level of deterioration). Weather conditions and the level of chloride observed in the bridge deck are essential factors for deciding the sealant type.

The goal of all preservation plans is to determine the most beneficial repair and maintenance methods to prolong the service life of concrete bridge decks while maintaining cost and time efficiency. To achieve this goal, it is critical to make maintenance decisions based upon key deck characteristics such as the condition of the existing deck, future rehabilitation plans, and desired long-term performance. Most of the findings in the literature and strategies currently used by transportation agencies depend on expert elicitation and experience. As new products and techniques become available, agencies test and utilize them in their bridge preservation programs. Therefore, tracking the performance of new products and technologies and sharing the experience on agency websites, in meetings, and through partnerships such as the Transportation System Preservation Technical Services Program (TSP2) Bridge Preservation Partnership Program are critical for keeping bridge preservation programs up to date.

3. REVIEW OF AGENCY PRACTICE IN MIDWEST STATES

The project team gathered information from Midwest states on their policies and practices regarding deck sealers and overlays. Findings from the review of agency policy documents and interviews with state DOT contacts on preservation policies and performance expectations for deck sealers and overlays are included in Appendix A.

The project team reached out to Midwest Bridge Preservation Partnership (MWBPP) states (Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, and Wisconsin) to examine regional policies and performance expectations regarding bridge deck preservation treatments. The project team identified and contacted DOT engineers in 13 Midwest states (specifically, all 14 MWBPP states except Wisconsin) by phone or email to gather information on their policies and experience regarding deck preservation treatments. Agencies were also asked to note any relevant lessons learned from the application of these treatments. Responses were received from 10 of the 13 states contacted (Table 3-1).

Table 3-1: Agency contacts

State	Main Contact
Illinois (IDOT)	Sarah Wilson
Indiana (INDOT)	Bill Dittrich
Iowa (Iowa DOT)	Ping Lu
Kansas (KDOT)	Don Whisler
Michigan (MDOT)	Brandon Boatman
Minnesota (MnDOT)	Sarah Sondag
Nebraska (NDOT)	Fouad Jaber
North Dakota (NDDOT)	Nancy Huether
Oklahoma (ODOT)	Walt Peters
South Dakota (SDDOT)	Todd Thompson

Figure 3-1 shows the nine responding states that neighbor Wisconsin and the types of overlays used in them. An Excel file that summarizes and compares the agency policies and the frequency of application and triggers for the overlays used by neighboring states was submitted to the project oversight committee (POC) as part of an intermediary report.

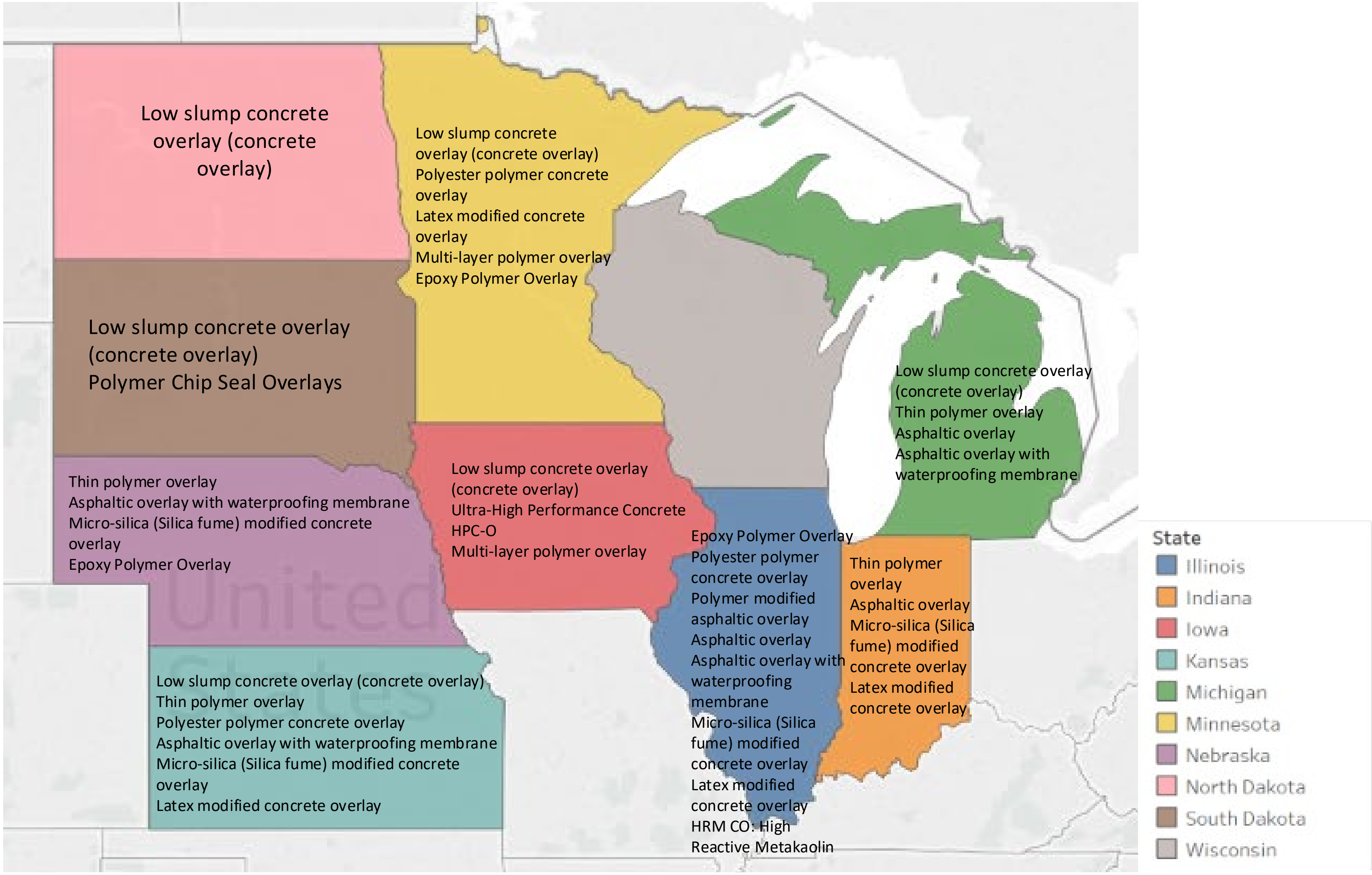


Figure 3-1: Types of overlays used in Wisconsin’s neighboring states

4. TREATMENT EFFICIENCY ANALYSIS

4.1 Wisconsin Data Analysis

An archive of overlay and sealant history for Wisconsin bridge decks was gathered, and the data were analyzed in conjunction with historic deck condition data. Two analyses were conducted: one involving element condition data and one involving general condition ratings.

4.1.1 *Analysis with Bridge Element Condition Data*

For this analysis, element condition data for Wisconsin bridge decks were combined with the decks' sealer and overlay treatment histories. The objective of the analysis with element condition data was to estimate Markovian transition probability matrices for deck and wearing surface elements to determine whether deck overlays increased the median number of years for the deck to transition from one condition state to another. This section covers the steps involved in gathering the data required for analysis, summarizes the required statistics, and describes the efforts involved in estimating Markovian deterioration models using the data.

4.1.1.1 Data Preparation

Wisconsin Highway Structures Information System (HSIS) data show 11 different types of bridge decks that are inspected by WisDOT and that appear in WisDOT's inventory. These 11 deck types and their share of inspection data in the sample are shown in Table 4-1.

Table 4-1: Different decks inspected by the WisDOT, share of total inspections

Element number	Element description	Count (all)	Count (CoRe inspection)	Count (AASHTO inspection)
12	Reinforced Concrete Deck	33,007	11,010	21,997
13	Prestressed Concrete Deck	40	0	40
15	Prestressed Concrete Top Flange	599	0	599
16	Reinforced Concrete Top Flange	88	0	88
28	Steel Deck with Open Grid	392	95	297
29	Steel Deck with Concrete Filled Grid	129	35	94
30	Steel Deck with Corrugated/Orthotropic	15	0	15
31	Timber Deck	929	224	705
38	Reinforced Concrete Slab	13,645	4,519	9,126
54	Timber Slab	1,829	503	1,326
60	Other Material Deck	14	0	14

On April 3, 2014, Wisconsin started using the new American Association of State and Highway Transportation Officials (AASHTO) element inspection methodology, moving from Commonly Recognized (CoRe) elements to new AASHTO elements. For this analysis, the data were analyzed separately for the two inspection methods. Table 4-1 shows that reinforced concrete (RC) decks and slabs have the highest number of inspections.

Based on the number of inspection observations by element, the project team initially focused on the most common RC deck and RC slab elements for the data analysis, since they provide a sufficient number of observations and dominate the inventory. The HSIS data for bridges was given for inspection years 2011 through 2018. Among the 291,330 inspection records for all bridges, 73,924 were blanks (25.37% of the records), which typically indicated defect or protective system placeholders, as shown in Table 4-2.

Table 4-2: Elements with placeholders

Element number	Element description	Number of blank inspections
520	Other Rebar Protective System	11
1000	Corrosion	130
1010	Cracking	130
1020	Connection	130
1080	Delamination/Spall/Patched Area	15,521
1130	Cracking (RC)	15,525
1140	Decay/Section Loss	726
1150	Checks/Shakes/Cracks/Splits/Delamination	726
1180	Abrasion/Wear (Timber)	15,954
3210	Debonding/Spall/Patched Area/Pothole	10,428
3220	Crack (Wearing Surface)	1
3600	Effectiveness – Protective System	13,683
8522	Coated Reinforcing	92
8523	Stainless Steel Reinforcing	3
8525	Black Steel Reinforcing	138

These blank records were excluded. The number of observations with defect inspections are shown in Table 4-3.

Table 4-3: Complete defect element inspections

Element number	Element description	Number of complete inspections
520	Other Rebar Protective System	1
1000	Corrosion	274
1010	Cracking	107
1020	Connection	135
1080	Delamination/Spall/Patched Area	20,538
1130	Cracking (RC)	27,710
1140	Decay/Section Loss	1,278
1150	Checks/Shakes/Cracks/Splits/Delamination	1,422
1180	Abrasion/Wear (Timber)	1,052
3210	Debonding/Spall/Patched Area/Pothole	22,082
3220	Crack (Wearing Surface)	26,593
3600	Effectiveness – Protective System	246
8522	Coated Reinforcing	9,697
8523	Stainless Steel Reinforcing	12
8525	Black Steel Reinforcing	249

Once the placeholders were removed, the remaining records were then checked for the number of complete inspections available for each element. The number of inspections, particularly the number of inspection pairs, is important when estimating Markovian deterioration models. Only a sufficient number of observations of inspection pairs can facilitate the estimation of transition matrices. In order to form inspection pairs, each bridge and element must have at least two inspections at different times (e.g., inspection data from a 2016 inspection and from a 2018 inspection). Out of 12,770 bridges, 12,305 (i.e., 96.37%) had at least two sets of inspections. However, due to the change in the element inspection methodology, the inspection data were divided into CoRe and AASHTO data sets. There are 3,260 RC decks and slabs inspected according to CoRe elements and 11,130 RC decks and slabs inspected according to AASHTO elements.

Based on the HSIS data, 14,390 RC decks and slabs could be assessed for further analyses. These data formed 2,795 inspection pairs for RC decks and 805 inspection pairs for RC slabs in the CoRe element data set and 4,436 inspection pairs for RC decks and 5,262 inspection pairs for RC slabs in the newer AASHTO element data set. As previously explained, the data were processed in multiple steps in order to be used for further analysis. The reduced data set is referred to as “useful inspections” in the following sections (Table 4-4).

Table 4-4: Useful decks for analysis, share of total bridges (AASHTO and CoRe elements)

Element number	Element description	Share of useful inspections	Count of inspections
12	Reinforced Concrete Deck	62.84%	8,081
13	Prestressed Concrete Deck	0.12%	16
15	Prestressed Concrete Top Flange	1.77%	227
16	Reinforced Concrete Top Flange	0.30%	39
28	Steel Deck with Open Grid	0.40%	52
29	Steel Deck with Concrete Filled Grid	0.21%	27
30	Steel Deck with Corrugated/Orthotropic	0.03%	4
31	Timber Deck	1.63%	209
38	Reinforced Concrete Slab	29.11%	3,743
54	Timber Slab	3.53%	454
60	Other Material Deck	0.06%	8

4.1.1.2 Markovian Deterioration Model

A Markovian transition probability matrix is a normalized non-negative square matrix that shows the transition in bridges from one condition state to another. The transition probability matrices described in this report were estimated using the process described by Thompson et al. (2012). This process is as follows:

- The first step in developing a Markov model is preparing the observations by specific elements.
- The second step is forming the inspection pairs. The important aspect to note when forming the inspection pairs is their length (duration). Each inspection pair is formed by two subsequent inspection events. The percentages of an element in condition states 1 through 4 for the first and second inspections form a pair. The change in these percentages between the two inspection events are used to determine the rate of change in condition state. Therefore, the time difference between pairs must be uniform in length. Since typical subsequent inspections are two years apart, the majority of the data set included such inspection pairs (e.g., inspections in 2012 and 2014). There were, however, exceptions. If two inspections were closer than 21 months or farther than 27 months apart, they were excluded from the analysis.
- Next, the pairs for which corrective actions had been performed between the first and second inspections are removed from the deterioration model. This elimination can be done by either checking the records of past activities or looking for improvements in the element's condition state.
- Ultimately, the transition probabilities are calculated with a linear regression. The analysis results in a Markovian deterioration matrix.
- The final step is to determine the life expectancy from the Markov deterioration model using the following equation:

$$t = \frac{\log(0.5)}{\log(p_{jj})}$$

In the equation, t is the life expectancy of the element, which states the number of years that it takes for the element to transition to a lower condition state. p_{jj} is the diagonal of the Markovian transition matrix. An important note regarding the life expectancy is that t is expressed in terms of the inspection intervals. For instance, since the inspection interval is two years in our case, in order to determine the actual life expectancy, t should be multiplied by 2.

Among all the inspections, the project team chose the three elements with the highest share of inspections for Markovian analysis. These wearing surfaces—wearing surface (bare), AC overlay, and concrete overlay—are highlighted in Table 4-5.

Table 4-5: Wearing surface types

Element number	Wearing surface
510	Wearing Surfaces (Other)
8000	Wearing Surfaces (Bare)
8511	AC Overlay
8512	AC Overlay with Membrane
8513	Thin Polymer Overlay
8514	Concrete Overlay
8515	Polyester Concrete Overlay

The number of inspections for different wearing surfaces and their shares are shown in Table 4-6 and Table 4-7.

Table 4-6: Number of inspections for wearing surfaces by year and element number

Year	No. 510	No. 8000	No. 8511	No. 8512	No. 8513	No. 8514	No. 8515	Total
2011		2,027	254	183	85	626		3,175
2012		6,179	1,894	291	179	709		9,252
2013	1	2,085	299	178	115	592		3,270
2014	65	7,236	2,296	349	294	1,013	3	11,256
2015	47	3,455	1,301	211	301	862		6,177
2016	89	6,913	2,034	281	365	1,070	4	10,756
2017	35	3,259	921	171	341	861	3	5,591
2018	8	165	72	19	6	64		334
Total	245	31,319	9,071	1,683	1,686	5,797	10	49,811

Table 4-7: Share of inspections for wearing surfaces by year and element number

Year	No. 510	No. 8000	No. 8511	No. 8512	No. 8513	No. 8514	No. 8515	Total
2011	0.00%	4.07%	0.51%	0.37%	0.17%	1.26%	0.00%	6.37%
2012	0.00%	12.40%	3.80%	0.58%	0.36%	1.42%	0.00%	18.57%
2013	0.00%	4.19%	0.60%	0.36%	0.23%	1.19%	0.00%	6.56%
2014	0.13%	14.53%	4.61%	0.70%	0.59%	2.03%	0.01%	22.60%
2015	0.09%	6.94%	2.61%	0.42%	0.60%	1.73%	0.00%	12.40%
2016	0.18%	13.88%	4.08%	0.56%	0.73%	2.15%	0.01%	21.59%
2017	0.07%	6.54%	1.85%	0.34%	0.68%	1.73%	0.01%	11.22%
2018	0.02%	0.33%	0.14%	0.04%	0.01%	0.13%	0.00%	0.67%
Total	0.49%	62.88%	18.21%	3.38%	3.38%	11.64%	0.02%	100.00%

The Markovian deterioration analyses were done for RC decks and slabs for both the CoRe and new AASHTO element data sets. Once the inspection pairs were divided between the CoRe and AASHTO element data sets, and then further divided between transitions in condition state from 1 to 2, 2 to 3, and 3 to 4, the numbers of observations were not sufficient for model estimation. As a result, the Markovian deterioration analyses were not conclusive, and any models that could converge were misguiding rather than guiding. The initial findings were presented to the POC. The POC and the project team mutually agreed that element condition data analyses should not be pursued for the remaining tasks of the project.

4.1.2 *Analysis with General Condition Ratings*

The scope for the analysis described in this section was to correlate alternative DOT preservation strategies and policies to historic NBI GCRs, with the objective of developing data-based estimates of treatment performance. The analysis in this section utilized NBI data, Long-Term Bridge Performance (LTBP) program data, deicer usage data, snowfall data, and traffic data to obtain a thorough assessment of deck and treatment performance.

Although historic GCR data provided the best data set for the purposes of this analysis, there are limitations in associating performance solely with GCR. GCR has an ordinal scale, which is quite subjective (Bektas 2011). Deck ratings from different inspectors may be within +/- 1 of each other. The subjective variability in the ratings also impacts any attempt to estimate the time a bridge deck spends in a specific rating if there is an unexplained drop or increase in the rating at the next inspection. While GCR has a 0 through 9 scale, only levels 3 through 8 are realistically used and comprise most of the observations. This leads to a six-level ordinal and qualitative assessment of condition. Also, most preservation treatments, such as sealers for decks or paint for steel elements, do not lead to a condition improvement in terms of GCR. A methodology more focused on evaluating element condition, which would tie separate elements to the preservation treatments and provide quantitative condition assessment, promises an improved data set to capture treatment performance in the future.

An application that imports a series of NBI files and creates a time series of any NBI variable such as bridge component condition or ADT was utilized for the GCR analysis. The application also calculates the time spent in a specific GCR throughout the available inspection history. This time spent is referred to as time in state (TIS). The same application was utilized to analyze the historic NBI data provided by the Minnesota and South Dakota DOTs. The analyses for these states are presented in subsequent sections of this chapter.

The damaging impact of deicing chemicals on deck reinforcement triggers faster deck deterioration in areas such as the Midwest, which experiences cold winters and significant snowfall. Ideally, external factors such as climatic conditions and traffic volume should be accounted for in order to accurately compare the efficiency of treatment strategies. The analysis in this research therefore explored correlations between TIS and external variables such as snowfall and traffic volume to assess treatment efficiency across different environments. To define external factors for bridge locations, available maps, and data from the National Oceanic and Atmospheric Administration and local agencies were used to develop geographic information System (GIS) datasets.

4.1.2.1 Data Sources

Data for the Wisconsin analyses were gathered from the following sources:

- LTBP data from 2019 (for data checks after processing the NBI data)
- NBI data from 1992 through 2017
- Wisconsin HSIS data:
  - Construction history
  - Deck maintenance history
- Treatment data via regional maintenance data collected by regions
- Data on additional factors:
  - Annual average daily traffic (AADT)
  - Truck AADT
  - Storm report data from 2017
  - Automatic vehicle location (AVL) deicer data (if available, for the most recent year)

4.1.2.2 Data Processing

The LTBP data indicate that there are 5,278 state-owned structures (bridges and culverts) in Wisconsin, 4,535 of which are bridges with concrete decks. The locations of these bridges are provided in Figure 4-1.

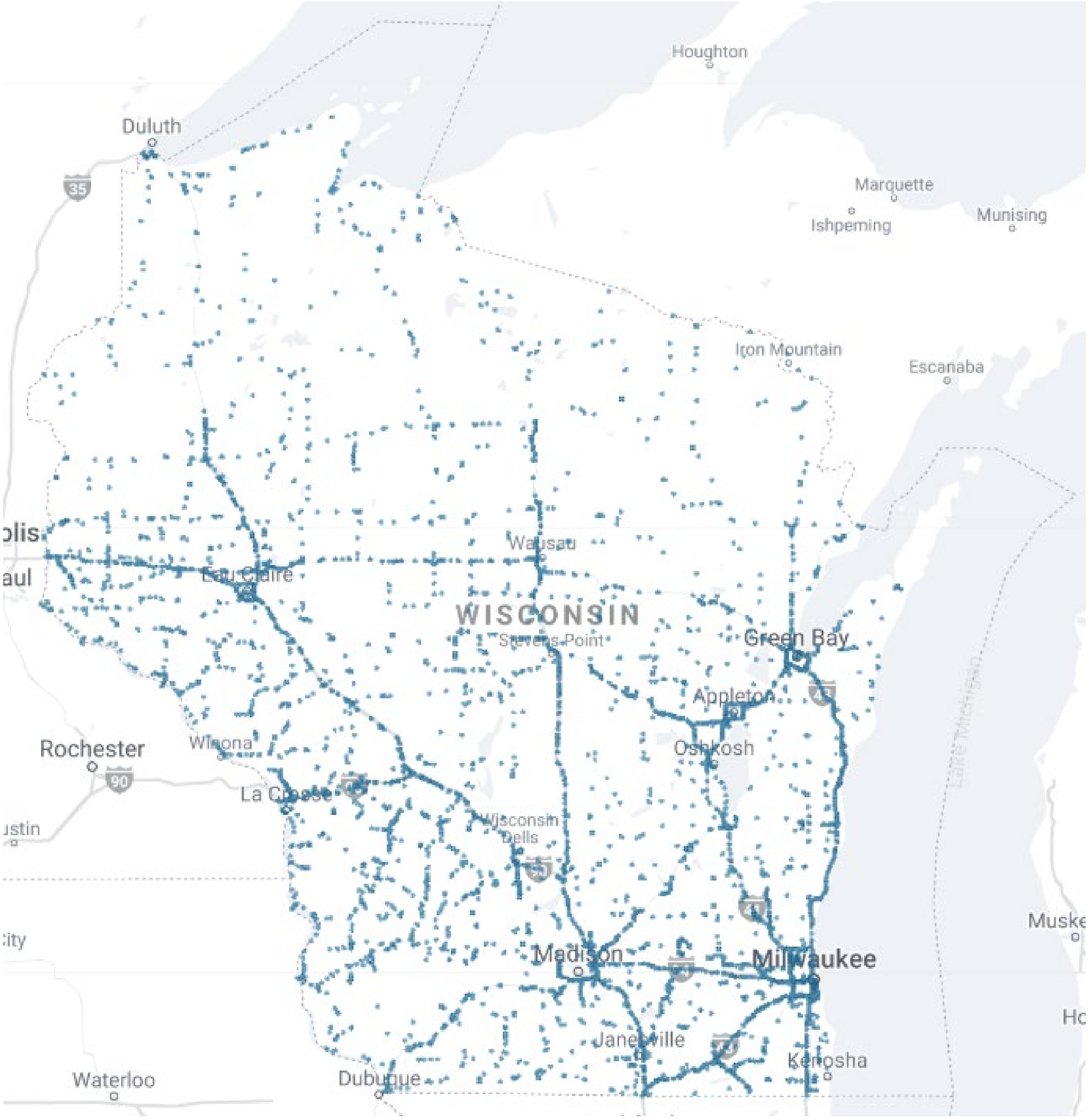
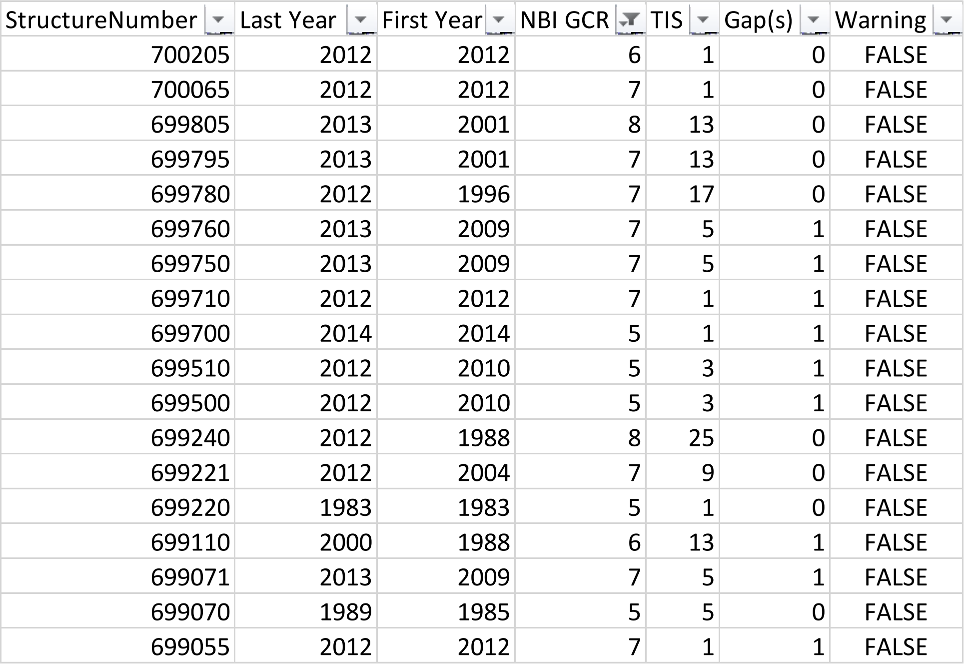


Figure 4-1: Wisconsin bridge locations

The application mentioned above was used to produce the TIS observations, which describe the time a bridge remains in a specific GCR before it changes to another GCR. The application algorithm imports NBI files and creates TIS observations for each structure and each different GCR in its life cycle. The resulting data sets give the time series of GCRs and the time spent in each observed deck GCR (NBI Item 58) during the available inspection years. Figure 4-2 shows a screenshot of a deck TIS file.



StructureNumber	Last Year	First Year	NBI GCR	TIS	Gap(s)	Warning
700205	2012	2012	6	1	0	FALSE
700065	2012	2012	7	1	0	FALSE
699805	2013	2001	8	13	0	FALSE
699795	2013	2001	7	13	0	FALSE
699780	2012	1996	7	17	0	FALSE
699760	2013	2009	7	5	1	FALSE
699750	2013	2009	7	5	1	FALSE
699710	2012	2012	7	1	1	FALSE
699700	2014	2014	5	1	1	FALSE
699510	2012	2010	5	3	1	FALSE
699500	2012	2010	5	3	1	FALSE
699240	2012	1988	8	25	0	FALSE
699221	2012	2004	7	9	0	FALSE
699220	1983	1983	5	1	0	FALSE
699110	2000	1988	6	13	1	FALSE
699071	2013	2009	7	5	1	FALSE
699070	1989	1985	5	5	0	FALSE
699055	2012	2012	7	1	1	FALSE

Figure 4-2: Example of output from TIS application

For each different GCR that was encountered during the life cycle of a structure and that could be captured with the available NBI data files, the algorithm records the first and last year of inspection with that GCR and the TIS in that GCR.

After the deck TIS files were processed, the treatments applied to the bridges were extracted from the HSIS data and regional maintenance data acquired from region engineers. The treatment data obtained from both sources were then compared to identify any duplicates. At this step, occasional questions were directed to WisDOT engineers so that the research team could better understand the data and process the data set accurately.

The data were then processed to ensure the proper association of condition and treatment data. Ideally, an increase in NBI condition should only be observed when an improvement is made through a treatment. Bridges with an increase in NBI deck condition with no recorded treatment were excluded from the data set, since they would otherwise provide an incorrect reference. Additionally, TIS observations that were higher than the third quartile (Q3) but that could not be associated with a recorded treatment were investigated. These observations typically overlapped with those regions where limited or no maintenance history could be provided. Since these observations could not be linked to maintenance records due to their unavailability and would provide an incorrect reference to untreated decks, these TIS observations (totaling 853) were also excluded from the data set. TIS observations for which deck GCRs were less than 4 (GCRs 3, 2, 1, and 0) were also excluded because there were very few observations with these GCRs.

4.1.2.3 Analysis for Treatment Impacts

Different types of treatments were identified from the HSIS and regional maintenance data, as shown in Table 4-8.

Table 4-8: Major Wisconsin deck treatments (initial list)

Major Rehabilitation	**Major Treatment**	**Minor Treatment**
New Deck	Deck Overlay	Sealants
New Superstructure	OVERLAY - BITUMINOUS	
New Substructure	OVERLAY - CONCRETE	
Deck Replacement	OVERLAY - CONCRETE - NEW JOINTS	
Rehabilitation	OVERLAY - CONCRETE - NEW RAIL & JOINTS	
Reconstruction	OVERLAY - CONCRETE - NEW RAIL & JOINTS.NEW SUPERSTRUCTURE	
	OVERLAY - CONCRETE - NEW RAIL & JOINTS>OVERLAY - EPOXY	
	OVERLAY - EPOXY	
	OVERLAY - PMA	
	OVERLAY - PMA.NEW SUPERSTRUCTURE	
	OVERLAY - POLYMER	
	OVERLAY -CONCRETE - WIDEN	

Based on the presence of a linked treatment, TIS observations were divided into two main groups: an “observation experienced treatment” group and an “observation did not experience treatment” group. The 4,637 observations with no treatment had an average TIS of 4.36 years, while the 10,225 observations that experienced a treatment had an average TIS of 6.28 years. The difference between the two groups’ means was statistically significant.

TIS observations were further analyzed with respect to deck GCRs. Figure 4-3 shows a statistically significant difference between the observations that experienced a treatment and their counterparts. The difference appears to be higher when the GCR is 6 or 7.

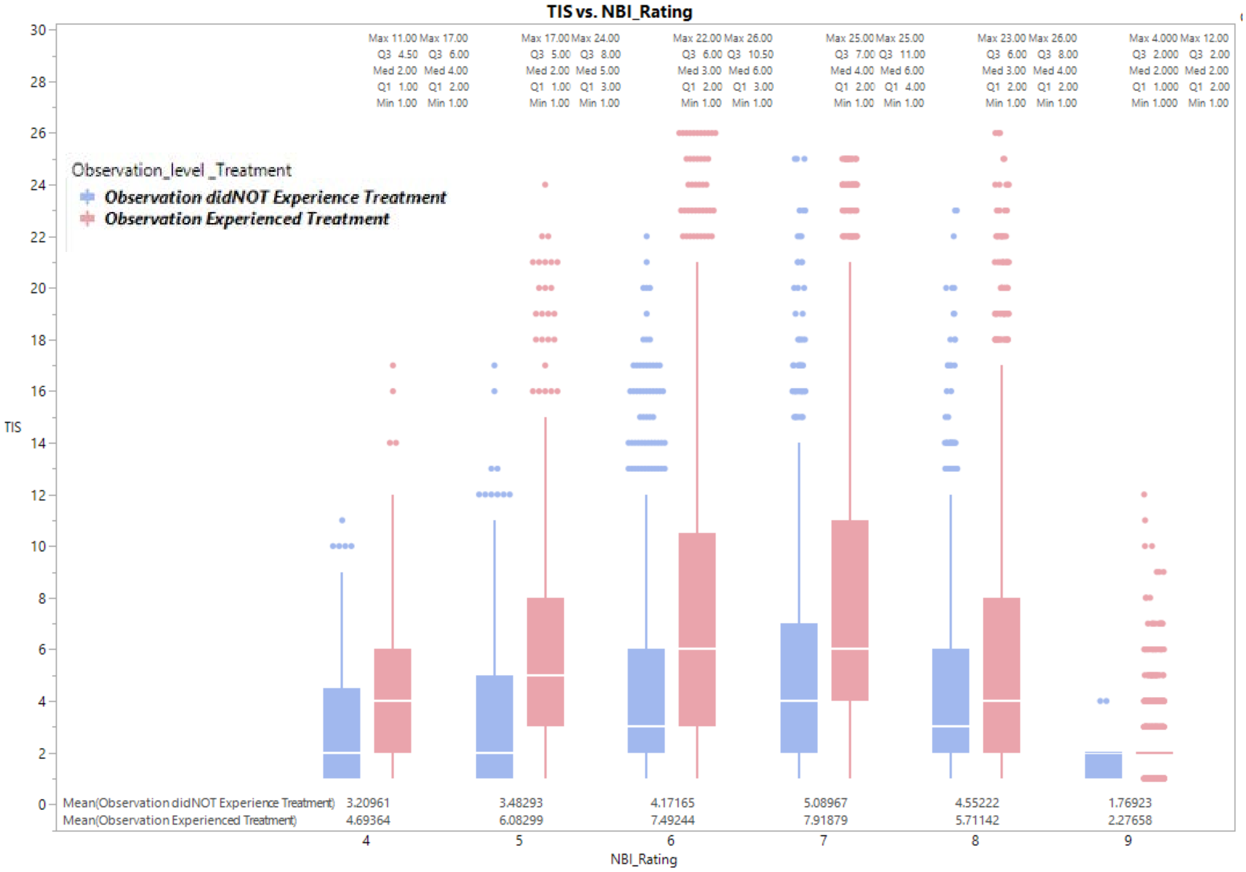


Figure 4-3: TIS by NBI deck GCR

Figure 4-4 provides mean TIS by NBI deck GCR and number of observations for each GCR and treatment status. The high numbers of observations lend credence to the reported values. These findings indicate that observations that experienced a treatment have significantly higher TIS values for each GCR, which aligns with the expectation that treatments decelerate deterioration.

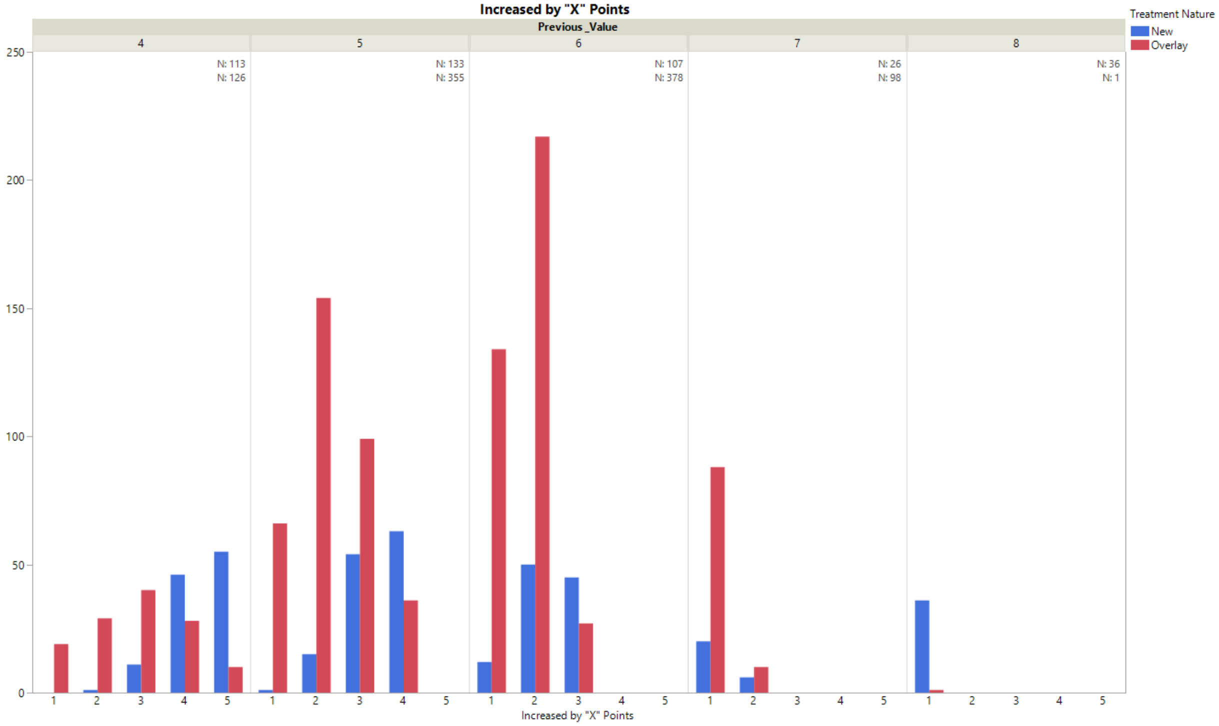


Figure 4-4: Deck GCR increase by type of treatment

The treatments shown in Figure 4-4 are also classified into two groups: “New” includes bridges that were replaced or underwent a substructure, superstructure, or deck replacement, and “Overlay” includes deck overlays. Figure 4-4 includes the relative frequency of observations by deck GCR before treatment (previous value) and the associated increase in GCR (“Increased by ‘X’ points”) with respect to these two treatment groups.

For lower GCR ratings of 4 and 5, a higher share of major rehabilitation and replacements are observed, while overlays are more prominent for GCR ratings of 6 and 7. Bridges with GCRs of 5 or 6 receive the majority of deck overlays.

Figure 4-5 shows the frequency of GCR increases for different overlay types. Concrete overlays are the most common treatments, applied when the GCR is 6, and typically result in a GCR of 8.

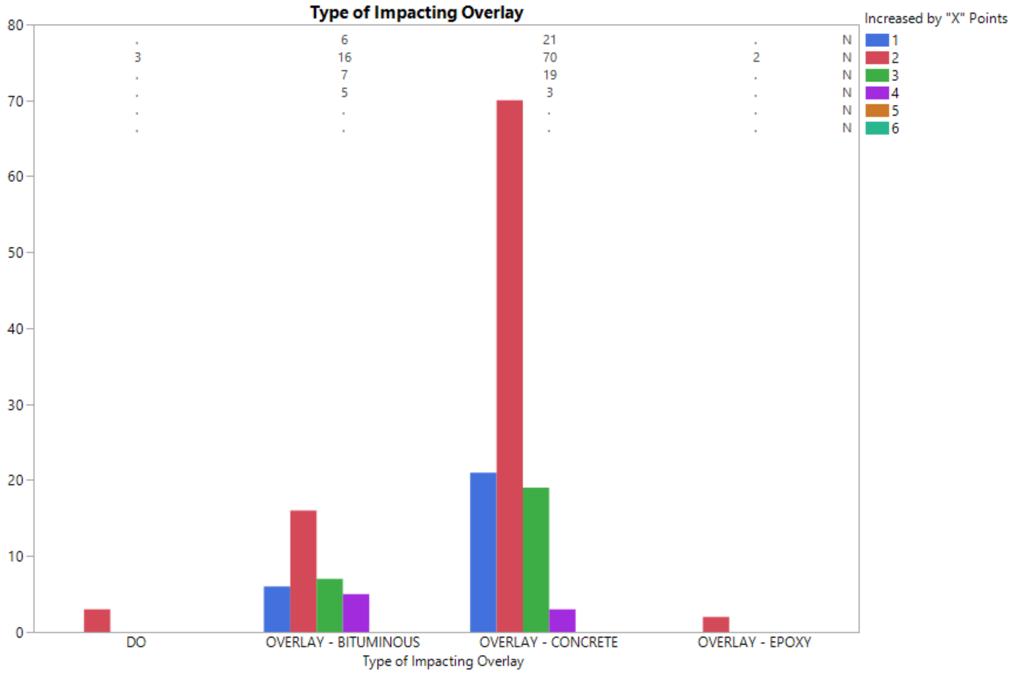


Figure 4-5: Increase in GCR by overlay type

Figure 4-6 shows a similar chart that further groups the observations by previous GCR; this chart indicates that while the most common GCR increase for concrete overlays is two ratings, one- and three-point increases are also observed.

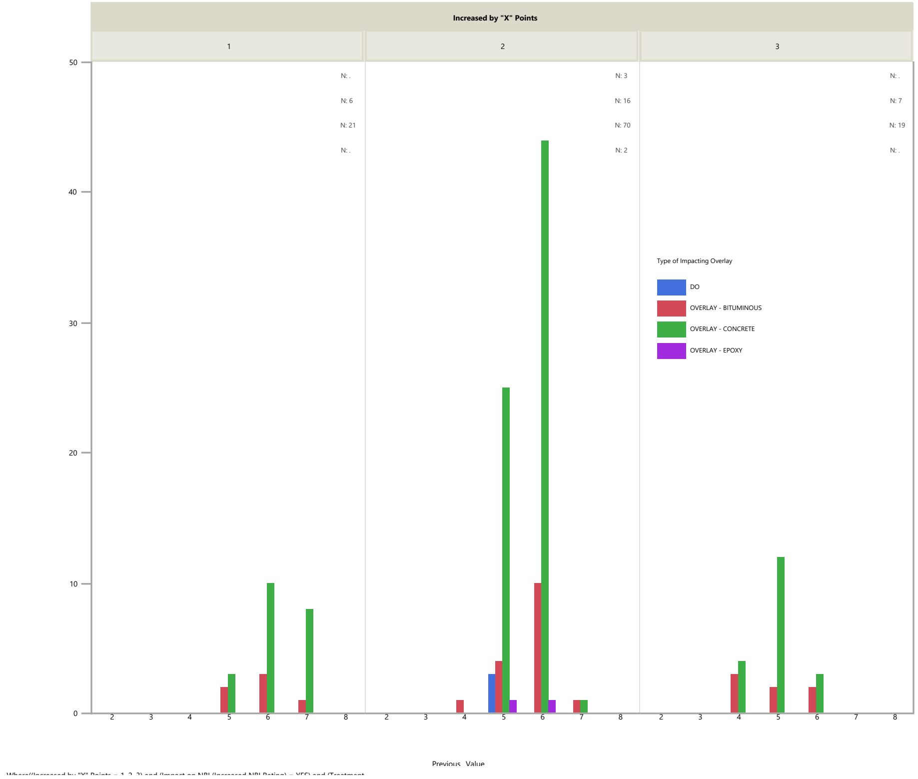


Figure 4-6: Increase in GCR by overlay type and previous GCR

For all deck GCRs, when sealants are applied the TIS is higher for that observation period (Table 4-9). TIS is 2.66 years longer on average when sealants are applied at GCR 6 and 3.35 years longer at GCR 7.

Table 4-9: Impact of sealants on TIS

Deck GCR	Sealants applied during TIS?			
	No		Yes	
	Number of obs.	Mean TIS	Number of obs.	Mean TIS
4	229	3.21	42	3.45
5	613	3.49	187	5.29
6	1385	4.2	552	6.86
7	1286	5.14	1295	8.49
8	955	4.59	972	6.15
9	7	1.71	425	2.38

Furthermore, TIS increases with more frequent applications of sealants (Table 4-10). While a second sealant application leads to three more years of TIS, a third application appears to add another six months. Fewer than 40 cases were observed with three or more sealant applications in the data set.

Table 4-10: Impact of sealant application frequency on TIS

Number of sealant applications during TIS	Number of obs.	Mean TIS
1	798	10
2	131	13.27
3	29	13.9
4	6	18.67
5	2	21.5

Median TIS and quartiles are provided in Figure 4-7 to visually show the distribution of TIS for varying frequencies of sealant application.

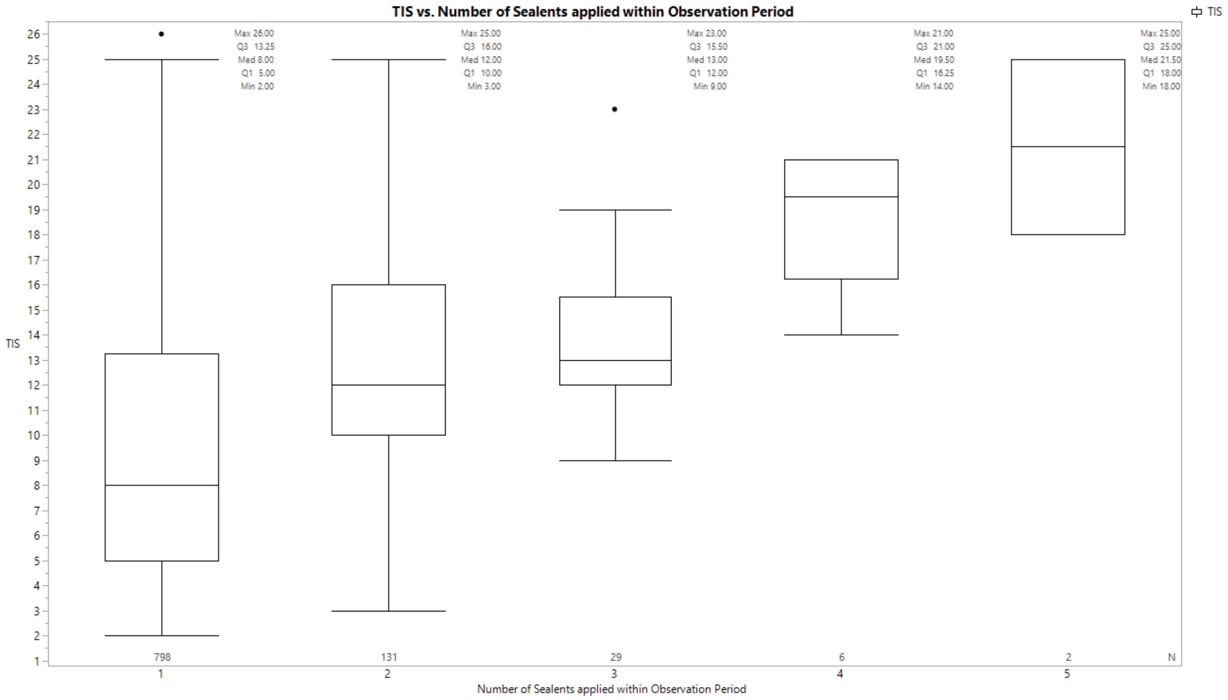


Figure 4-7: TIS distribution with respect to number of sealant applications

As previously noted, observations with more than two sealant applications were rare in the data set. While the median TIS for two applications is higher than the median TIS for only one application, the overall TIS ranges are similar.

4.1.2.4 Analysis of Refined Treatment Impacts

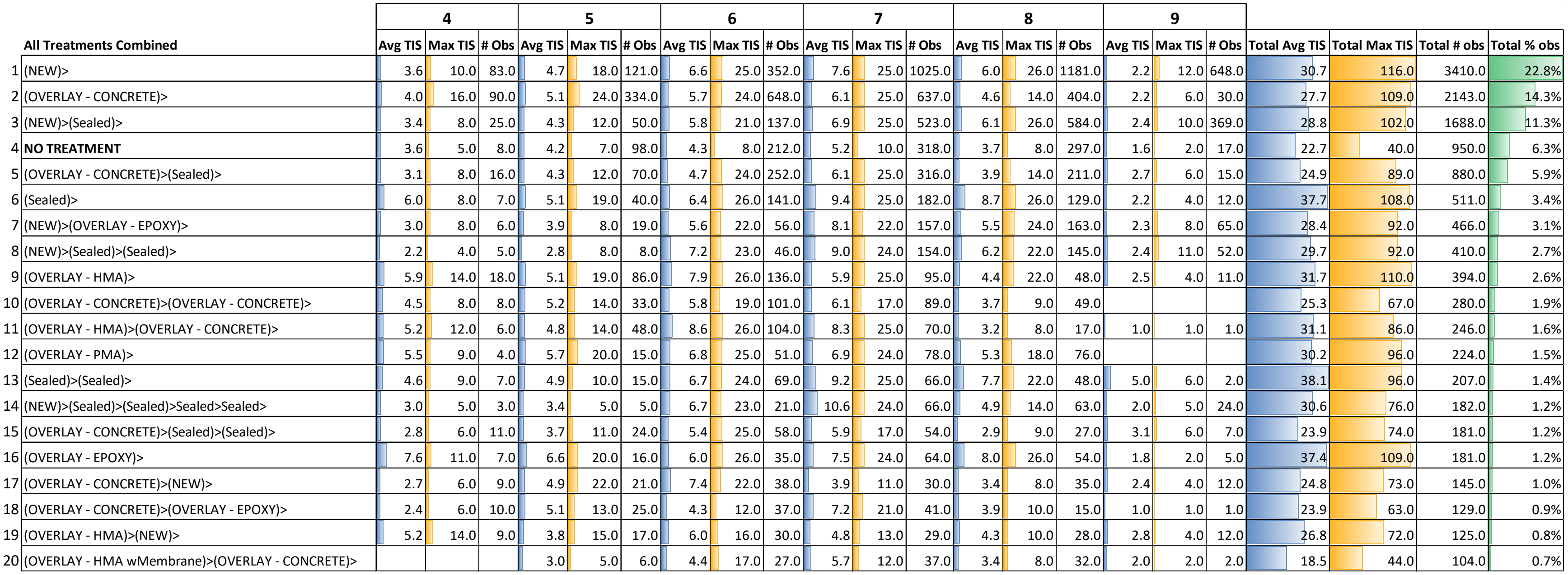
Based on POC comments on an intermediary report, the list of deck treatments was further refined by limiting the treatment scope to decks only and regrouping the deck overlays (see Table 4-11).

Table 4-11: Major Wisconsin deck treatments (final list)

Major Rehabilitation	Major Treatment	Minor Treatment
New Deck*	OVERLAY - CONCRETE	Sealed
New Superstructure*	OVERLAY - EPOXY	
New Substructure *	OVERLAY - PMA	
Deck Replacement*	OVERLAY - HMA	
Reconstruction*	OVERLAY - HMA with Membrane	

*Later combined as “New”

The WisDOT Bureau of Structures shared additional historic overlay data to facilitate reclassification of hot mix asphalt (HMA) overlays into HMA, HMA with membrane, and polymer-modified asphalt (PMA) overlays. The data set was updated with these new classifications. In Figure 4-8, the most common combinations of refined treatments that were observed for bridges during the period from 1992 through 2017 are given, along with TIS statistics by deck GCR.



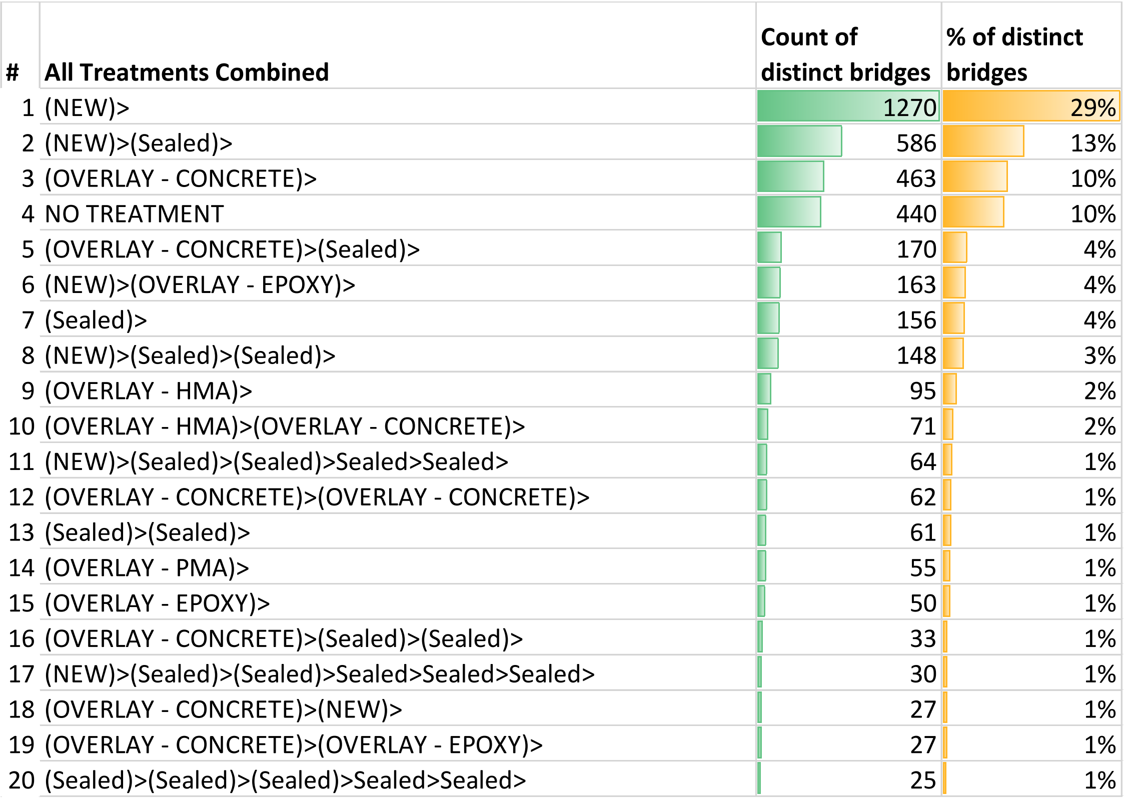
		4			5			6			7			8			9						
	All Treatments Combined	Avg TIS	Max TIS	# Obs	Avg TIS	Max TIS	# Obs	Avg TIS	Max TIS	# Obs	Avg TIS	Max TIS	# Obs	Avg TIS	Max TIS	# Obs	Avg TIS	Max TIS	# Obs	Total Avg TIS	Total Max TIS	Total # obs	Total % obs
1	(NEW)>	3.6	10.0	83.0	4.7	18.0	121.0	6.6	25.0	352.0	7.6	25.0	1025.0	6.0	26.0	1181.0	2.2	12.0	648.0	30.7	116.0	3410.0	22.8%
2	(OVERLAY - CONCRETE)>	4.0	16.0	90.0	5.1	24.0	334.0	5.7	24.0	648.0	6.1	25.0	637.0	4.6	14.0	404.0	2.2	6.0	30.0	27.7	109.0	2143.0	14.3%
3	(NEW)>(Sealed)>	3.4	8.0	25.0	4.3	12.0	50.0	5.8	21.0	137.0	6.9	25.0	523.0	6.1	26.0	584.0	2.4	10.0	369.0	28.8	102.0	1688.0	11.3%
4	**NO TREATMENT**	3.6	5.0	8.0	4.2	7.0	98.0	4.3	8.0	212.0	5.2	10.0	318.0	3.7	8.0	297.0	1.6	2.0	17.0	22.7	40.0	950.0	6.3%
5	(OVERLAY - CONCRETE)>(Sealed)>	3.1	8.0	16.0	4.3	12.0	70.0	4.7	24.0	252.0	6.1	25.0	316.0	3.9	14.0	211.0	2.7	6.0	15.0	24.9	89.0	880.0	5.9%
6	(Sealed)>	6.0	8.0	7.0	5.1	19.0	40.0	6.4	26.0	141.0	9.4	25.0	182.0	8.7	26.0	129.0	2.2	4.0	12.0	37.7	108.0	511.0	3.4%
7	(NEW)>(OVERLAY - EPOXY)>	3.0	8.0	6.0	3.9	8.0	19.0	5.6	22.0	56.0	8.1	22.0	157.0	5.5	24.0	163.0	2.3	8.0	65.0	28.4	92.0	466.0	3.1%
8	(NEW)>(Sealed)>(Sealed)>	2.2	4.0	5.0	2.8	8.0	8.0	7.2	23.0	46.0	9.0	24.0	154.0	6.2	22.0	145.0	2.4	11.0	52.0	29.7	92.0	410.0	2.7%
9	(OVERLAY - HMA)>	5.9	14.0	18.0	5.1	19.0	86.0	7.9	26.0	136.0	5.9	25.0	95.0	4.4	22.0	48.0	2.5	4.0	11.0	31.7	110.0	394.0	2.6%
10	(OVERLAY - CONCRETE)>(OVERLAY - CONCRETE)>	4.5	8.0	8.0	5.2	14.0	33.0	5.8	19.0	101.0	6.1	17.0	89.0	3.7	9.0	49.0				25.3	67.0	280.0	1.9%
11	(OVERLAY - HMA)>(OVERLAY - CONCRETE)>	5.2	12.0	6.0	4.8	14.0	48.0	8.6	26.0	104.0	8.3	25.0	70.0	3.2	8.0	17.0	1.0	1.0	1.0	31.1	86.0	246.0	1.6%
12	(OVERLAY - PMA)>	5.5	9.0	4.0	5.7	20.0	15.0	6.8	25.0	51.0	6.9	24.0	78.0	5.3	18.0	76.0				30.2	96.0	224.0	1.5%
13	(Sealed)>(Sealed)>	4.6	9.0	7.0	4.9	10.0	15.0	6.7	24.0	69.0	9.2	25.0	66.0	7.7	22.0	48.0	5.0	6.0	2.0	38.1	96.0	207.0	1.4%
14	(NEW)>(Sealed)>(Sealed)>Sealed>Sealed>	3.0	5.0	3.0	3.4	5.0	5.0	6.7	23.0	21.0	10.6	24.0	66.0	4.9	14.0	63.0	2.0	5.0	24.0	30.6	76.0	182.0	1.2%
15	(OVERLAY - CONCRETE)>(Sealed)>(Sealed)>	2.8	6.0	11.0	3.7	11.0	24.0	5.4	25.0	58.0	5.9	17.0	54.0	2.9	9.0	27.0	3.1	6.0	7.0	23.9	74.0	181.0	1.2%
16	(OVERLAY - EPOXY)>	7.6	11.0	7.0	6.6	20.0	16.0	6.0	26.0	35.0	7.5	24.0	64.0	8.0	26.0	54.0	1.8	2.0	5.0	37.4	109.0	181.0	1.2%
17	(OVERLAY - CONCRETE)>(NEW)>	2.7	6.0	9.0	4.9	22.0	21.0	7.4	22.0	38.0	3.9	11.0	30.0	3.4	8.0	35.0	2.4	4.0	12.0	24.8	73.0	145.0	1.0%
18	(OVERLAY - CONCRETE)>(OVERLAY - EPOXY)>	2.4	6.0	10.0	5.1	13.0	25.0	4.3	12.0	37.0	7.2	21.0	41.0	3.9	10.0	15.0	1.0	1.0	1.0	23.9	63.0	129.0	0.9%
19	(OVERLAY - HMA)>(NEW)>	5.2	14.0	9.0	3.8	15.0	17.0	6.0	16.0	30.0	4.8	13.0	29.0	4.3	10.0	28.0	2.8	4.0	12.0	26.8	72.0	125.0	0.8%
20	(OVERLAY - HMA wMembrane)>(OVERLAY - CONCRETE)>				3.0	5.0	6.0	4.4	17.0	27.0	5.7	12.0	37.0	3.4	8.0	32.0	2.0	2.0	2.0	18.5	44.0	104.0	0.7%

Figure 4-8: Treatment combinations by average TIS, deck GCR, and number of observations

Given that the focus of this research was to find data-driven estimates of treatment efficiency, these most common combinations are prioritized in subsequent analyses.

The numbers of observations for GCRs 5 to 7 provide sufficient data sets to have representative average TIS values for each group. With few exceptions, observations that experienced any treatment combination have higher TIS values than observations with no treatment. New construction, new construction followed by an epoxy overlay, HMA overlays, epoxy overlays, and sealants appear to have the greatest impact on cumulative TIS over a deck's life cycle.

While Figure 4-8 provides some information on the life-cycle impact of combined treatments, the findings are limited to the portion of the life cycle observed in the data set. For the years 1992 through 2017, we were able to capture up to 25 years of the life cycle for the decks in the data set. Therefore, capturing treatment efficiency at the GCR level rather than at the level of a bridge's lifespan (bridge level) and using GCR as a building block for life-cycle profiles is more pertinent for identifying the best life-cycle treatment plans. It should also be noted that the total number of observations for each treatment combination in Figure 4-8 is at the GCR level, which means the same structure can be counted multiple times, i.e., for as many GCRs as the deck was in during the period from 1992 through 2017. Alternatively, Figure 4-9 shows the most common treatment combinations by number of distinct bridges.



#	All Treatments Combined	Count of distinct bridges	% of distinct bridges
1	(NEW)>	1270	29%
2	(NEW)>(Sealed)>	586	13%
3	(OVERLAY - CONCRETE)>	463	10%
4	NO TREATMENT	440	10%
5	(OVERLAY - CONCRETE)>(Sealed)>	170	4%
6	(NEW)>(OVERLAY - EPOXY)>	163	4%
7	(Sealed)>	156	4%
8	(NEW)>(Sealed)>(Sealed)>	148	3%
9	(OVERLAY - HMA)>	95	2%
10	(OVERLAY - HMA)>(OVERLAY - CONCRETE)>	71	2%
11	(NEW)>(Sealed)>(Sealed)>Sealed>Sealed>	64	1%
12	(OVERLAY - CONCRETE)>(OVERLAY - CONCRETE)>	62	1%
13	(Sealed)>(Sealed)>	61	1%
14	(OVERLAY - PMA)>	55	1%
15	(OVERLAY - EPOXY)>	50	1%
16	(OVERLAY - CONCRETE)>(Sealed)>(Sealed)>	33	1%
17	(NEW)>(Sealed)>(Sealed)>Sealed>Sealed>Sealed>	30	1%
18	(OVERLAY - CONCRETE)>(NEW)>	27	1%
19	(OVERLAY - CONCRETE)>(OVERLAY - EPOXY)>	27	1%
20	(Sealed)>(Sealed)>(Sealed)>Sealed>Sealed>	25	1%

Figure 4-9: Most common treatment combinations by number of distinct bridges

The top 20 combinations shown in Figure 4-9 capture 90% of the 4,449 bridges in the data set. New decks, new decks that were later sealed, concrete overlays, and decks that were never treated constitute 62% of the structures observed in the data set.

For each treatment, a table that summarizes the increase in GCR by previous NBI rating and by the percentage of overall TIS observations is presented in Appendix B. In these tables, if the previous GCR is not known (censored), it is marked with an *x*. With the information from these tables, we can identify the most common before- and after-treatment GCRs. This information can then be used to identify the most common life-cycle profiles. We define a life-cycle profile as the series of GCRs that a deck goes through in its life cycle, along with the treatments that either lead to an increase in condition rating and/or an increased TIS for particular GCRs. The most critical findings from these tables are presented by treatment type as follows:

- Decks are typically replaced when they have a condition rating of 4, 5, or 6. For most observations in the data set, we do not know the previous rating.
- Epoxy overlays are typically applied when the deck condition rating is a 6 or a 7 and lead to a 1-point increase in GCR.
- HMA overlays with membrane are typically placed on decks with a condition rating of 5, 6, or 7 and lead to a 1- to 3-point increase in GCR.
- HMA overlays are typically applied to decks with a condition rating of 5 or 6 and lead to a 1-point improvement in condition rating.
- PMA overlays are most commonly applied to decks with a condition rating of 6 or a 7 and lead to a condition rating of 8.
- Concrete overlays lead to a 1- to 2-point increase in GCR and are applied when decks have a condition rating of 5, 6, or 7.
- Decks are most commonly sealed at condition ratings of 6 and 7 and sometimes result in a 1-point increase in condition rating but typically result in an increased TIS in the current GCR.

The most common before- and after-treatment GCRs, as refined with feedback from the POC, are given in Figure 4-10.

New • 4 > 9 • 5 > 9 • 6 > 9	**HMA Overlay** • 5 > 6 • 6 > 7	**Epoxy Overlay** • 6 > 7 • 7 > 8 (36%)
HMA Overlay with Membrane • 5 > 6 • 6 > 7 • 7 > 8	**Concrete Overlay** • 5 > 7 • 6 > 8 • 7 > 8	**PMA Overlay** • 7 > 8 • 6 > 8
		Sealed • Increased TIS

Figure 4-10: Most common before- and after-treatment GCRs by treatment

These treatment impacts are used in building the life-cycle profiles in the following chapter, which, in turn, are used to identify cost-effective, data-driven life-cycle treatment plans for the preservation of Wisconsin bridge decks.

Tables that summarize the count and percentage of TIS observations by impacting treatment type and GCR rating are also given in Appendix B. Although some treatments are linked to an NBI condition rating of 5, the majority of the treated decks have condition ratings of 6 through 9.

A concern that arose due to the nature of the data set was whether censoring had an impact on the TIS observations. Censored observations (right-censored in this case) are those TIS observations for which we do not know how long the deck will stay or has stayed in a particular GCR. For example, if the first GCR for a deck in this data set in 1992 was 8, and the deck stayed in GCR 8 until 2000, we know that the TIS in GCR 8 is at least nine years, but the TIS could be higher depending on the GCRs before 1992. Likewise, if a deck had a GCR of 7 in 2014 and then again in 2016, we know that the TIS for GCR 7 for this deck is at least four years, but the TIS could be higher depending on future GCRs.

Figure 4-11 shows the impact of the first year of TIS observation on the length of the TIS. Naturally, when a deck's GCR is first observed in the later years of the data set (e.g., a rating of 8 drops to a 7 in 2012 and that rating remains until 2017, the last year of the data set), that GCR is observed for a limited number of years. Therefore, for observations with a first year of observation in the later years of the data set, the TIS is shorter. These right-censored observations were excluded from the data set that was used for the TIS estimates, which, in turn, were used to develop the life-cycle profiles and the life-cycle cost analysis described in the next chapter. For the tables in Appendix B, if the first year of TIS observation is 2011 or later and the next rating is *x*, then that observation was excluded from the analysis for estimating TIS. A total of 2,033 observations were excluded from the initial 14,805 observations (13.7% of observations).

Figure 4-12 further shows the impact of right-censoring, in this case by treatment type. The TIS box plots after 2011 all indicate relatively lower TIS values, regardless of the treatment type. Including these observations in the TIS estimates used for economic analysis would lead to underestimated deck life cycles.

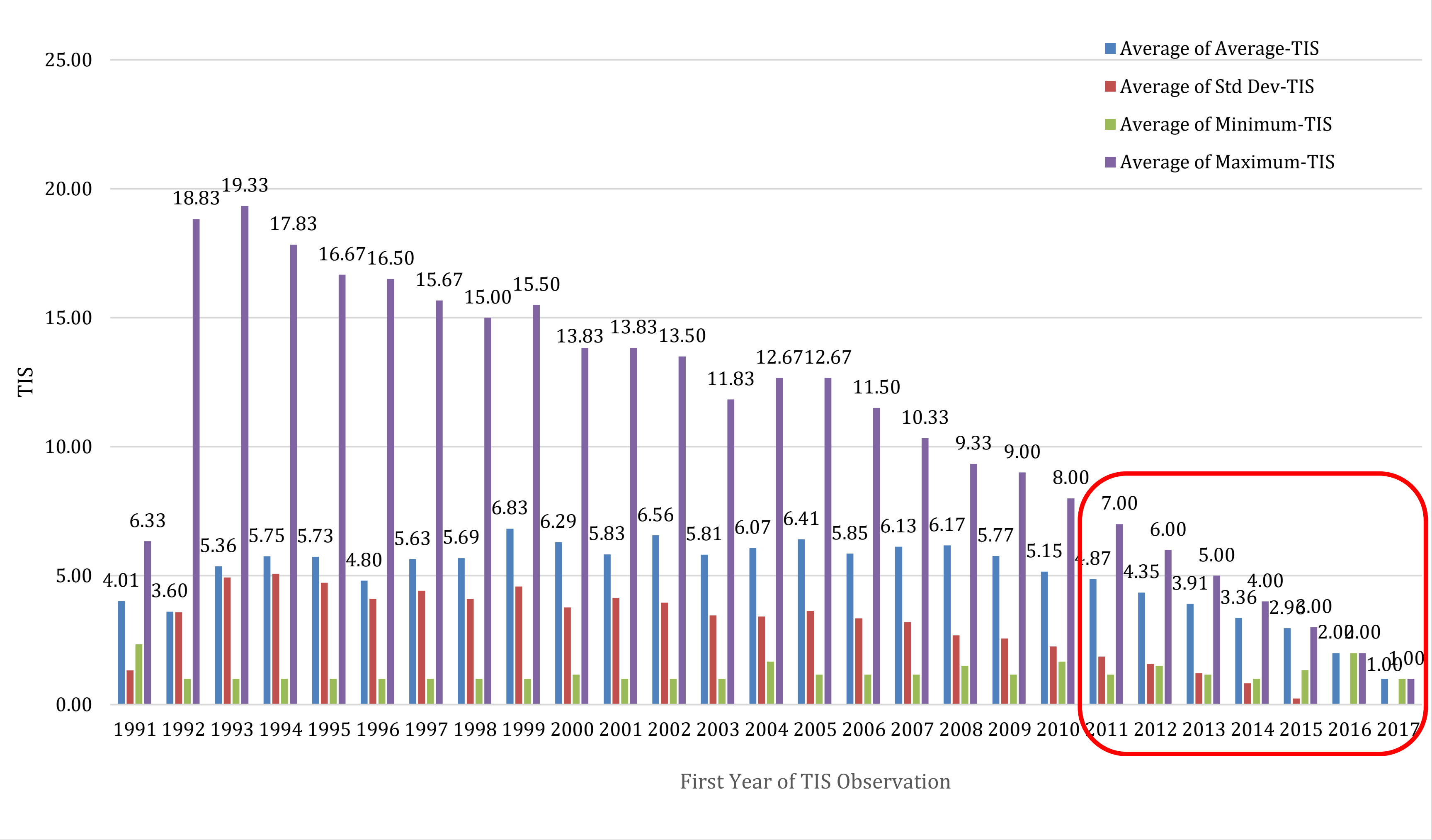
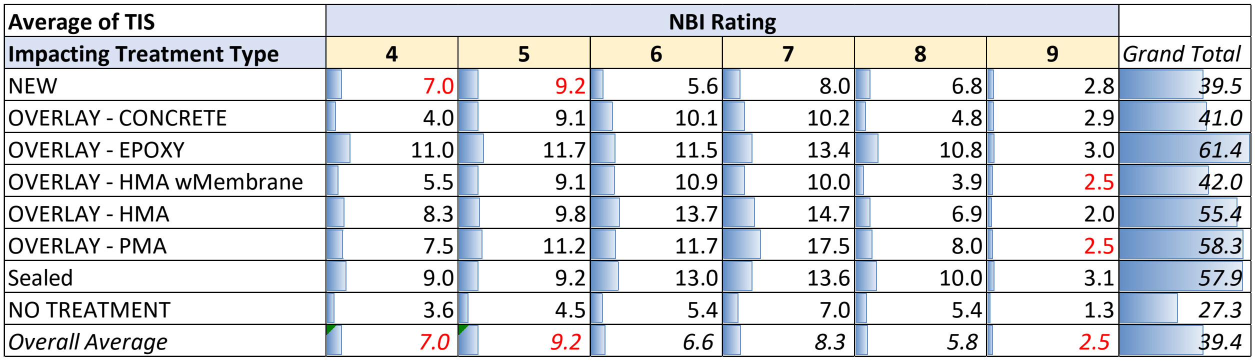


Figure 4-11: TIS by first year of observation

Figure 4-12: TIS by first year of observation and by impacting treatment type

4.1.2.5 Treatment Impact by GCR

Having identified before- and after-treatment GCRs by treatment type, the next element to build life-cycle profiles is data-driven TIS estimates by impacting treatment type. Figure 4-13 presents these values.



Average of TIS	**NBI Rating**						
Impacting Treatment Type	**4**	**5**	**6**	**7**	**8**	**9**	*Grand Total*
NEW	7.0	9.2	5.6	8.0	6.8	2.8	*39.5*
OVERLAY - CONCRETE	4.0	9.1	10.1	10.2	4.8	2.9	*41.0*
OVERLAY - EPOXY	11.0	11.7	11.5	13.4	10.8	3.0	*61.4*
OVERLAY - HMA wMembrane	5.5	9.1	10.9	10.0	3.9	2.5	*42.0*
OVERLAY - HMA	8.3	9.8	13.7	14.7	6.9	2.0	*55.4*
OVERLAY - PMA	7.5	11.2	11.7	17.5	8.0	2.5	*58.3*
Sealed	9.0	9.2	13.0	13.6	10.0	3.1	*57.9*
NO TREATMENT	3.6	4.5	5.4	7.0	5.4	1.3	*27.3*
Overall Average	*7.0*	*9.2*	*6.6*	*8.3*	*5.8*	*2.5*	*39.4*

Figure 4-13: Average TIS by GCR and impacting treatment type

The red values indicate four cases without any observations. Overall averages were used for these cases to calculate the total TIS from condition rating 4 to condition rating 9 by treatment type. These totals, however, are not a clear indicator of performance for these treatments. A deck does not receive the same treatment at all ratings throughout its life cycle, yet the sums of TIS values for NBI ratings that could be linked to a treatment are consistently higher than those of untreated decks. Detailed analyses by each deck GCR were done to estimate the most accurate TIS values for the life-cycle profiles. The details of the analysis are presented in Appendix B, with the most critical findings given in the following sections.

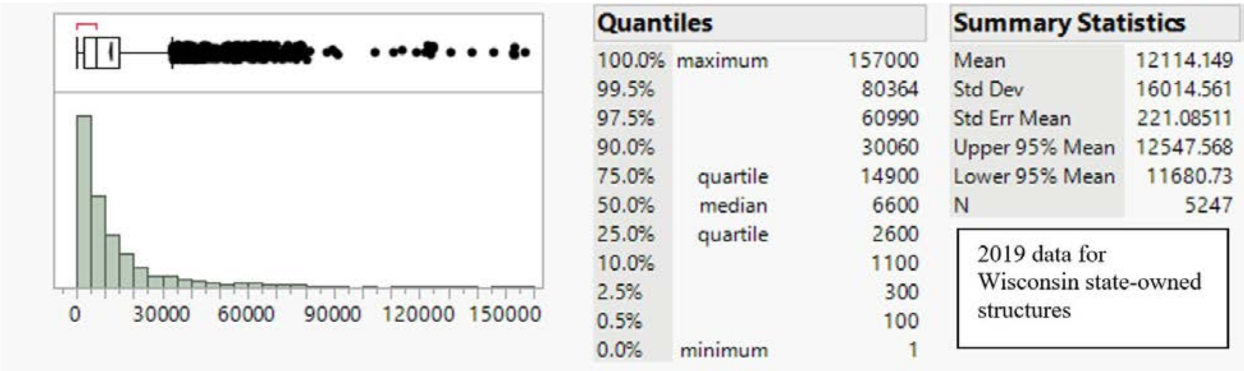
GCR 9

Decks with a GCR of 9 are typically new decks (reconstructed after 1992 and before 2010) but may also be decks that are not linked to new construction or reconstruction. Sealant was applied to 9 decks and concrete overlays were applied to 35 decks to increase the GCRs of these decks to 9. For GCR-level analyses, an impacting treatment is a treatment that leads to the rating under analysis (e.g., for 35 decks, the resulting rating of 9 was linked to a concrete overlay). There were limited numbers of decks for which concrete overlays or seals led to a rating of 9. The TIS values for treated decks were not different from each other but were significantly different than the TIS values for untreated decks, as shown by Dunnett's method of comparison of means (Appendix B). This method compares the mean values of a control group (untreated decks in our analysis) with the mean values of other groups. The nine sealed decks had the longest TIS for a condition rating of 9.

Decks with no identified treatment had the shortest TIS values at an average of 1.3 years. The TIS values for new decks, decks with an impacting treatment such as a concrete overlay, and sealed decks are 1.48, 1.56 and 1.76 years longer, respectively, than the TIS values of untreated decks. Intuitively, a rating of 9 should be the result of new construction or a treatment. However, any TIS observation that was not successfully linked to a treatment was specified as a deck with no treatment throughout this study, and decks with no treatment were used as the control group.

GCR 8

Only three treatments had significantly different TIS values than those of untreated decks. Decks with an epoxy overlay stayed in GCR 8 5.43 years longer, sealed decks stayed 4.58 years longer, and new decks stayed 1.41 years longer than untreated decks. Although a strong correlation between AADT and TIS could not be found for most GCRs, as discussed in the following sections, TIS means were compared by AADT level and by treatment type to investigate any difference in performance. Sealed decks at a condition rating of 8 performed significantly different at different traffic levels. The AADT thresholds are approximately quartile thresholds and divide the AADT observations into four groups (Figure 4-14).



Quantiles

100.0%	maximum	157000
99.5%		80364
97.5%		60990
90.0%		30060
75.0%	quartile	14900
50.0%	median	6600
25.0%	quartile	2600
10.0%		1100
2.5%		300
0.5%		100
0.0%	minimum	1

Summary Statistics

Mean	12114.149
Std Dev	16014.561
Std Err Mean	221.08511
Upper 95% Mean	12547.568
Lower 95% Mean	11680.73
N	5247

2019 data for Wisconsin state-owned structures

Figure 4-14: Summary statistics for AADT

The TIS box plots by AADT level (Appendix B) show that TIS decreases significantly with increasing traffic. This finding suggests that more frequent seals may be of value for higher traffic corridors. Initial traffic levels were chosen as follows: L1 = AADT<2,500, L2 = 2,500<AADT<6,500, L3 = 6,500<AADT<15,000, L4 = AADT>15,000. However, L1 and L2 did not have significantly different TIS values. Levels were later adjusted as follows: L1 = AADT < 6,500, L2 = 6,500<AADT<15,000, L3 = AADT>15,000. These levels showed significantly different TIS values. The TIS for L1 (the lowest traffic volume) was 4.51 years longer than that of L3, and the TIS for L2 was 2.64 years longer than that of L3. For L2 and L3, more frequent seals are recommended.

GCR 7

Five treatments performed significantly different than untreated decks based on Dunnett's method (Appendix B). PMA overlays performed the best, followed by HMA overlays and sealed decks. Traffic did not have a significant impact on treatment performance. HMA overlay with membrane was the lowest performing overlay at this condition rating. PMA overlays added 10.47 years to TIS, while HMA overlays and seals added 7.7 and 6.6 years, respectively.

GCR 6

Observations were available for most treatments for condition rating 6 and showed significantly different performance (Appendix B). The best performer was HMA overlays, which added 8.23 years to TIS compared to untreated decks. Sealed decks stayed in GCR 6 7.56 years longer than untreated decks, while decks with PMA overlays stayed in GCR 6 6.23 years longer.

GCR 5

87 % of the observations for GCR 5 were untreated decks. Treated decks had significantly higher TIS values than untreated decks but their values were fairly close to each other (Appendix B).

4.1.2.6 Impact of External Variables

Before exploring the impact of external variables on TIS, a correlation analysis was conducted among the external factors to check for potential multivariate correlations. The results showed that most variables were not highly correlated, except for AADT and heavy vehicle AADT (HV-AADT, i.e., truck traffic). Figure 4-15 presents the multivariate correlation calculations and the covariance matrix.

Multivariate Correlations

	TotalNaCl/FT^2	Average HV-AADT	AverageAADT	SnowfallTotalsForCounties
TotalNaCl/FT^2	1.0000	0.2350	0.4132	-0.2217
Average HV-AADT	0.2350	1.0000	0.8097	-0.2487
AverageAADT	0.4132	0.8097	1.0000	-0.2974
SnowfallsTotalsForCounties	-0.2217	-0.2487	-0.2974	1.0000

Covariance Matrix

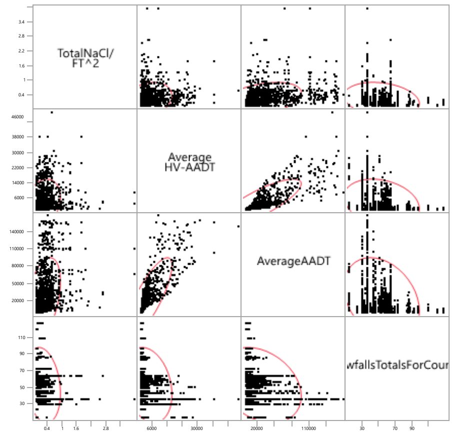


Figure 4-15: Multivariate correlations among external factors

Due to the high correlation between truck AADT and AADT, only one of these variables was used for analysis and presentation purposes. Since AADT values are consistently better populated in databases and truck AADT is populated as a percentage of AADT in most cases, only AADT was used as an external variable.

Effect of Snowfall on TIS

Figure 4-16 shows the distribution of TIS by GCR and three levels of total annual snowfall.

For GCRs 4 through 8, treated decks consistently perform better than untreated decks. Table 4-12 presents mean TIS values by GCR and snowfall range. Table 4-12 also reports the number of observations in each group. Particularly for GCRs 5 through 7, treated decks outperform untreated decks where medium to high annual snowfall is observed.

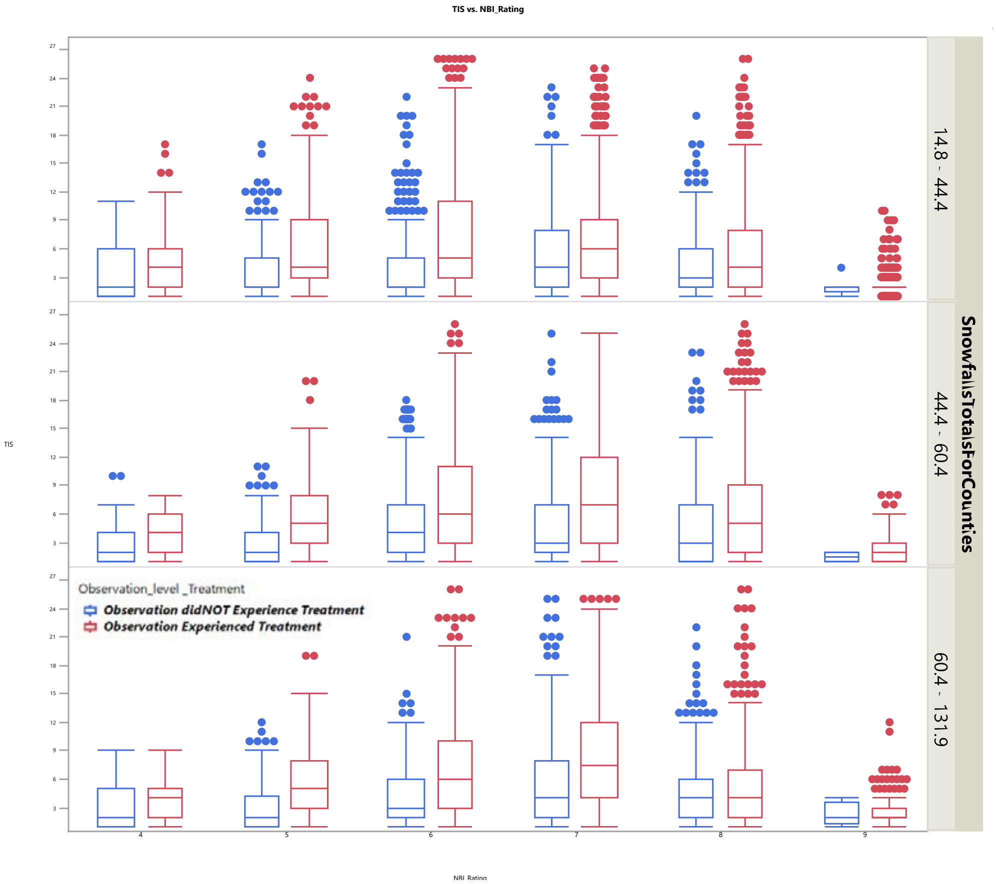


Figure 4-16: TIS distribution by GCR and snowfall

Table 4-12: Mean TIS and number of observations by GCR and snowfall ranges

	TIS											
	Observation Level Treatment											
	Treated Observation						Untreated Observation					
	Snowfall Range (inch)						Snowfall Range (inch)					
	18.8–44.4		44.4–60.4		60.4–131.9		18.8–44.4		44.4–60.4		60.4–131.9	
GCR	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean
4	102	3.6	73	2.68	54	3.19	101	5.37	28	3.89	44	3.66
5	279	3.63	162	3.26	174	3.45	332	6.53	153	5.85	238	5.61
6	609	3.92	374	4.84	421	3.94	662	7.69	451	7.91	540	6.89
7	513	5	355	4.91	448	5.33	1,210	7.17	1,069	8.48	1,058	8.21
8	357	4.13	396	4.89	381	4.68	1,031	5.73	1,014	6.27	949	5.1
9	21	1.86	14	1.5	4	2.25	647	2.24	424	2.26	274	2.38

The mean TIS (Table 4-13) and added TIS (Table 4-14) values by treatment type and snowfall level indicate that some treatment types (e.g., major rehabilitation followed by minor treatment) have slightly higher TIS values in higher snowfall ranges, but the differences are typically within two years and not particularly different for a given snowfall range. While most treatments appear to perform slightly better at lower snowfall levels, the differences are not consistent with a specific level.

Table 4-13: Mean TIS by snowfall and treatment type

	Snowfall Range (inches)					
	18.8–44.4		44.4–60.4		60.4–131.9	
	TIS					
Treatment Scale	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**
Major Rehabilitation	1,526	5.51	878	6.56	653	6.09
Major Rehabilitation + Major Treatment	297	5.6	271	6.19	408	5.81
Major Rehab+ Major Trt. + Minor Treatment	71	6.14	9	5.89	57	4.89
Major Rehabilitation + Minor Treatment	624	5.19	927	6.31	704	6.3
Major Treatment	1,105	6.96	658	6.85	749	6.2
Major Treatment + Minor Treatment	264	5.89	255	6.12	387	5.94
Minor Treatment	91	8.99	141	10.97	145	9.59

Table 4-14: Added TIS by snowfall and treatment type

	Snowfall Range (inches)					
	18.8–44.4		44.4–60.4		60.4–131.9	
	TIS					
Treatment Scale	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**
Major Rehabilitation	359	2.62	181	4.44	172	3.13
Major Rehabilitation + Major Treatment	80	4.85	105	3.62	181	3.76
Major Rehab+ Major Trt. + Minor Treatment	41	5.88	6	3.33	24	4.25
Major Rehabilitation + Minor Treatment	276	2.88	463	3.73	360	3.8
Major Treatment	370	6.52	201	6.02	213	4.32
Major Treatment + Minor Treatment	127	4.7	108	3.85	187	3.55
Minor Treatment	57	4.4	83	3.46	91	4.59

Table 4-15 shows the added TIS by specific treatment and snowfall level.

Table 4-15: Added TIS by snowfall and specific treatment

	Snowfall Range (inches)					
	18.8–44.4		44.4–60.4		60.4–131.9	
	TIS					
Treatment Scale	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**
New Structure	463	2.78	384	4.14	373	3.29
Sealed	194	3.83	362	3.4	412	3.99
Overlay - Concrete	180	3.93	115	4.82	161	4.44
Overlay - Bituminous	223	8.79	98	6.76	45	6.27
New Deck	78	2.32	45	4.13	51	3.41
Overlay - Epoxy	14	5.07	50	5.42	43	4.81
Overlay - Concrete - New Joints	27	3.96	16	5.69	51	2.94
Overlay - Polymer	11	2.91	11	1.64	32	2.13
New Superstructure	23	3.74	16	2.06	4	5.75
[Overlay - Concrete>>Sealed]	7	5	4	2	16	3.31
Overlay - Concrete - New Rail & Joints	7	5.71	10	5.1	6	5.67
[New Structure>> Sealed]	1	4	13	5.62	8	2.38

Effect of AADT on TIS

Figure 4-17 shows the distribution of TIS by GCR and three levels of average AADT.

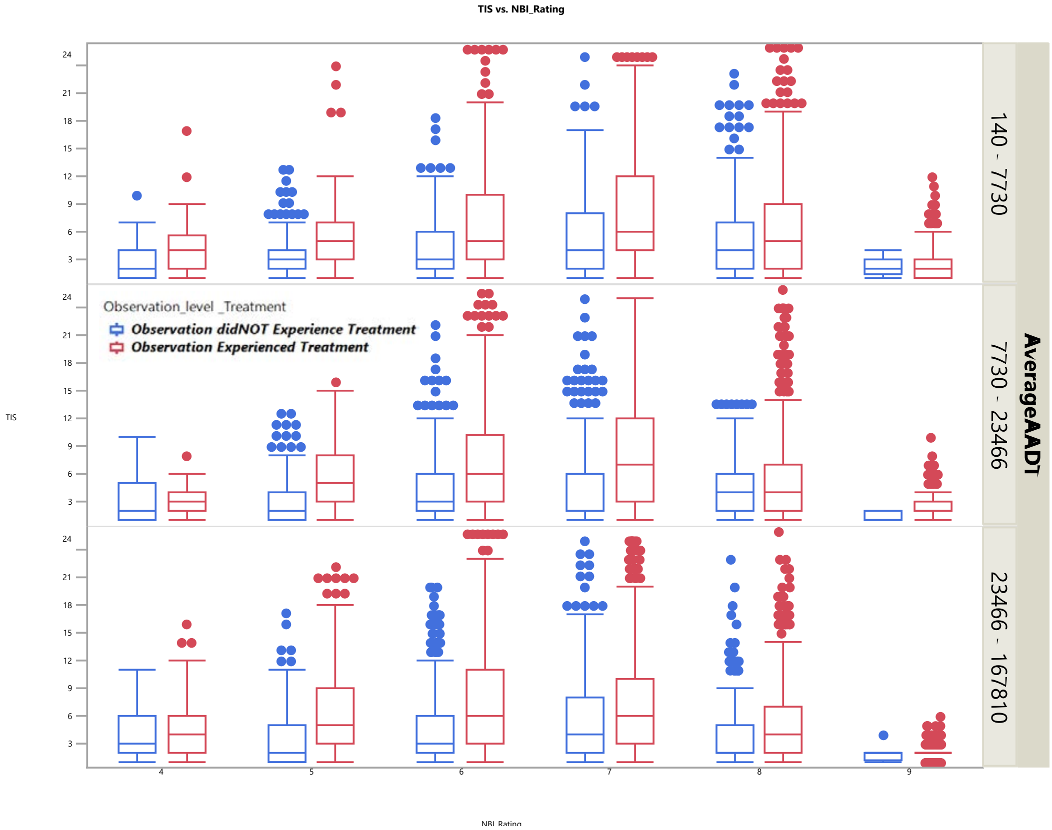


Figure 4-17: TIS distribution by GCR and AADT

For GCRs 4 through 8, treated decks consistently perform better than untreated decks. Table 4-16 presents the mean TIS values by GCR and AADT level.

Table 4-16: Mean TIS and number of observations by GCR and AADT

	TIS															
	Observation Level Treatment															
	Treated Observation								**Treated Observation**							
	AADT Range								**AADT Range**							
	140–7,730		**7,730–23,466**		**Missing**		**> 23,466**		**140–7,730**		**7,730–23,466**		**Missing**		**> 23,466**	
GCR	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**
4	80	2.48	65	3.22	4	2.5	80	3.98	40	4.4	34	2.97	11	8.09	88	5.07
5	195	3.47	194	3.34	29	3.38	197	3.65	187	5.44	212	6.05	29	6.59	295	6.47
6	420	3.84	473	4.07	47	4.79	464	4.52	482	6.98	538	7.38	63	8.27	570	7.95
7	430	5.26	399	4.46	44	3.82	443	5.62	1,133	8.03	1,154	8.34	56	6.79	994	7.36
8	381	5.44	313	4.09	30	4.03	310	3.99	1,010	6.47	1,015	5.37	45	5.27	924	5.28
9	5	2.2	10	1.4	0	.	24	1.83	470	2.32	446	2.35	15	2.6	414	2.14

Table 4-16 also reports the number of observations in each group. For GCRs 4 through 8 and for known AADT values, treated decks have consistently higher TIS values, and two to three years of added TIS is observed for GCRs 5 through 7. The differences in TIS for different AADT values are more pronounced than those for different snowfall levels, discussed in the previous section. For the overall life-cycle plan for decks, AADT would be a more critical variable than snowfall level for decision trees.

When specific treatments and added TIS for different levels of AADT are assessed (Table 4-17), we see that performance is not much different across AADT ranges, but the impact of higher AADT levels is observed for some treatments with smaller added TIS values (e.g., sealed decks or concrete overlays with joint work).

Table 4-17: Added TIS by AADT level and specific treatment

	Treatment Impact on TIS					
	AADT Range					
	140–7,730		**7,730–23,466**		**> 23,466**	
Treatment Scale	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**
New Structure	424	3.88	456	3.05	340	3.15
Sealed	568	3.71	286	4.45	114	2.06
Overlay - Concrete	119	4.92	177	4.02	160	4.25
Overlay - Bituminous	44	8.59	125	7.42	197	8.12
New Deck	41	4.1	53	2.7	80	2.88
Overlay - Epoxy	28	5	41	5.73	38	4.58
Overlay - Concrete - New Joints	25	5	32	4.34	37	2.27
Overlay - Polymer	15	1.67	10	1.7	29	2.62
New Superstructure	13	4.92	10	2.1	20	2.85
[Overlay - Concrete>>Sealed]	13	5.15	13	2.15	1	1
Overlay - Concrete - New Rail & Joints	8	4.88	6	4.33	9	6.67
[New Structure>> Sealed]	12	3.67	10	5.2	0	.

Bituminous overlays have higher added TIS values than the other treatments, followed by epoxy overlays and concrete overlays.

Effect of Deicer on TIS

Figure 4-18 shows that treated decks consistently perform better than untreated decks for low, medium, and high annual deicer usage levels. However, treated decks do not have significantly different TIS values across different levels of deicer usage (Table 4-18).

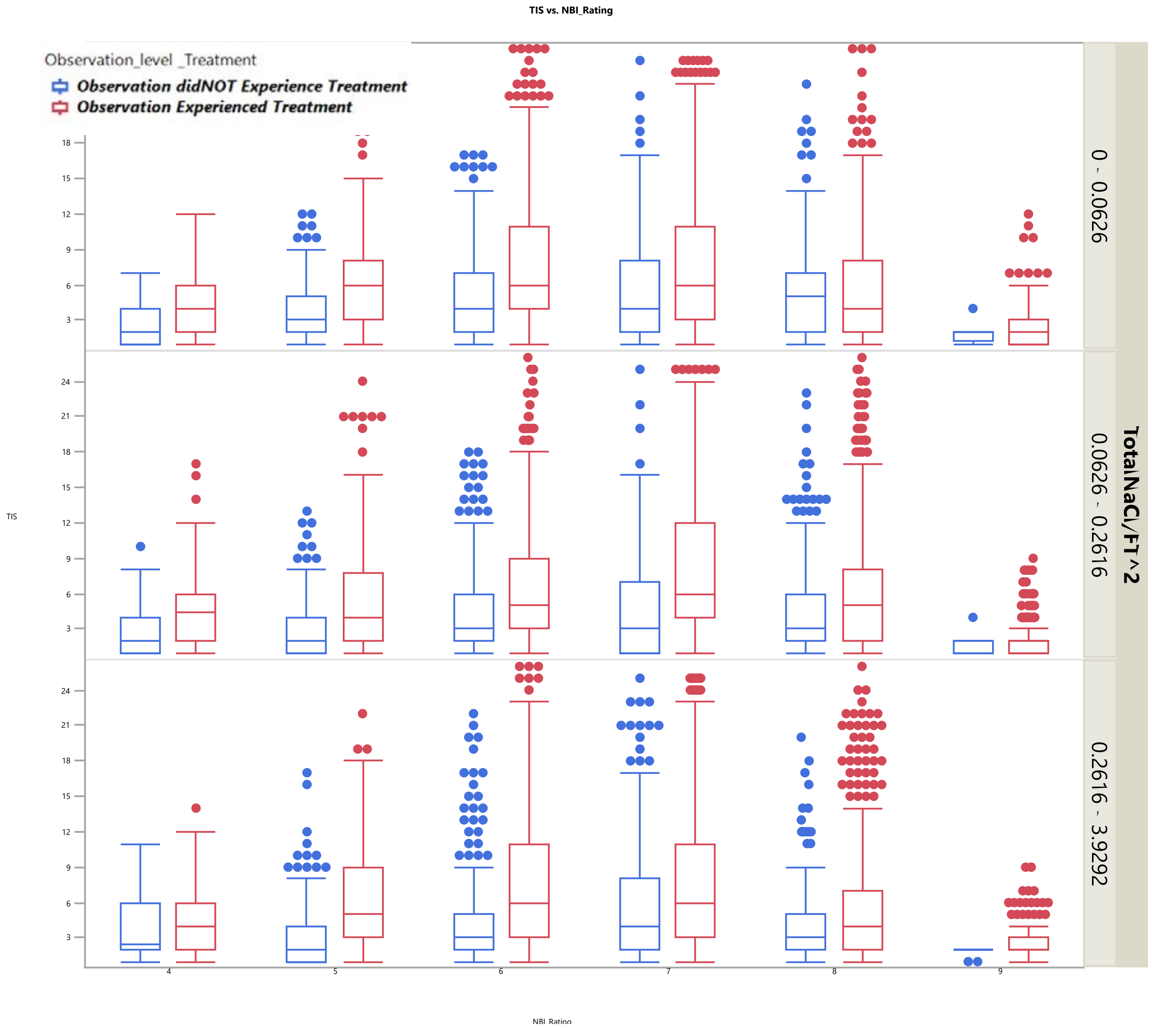


Figure 4-18: TIS distribution by GCR, snowfall, and deicer usage

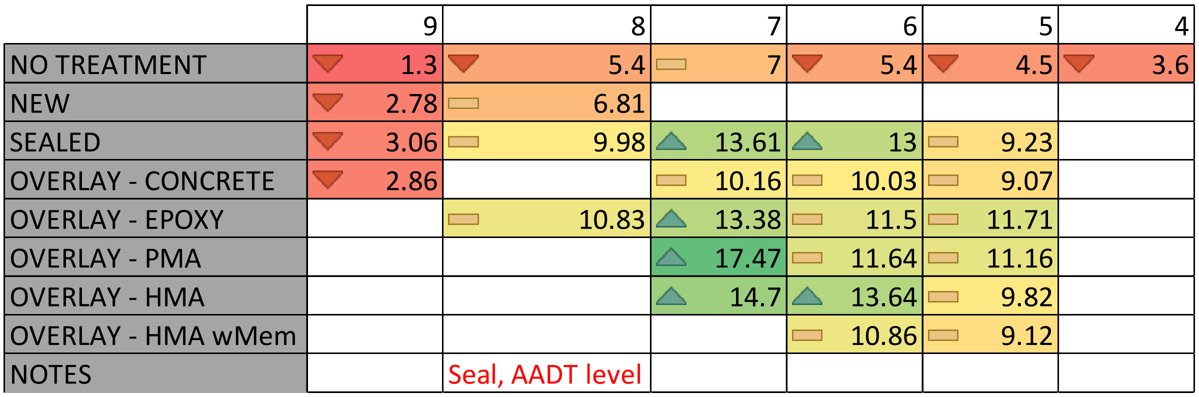
Table 4-18: Mean TIS and number of observations by GCR and deicer usage

	TIS											
	Observation Level Treatment											
	Treated Observation						Treated Observation					
	Deicer Range (lb/ft^2 per winter season)						Deicer Range (lb/ft^2 per winter season)					
	0.0626–0.2616		0-0.0626		> 0.2616		0.0626–0.2616		0–0.0626		> 0.2616	
GCR	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean
4	66	2.73	77	2.87	64	3.94	38	5.34	51	4.35	67	4.49
5	164	3.33	226	3.63	159	3.36	204	5.53	217	6.11	248	6.3
6	366	4.14	446	4.54	451	3.87	479	6.87	495	7.8	509	7.74
7	382	4.54	423	5.29	391	5.62	1,043	8.16	971	7.7	974	7.97
8	304	4.36	367	5.3	284	3.94	966	6.09	871	5.71	846	5.37
9	11	1.73	8	2	13	1.85	475	2.19	350	2.27	390	2.37

Among all of the external factors considered, AADT is a potential variable to be included in decision trees in order to justify more frequent treatments for higher AADT ranges.

4.2 Summary

Figure 4-19 summarizes the findings for treatment impacts by NBI rating level.



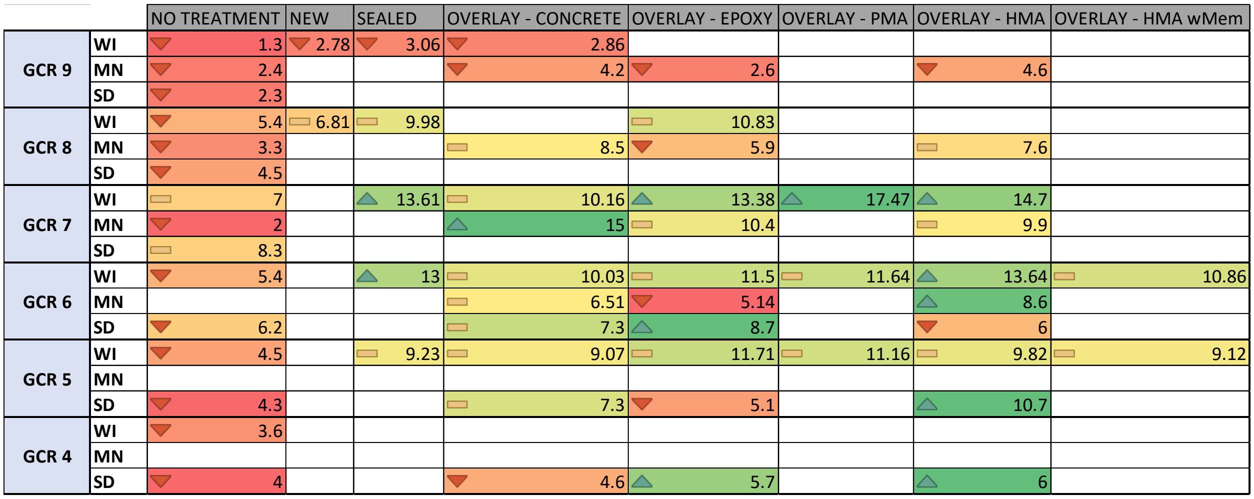
	9	8	7	6	5	4
NO TREATMENT	▼ 1.3	▼ 5.4	▭ 7	▼ 5.4	▼ 4.5	▼ 3.6
NEW	▼ 2.78	▭ 6.81				
SEALED	▼ 3.06	▭ 9.98	▲ 13.61	▲ 13	▭ 9.23	
OVERLAY - CONCRETE	▼ 2.86		▭ 10.16	▭ 10.03	▭ 9.07	
OVERLAY - EPOXY		▭ 10.83	▲ 13.38	▭ 11.5	▭ 11.71	
OVERLAY - PMA			▲ 17.47	▭ 11.64	▭ 11.16	
OVERLAY - HMA			▲ 14.7	▲ 13.64	▭ 9.82	
OVERLAY - HMA wMem				▭ 10.86	▭ 9.12	
NOTES		Seal, AADT level				

Includes only significantly different values at α=0.05 significance level.

Figure 4-19: Treatment efficiency by GCR

Only treatments that perform significantly differently than untreated decks have been included in this list and the life-cycle profiles for economic analysis. The TIS values shown for each GCR are a sum of the difference between the TIS values attributable to the treatment and the TIS values for untreated decks, based on the results of Dunnett's method (Appendix B).

Figure 4-20 presents a comparison of TIS values by treatment and GCR for the states of Wisconsin, Minnesota, and South Dakota. However, the values presented in Figure 4-20 should not be used for a true comparison. Neither should they be taken as data-driven estimates of performance for Minnesota and South Dakota (see Appendix C for details).



		NO TREATMENT	NEW	SEALED	OVERLAY - CONCRETE	OVERLAY - EPOXY	OVERLAY - PMA	OVERLAY - HMA	OVERLAY - HMA wMem
GCR 9	**WI**	▼ 1.3	▼ 2.78	▼ 3.06	▼ 2.86				
	MN	▼ 2.4			▼ 4.2	▼ 2.6		▼ 4.6	
	SD	▼ 2.3							
GCR 8	**WI**	▼ 5.4	▭ 6.81	▭ 9.98		▭ 10.83			
	MN	▼ 3.3			▭ 8.5	▼ 5.9		▭ 7.6	
	SD	▼ 4.5							
GCR 7	**WI**	▭ 7		▲ 13.61	▭ 10.16	▲ 13.38	▲ 17.47	▲ 14.7	
	MN	▼ 2			▲ 15	▭ 10.4		▭ 9.9	
	SD	▭ 8.3							
GCR 6	**WI**	▼ 5.4		▲ 13	▭ 10.03	▭ 11.5	▭ 11.64	▲ 13.64	▭ 10.86
	MN				▭ 6.51	▼ 5.14		▲ 8.6	
	SD	▼ 6.2			▭ 7.3	▲ 8.7		▼ 6	
GCR 5	**WI**	▼ 4.5		▭ 9.23	▭ 9.07	▭ 11.71	▭ 11.16	▭ 9.82	▭ 9.12
	MN								
	SD	▼ 4.3			▭ 7.3	▼ 5.1		▲ 10.7	
GCR 4	**WI**	▼ 3.6							
	MN								
	SD	▼ 4			▼ 4.6	▲ 5.7		▲ 6	

*Limited data from SD and MN, not a true comparison

Figure 4-20: TIS by treatment comparison for Wisconsin, Minnesota, and South Dakota

This study focused primarily on treatment data from Wisconsin, and the project team gathered an extensive work history database of overlays and sealers by working with WisDOT engineers for more than six months. The data from Minnesota and South Dakota were in very different formats and contained partial work histories that did not include data on sealers. Due to these data limitations, the values from Minnesota and South Dakota should not be used as comparative values.

While the potential correlation of external variables (AADT, snowfall, and deicer usage) with TIS values was investigated, only the impact of AADT on sealed decks at GCR 8 was statistically significant for Wisconsin. For Minnesota decks, higher AADT significantly reduced TIS for GCRs 8 and 9. One challenge with analyzing these external variables along with bridge condition data is the difficulty in bringing these variables to the bridge and TIS level. For example, deicer usage from AVL data was first projected onto the roadway and then brought to the bridge level as proportional to the deck area. AVL data are only available for recent years, so they do not represent historical deicer usage. Ideally, a deicer usage variable should be calculated for the duration of a given TIS (e.g., if a given TIS is observed between 2000 and 2007, deicer usage data should also be collected for that timeframe). Nevertheless, the statistically significant relationship that was found between higher deck GCRs and treatments indicate that agencies should consider guiding treatment decisions based on AADT levels.

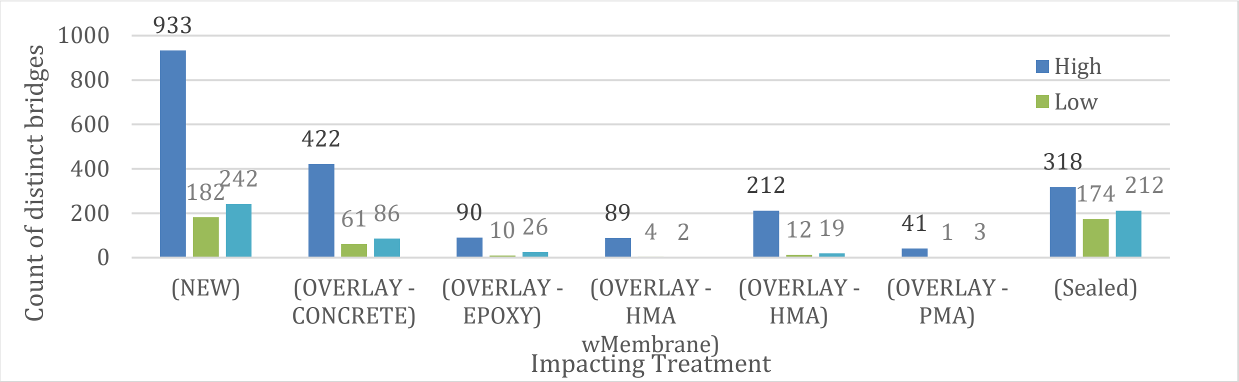
Sealed decks had the longest TIS values for GCR 9, though data meeting the analysis criteria were available for only nine bridges. Findings of this nature do not justify a recommendation for practice but can identify areas where agencies could consider collecting more data over time.

5. LIFE-CYCLE TREATMENT PLAN

This chapter focuses on the engineering economic analyses for the most common life-cycle profiles that were observed for Wisconsin bridge decks. In addition to the findings from the treatment impact analysis described in the previous chapter, further analyses of the statistical distributions of the TIS values were performed to assign more specific TIS ranges, when possible, in the economic analyses. The statistical distributions of specific cases are included in Appendix D. For example, for decks that were sealed twice while they were in GCR 7, the TIS range for this particular group was used instead of the TIS range for a single seal at GCR 7. Also, the most common case involving a concrete overlay followed by a seal was when a concrete overlay was applied at GCR 6, which improved the GCR to 8, and a seal was then applied when the GCR decreased to 7. For these cases, the average TIS for GCR 7 was 10 years.

Although two life-cycle profiles with PMA overlays were analyzed, the findings should be taken with caution because the data set included a limited number of PMA overlays. Overall, the data set included 56 observations of PMA overlays among all GCRs, and most of these overlays were recent. Among these PMA overlays, 37 were associated with GCRs 6 through 8. Future analyses would likely be in a better position to assess economic efficiency because the current data set is limited. For this analysis, the TIS values for bridge decks with PMA overlays were used in the simulation. Unlike other treatments, bridge-level TIS values were used, regardless of the GCR at which the PMA overlay was applied and the resulting GCR.

Also, due to the limited number of observations by treatment, impacted GCR, and traffic volume (AADT), a statistically significant relationship between traffic volume and TIS could not be found (with the exception of sealed decks at GCR 8). However, smaller TIS values for higher AADT levels resulted for some treatments (e.g., sealed decks or concrete overlays) in the treatment efficiency analyses. When a particular treatment is typically applied to bridges that carry higher volumes of traffic, that treatment may appear to underperform when compared with other treatments. HMA overlays with membrane and PMA overlays were typically applied to structures that carry high AADT levels (Figure 5-1). Therefore, the findings of the economic analysis for these overlays do not present a true comparison with respect to other treatments. Decisions regarding these treatments should also consider other factors that vary by bridge location and funding eligibility.



AADT levels: Low: AADT < 6,500; Medium: 6,500 < AADT < 15,000; High: AADT > 15,000

Figure 5-1: Number of distinct structures by treatment type and AADT level

In order to simulate the life-cycle cost and economic efficiency of deck treatment plans for Wisconsin, Monte Carlo simulation was used. The analysis steps are summarized as follows:

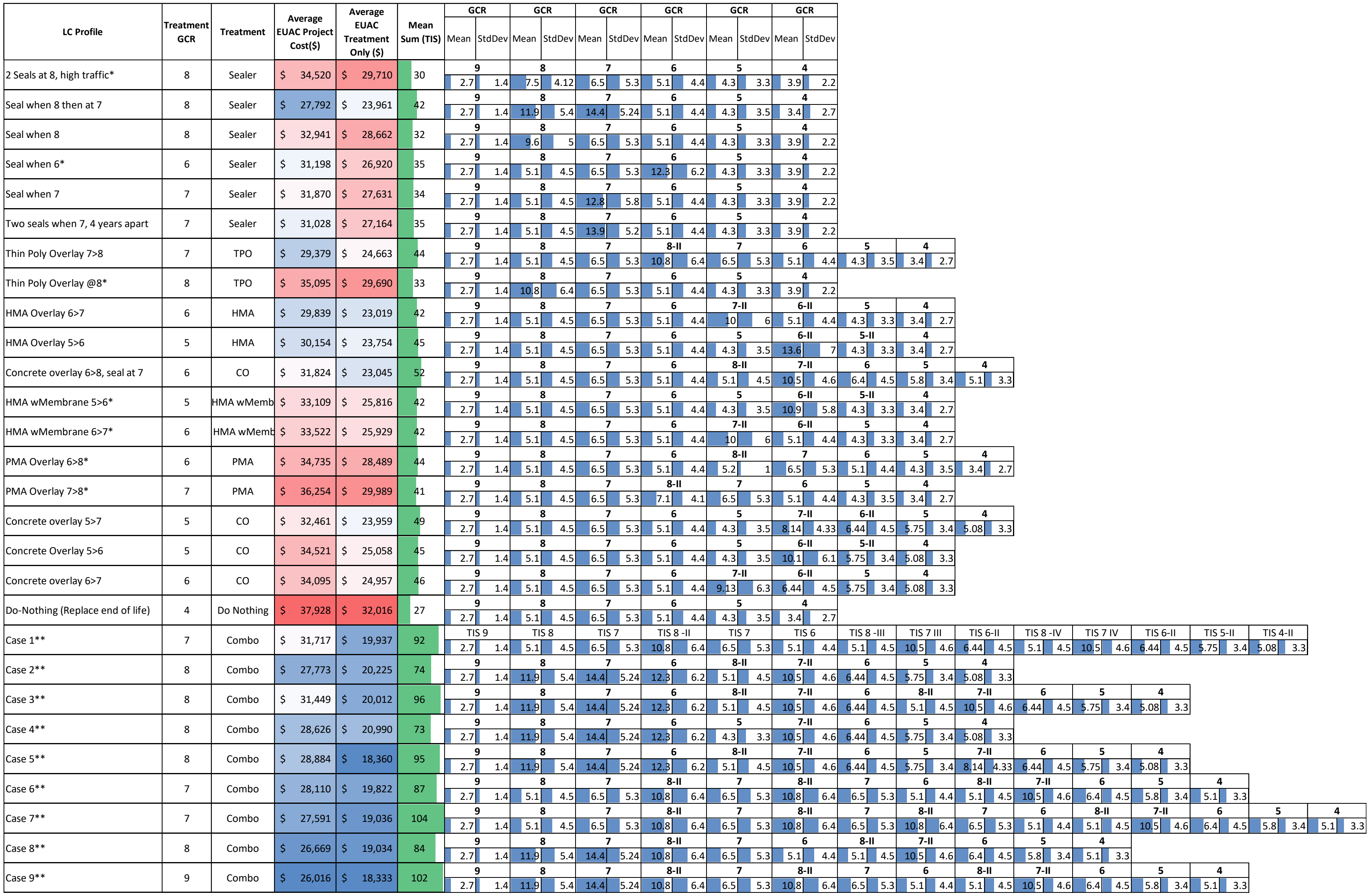
- Based on the most common treatment combinations and identified life-cycle profiles, a Monte Carlo simulation to calculate the equivalent uniform annual cost (EUAC) was run for all life-cycle profiles. In addition to the most common treatment combinations observed in the data set, the WisDOT Bureau of Structures requested that nine special cases for deck preservation also be included in the simulation (Table 5-1). These cases are a combination of the most common treatments in a sequence that could be applied to Wisconsin decks over their life cycles. The TIS ranges resulting from the treatment efficiency analysis were used as building blocks for these cases. These deck life-cycle profiles and EUAC values after 500 runs are given in Figure 5-2.
- The specific TIS ranges presented in Appendix D were used when available. For each run and GCR in the profile, TIS values were simulated within a range described by [(Mean TIS - Standard Deviation of TIS), (Mean TIS + Standard Deviation of TIS)], within which approximately 68% of the potential TIS values lie, based on the 68-95-99.7 rule.
- All life-cycle profiles were started at GCR 9 as a new deck. For deck overlays, TIS ranges for untreated decks were used until the overlay took place. Overlays were assumed to have been applied at the end of the TIS of the application GCR. For example, for the life-cycle profile of a PMA overlay 7 > 8, it was assumed that the overlay happened at the end of condition rating 7 and increased the GCR to an 8. After the overlay, the TIS ranges that reflect the increased TIS ranges after treatment were used in the simulation.
- For sealed decks, increased TIS values were used that were specific to the GCR and the number of seals, when available.
- EUAC was chosen as the economic measure for comparison since it can be used regardless of the number of years in the life-cycle profiles. The assumption here is that all life-cycle profiles portray a deck in service within a GCR range of 9 to 4.
- Treatment costs were calculated based on the cost values provided by the WisDOT Bureau of Structures (Table 5-2). Two sets of costs were provided: the first set included estimated project costs for these treatments that included secondary items and mobilization, and the second set included treatment costs only. All costs were calculated for a deck of 6,600 square feet, the median deck area for state-owned Wisconsin bridges according to 2019 NBI data. The cost values were then inflated based on a construction inflation rate of 3.5% and on the cumulative TIS values at that point in the life cycle. The future net worth of all treatment costs was then calculated at the end of life-cycle profile based on a 4% interest rate. Finally, EUAC values were calculated based on the same rate and the sum of the TIS for the life-cycle profile. Figure 5-2 shows all life-cycle profiles, along with the average EUAC, based on project and treatment costs.

The simulations appear to have converged (i.e., experienced minimal changes to mean and median EUAC with more runs) at approximately 200 repetitions, but 500 runs were performed to be on the safe side. Figure 5-3 shows a partial screenshot of the simulation for a concrete overlay at GCR 6 followed by a seal at GCR 7. The red TIS columns indicate the increased TIS values after treatments (overlay and seal).

Figure 5-4 and Figure 5-5 provide life-cycle profiles ranked by EUAC based on project costs and treatment costs only, respectively.

Table 5-1: Selected sequence of treatments

Case #	Sequence of Treatments
Case 1	a. TPO 7>8 b. concrete overlay at 6>8, seal at 7 c. concrete overlay at 6>8, seal at 7
Case 2	a. Seal when 8 then at 7 b. Seal when 6 c. Concrete overlay 6>8, seal at 7
Case 3	a. Seal when 8 then at 7 b. Seal when 6 c. Concrete overlay 6>8, seal at 7 d. Concrete overlay 6>8, seal at 7
Case 4	a. Seal when 8 then at 7 b. Seal when 6 c. Concrete overlay 5>7
Case 5	a. Seal when 8 then at 7 b. Seal when 6 c. Concrete overlay 6>8, seal at 7 d. Concrete overlay 5>7
Case 6	a. TPO 7>8 b. TPO 7>8, c. concrete overlay at 6>8, seal at 7
Case 7	a. TPO 7>8 b. TPO 7>8 c. TPO 7>8 d. concrete overlay at 6>8, seal at 7
Case 8	a. Seal when 8 then at 7 b. TPO 7>8 c. concrete overlay at 6>8, seal at 7
Case 9	a. Seal when 8 then at 7 b. TPO 7>8 c. TPO 7>8 d. concrete overlay at 6>8, seal at 7



LC Profile	Treatment GCR	Treatment	Average EUAC Project Cost($)	Average EUAC Treatment Only ($)	Mean Sum (TIS)	GCR		GCR		GCR		GCR		GCR		GCR																	
						Mean	StdDev	Mean	StdDev	Mean	StdDev	Mean	StdDev	Mean	StdDev	Mean	StdDev																		
2 Seals at 8, high traffic*	8	Sealer	$ 34,520	$ 29,710	30	9		8		7		6		5		4																			
						2.7	1.4	7.5	4.12	6.5	5.3	5.1	4.4	4.3	3.3	3.9	2.2																		
Seal when 8 then at 7	8	Sealer	$ 27,792	$ 23,961	42	9		8		7		6		5		4																			
						2.7	1.4	11.9	5.4	14.4	5.24	5.1	4.4	4.3	3.5	3.4	2.7																		
Seal when 8	8	Sealer	$ 32,941	$ 28,662	32	9		8		7		6		5		4																			
						2.7	1.4	9.6	5	6.5	5.3	5.1	4.4	4.3	3.3	3.9	2.2																		
Seal when 6*	6	Sealer	$ 31,198	$ 26,920	35	9		8		7		6		5		4																			
						2.7	1.4	5.1	4.5	6.5	5.3	12.3	6.2	4.3	3.3	3.9	2.2																		
Seal when 7	7	Sealer	$ 31,870	$ 27,631	34	9		8		7		6		5		4																			
						2.7	1.4	5.1	4.5	12.8	5.8	5.1	4.4	4.3	3.3	3.9	2.2																		
Two seals when 7, 4 years apart	7	Sealer	$ 31,028	$ 27,164	35	9		8		7		6		5		4																			
						2.7	1.4	5.1	4.5	13.9	5.2	5.1	4.4	4.3	3.3	3.9	2.2																		
Thin Poly Overlay 7>8	7	TPO	$ 29,379	$ 24,663	44	9		8		7		8-II		7		6		5		4															
						2.7	1.4	5.1	4.5	6.5	5.3	10.8	6.4	6.5	5.3	5.1	4.4	4.3	3.5	3.4	2.7														
Thin Poly Overlay @8*	8	TPO	$ 35,095	$ 29,690	33	9		8		7		6		5		4																			
						2.7	1.4	10.8	6.4	6.5	5.3	5.1	4.4	4.3	3.3	3.9	2.2																		
HMA Overlay 6>7	6	HMA	$ 29,839	$ 23,019	42	9		8		7		6		7-II		6-II		5		4															
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	10	6	5.1	4.4	4.3	3.3	3.4	2.7														
HMA Overlay 5>6	5	HMA	$ 30,154	$ 23,754	45	9		8		7		6		5		6-II		5-II		4															
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	4.3	3.5	13.6	7	4.3	3.3	3.4	2.7														
Concrete overlay 6>8, seal at 7	6	CO	$ 31,824	$ 23,045	52	9		8		7		6		8-II		7-II		6		5		4													
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	5.1	4.5	10.5	4.6	6.4	4.5	5.8	3.4	5.1	3.3												
HMA wMembrane 5>6*	5	HMA wMemb	$ 33,109	$ 25,816	42	9		8		7		6		5		6-II		5-II		4															
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	4.3	3.5	10.9	5.8	4.3	3.3	3.4	2.7														
HMA wMembrane 6>7*	6	HMA wMemb	$ 33,522	$ 25,929	42	9		8		7		6		7-II		6-II		5		4															
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	10	6	5.1	4.4	4.3	3.3	3.4	2.7														
PMA Overlay 6>8*	6	PMA	$ 34,735	$ 28,489	44	9		8		7		6		8-II		7		6		5		4													
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	5.2	1	6.5	5.3	5.1	4.4	4.3	3.5	3.4	2.7												
PMA Overlay 7>8*	7	PMA	$ 36,254	$ 29,989	41	9		8		7		8-II		7		6		5		4															
						2.7	1.4	5.1	4.5	6.5	5.3	7.1	4.1	6.5	5.3	5.1	4.4	4.3	3.5	3.4	2.7														
Concrete overlay 5>7	5	CO	$ 32,461	$ 23,959	49	9		8		7		6		5		7-II		6-II		5		4													
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	4.3	3.5	8.14	4.33	6.44	4.5	5.75	3.4	5.08	3.3												
Concrete Overlay 5>6	5	CO	$ 34,521	$ 25,058	45	9		8		7		6		5		6-II		5-II		4															
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	4.3	3.5	10.1	6.1	5.75	3.4	5.08	3.3														
Concrete overlay 6>7	6	CO	$ 34,095	$ 24,957	46	9		8		7		6		7-II		6-II		5		4															
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	9.13	6.3	6.44	4.5	5.75	3.4	5.08	3.3														
Do-Nothing (Replace end of life)	4	Do Nothing	$ 37,928	$ 32,016	27	9		8		7		6		5		4																			
						2.7	1.4	5.1	4.5	6.5	5.3	5.1	4.4	4.3	3.5	3.4	2.7																		
Case 1**	7	Combo	$ 31,717	$ 19,937	92	TIS 9		TIS 8		TIS 7		TIS 8 -II		TIS 7		TIS 6		TIS 8 -III		TIS 7 III		TIS 6-II		TIS 8 -IV		TIS 7 IV		TIS 6-II		TIS 5-II		TIS 4-II			
						2.7	1.4	5.1	4.5	6.5	5.3	10.8	6.4	6.5	5.3	5.1	4.4	5.1	4.5	10.5	4.6	6.44	4.5	5.1	4.5	10.5	4.6	6.44	4.5	5.75	3.4	5.08	3.3		
Case 2**	8	Combo	$ 27,773	$ 20,225	74	9		8		7		6		8-II		7-II		6		5		4													
						2.7	1.4	11.9	5.4	14.4	5.24	12.3	6.2	5.1	4.5	10.5	4.6	6.44	4.5	5.75	3.4	5.08	3.3												
Case 3**	8	Combo	$ 31,449	$ 20,012	96	9		8		7		6		8-II		7-II		6		8-II		7-II		6		5		4							
						2.7	1.4	11.9	5.4	14.4	5.24	12.3	6.2	5.1	4.5	10.5	4.6	6.44	4.5	5.1	4.5	10.5	4.6	6.44	4.5	5.75	3.4	5.08	3.3						
Case 4**	8	Combo	$ 28,626	$ 20,990	73	9		8		7		6		5		7-II		6		5		4													
						2.7	1.4	11.9	5.4	14.4	5.24	12.3	6.2	4.3	3.3	10.5	4.6	6.44	4.5	5.75	3.4	5.08	3.3												
Case 5**	8	Combo	$ 28,884	$ 18,360	95	9		8		7		6		8-II		7-II		6		5		7-II		6		5		4							
						2.7	1.4	11.9	5.4	14.4	5.24	12.3	6.2	5.1	4.5	10.5	4.6	6.44	4.5	5.75	3.4	8.14	4.33	6.44	4.5	5.75	3.4	5.08	3.3						
Case 6**	7	Combo	$ 28,110	$ 19,822	87	9		8		7		8-II		7		8-II		7		6		8-II		7-II		6		5		4					
						2.7	1.4	5.1	4.5	6.5	5.3	10.8	6.4	6.5	5.3	10.8	6.4	6.5	5.3	5.1	4.4	5.1	4.5	10.5	4.6	6.4	4.5	5.8	3.4	5.1	3.3				
Case 7**	7	Combo	$ 27,591	$ 19,036	104	9		8		7		8-II		7		8-II		7		8-II		7		6		8-II		7-II		6		5		4	
						2.7	1.4	5.1	4.5	6.5	5.3	10.8	6.4	6.5	5.3	10.8	6.4	6.5	5.3	10.8	6.4	6.5	5.3	5.1	4.4	5.1	4.5	10.5	4.6	6.4	4.5	5.8	3.4	5.1	3.3
Case 8**	8	Combo	$ 26,669	$ 19,034	84	9		8		7		8-II		7		6		8-II		7-II		6		5		4									
						2.7	1.4	11.9	5.4	14.4	5.24	10.8	6.4	6.5	5.3	5.1	4.4	5.1	4.5	10.5	4.6	6.4	4.5	5.8	3.4	5.1	3.3								
Case 9**	9	Combo	$ 26,016	$ 18,333	102	9		8		7		8-II		7		8-II		7		6		8-II		7-II		6		5		4					
						2.7	1.4	11.9	5.4	14.4	5.24	10.8	6.4	6.5	5.3	10.8	6.4	6.5	5.3	5.1	4.4	5.1	4.5	10.5	4.6	6.4	4.5	5.8	3.4	5.1	3.3				

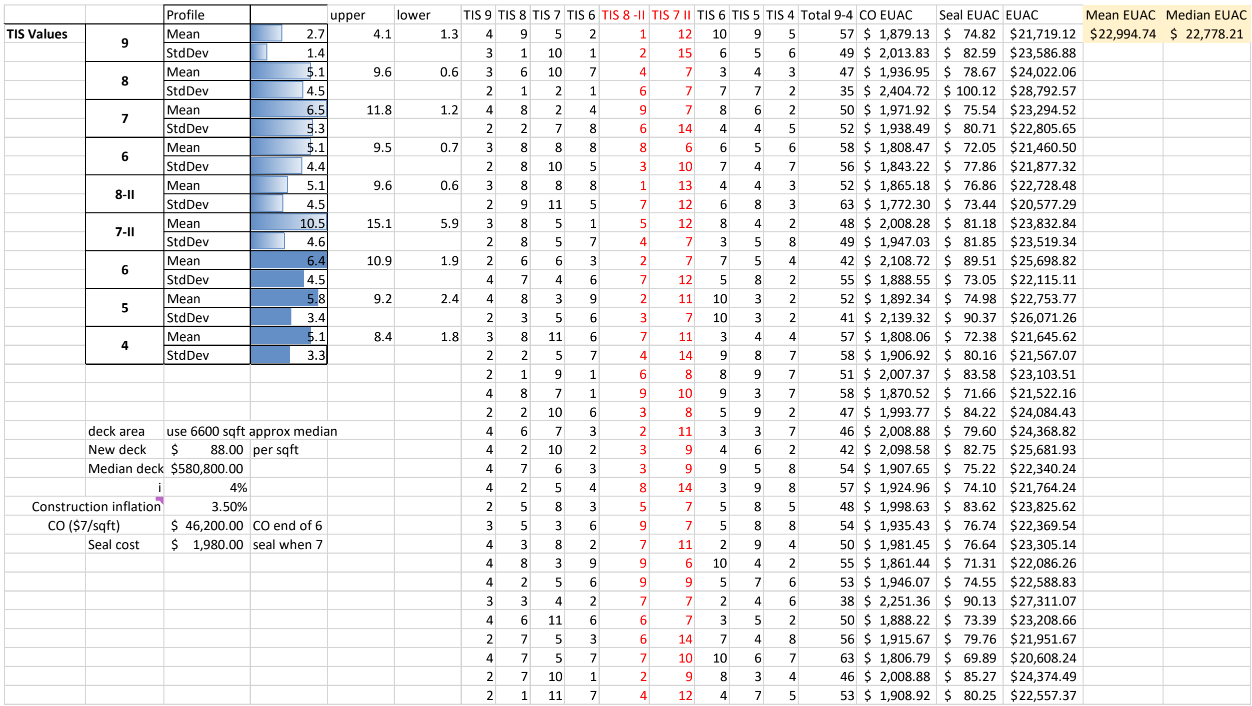
*Limited data

**Life-cycle profile built based on most common treatments

Figure 5-2: Life-cycle profiles and EUAC values from Monte Carlo simulation

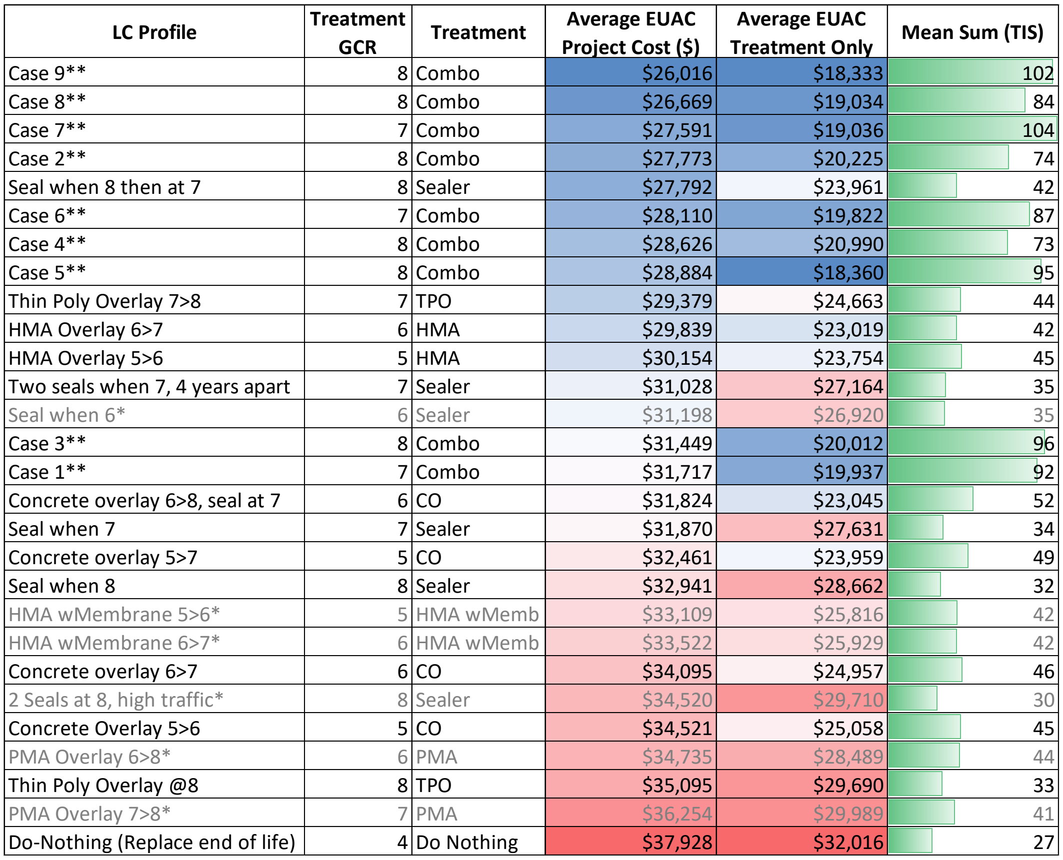
Table 5-2: Treatments costs

Treatment	Project Cost ($/ft^2)	Treatment Cost ($/ft^2)
OVERLAY - CONCRETE	26.71	7
OVERLAY - EPOXY (THIN POLYMER OVERLAY)	8.66	5
OVERLAY - PMA	26.31	18
OVERLAY - HMA	12.41	2
OVERLAY - HMA with Membrane	19	7
Deck Seal	0.28	0.3
New Deck	101.6	88



		Profile		upper	lower	TIS 9	TIS 8	TIS 7	TIS 6	TIS 8 -II	TIS 7 II	TIS 6	TIS 5	TIS 4	Total 9-4	CO EUAC	Seal EUAC	EUAC	Mean EUAC	Median EUAC
TIS Values	**9**	Mean	2.7	4.1	1.3	4	9	5	2	1	12	10	9	5	57	$ 1,879.13	$ 74.82	$21,719.12	$22,994.74	$ 22,778.21
		StdDev	1.4			3	1	10	1	2	15	6	5	6	49	$ 2,013.83	$ 82.59	$23,586.88		
	8	Mean	5.1	9.6	0.6	3	6	10	7	4	7	3	4	3	47	$ 1,936.95	$ 78.67	$24,022.06		
		StdDev	4.5			2	1	2	1	6	7	7	7	2	35	$ 2,404.72	$ 100.12	$28,792.57		
	7	Mean	6.5	11.8	1.2	4	8	2	4	9	7	8	6	2	50	$ 1,971.92	$ 75.54	$23,294.52		
		StdDev	5.3			2	2	7	8	6	14	4	4	5	52	$ 1,938.49	$ 80.71	$22,805.65		
	6	Mean	5.1	9.5	0.7	3	8	8	8	8	6	6	5	6	58	$ 1,808.47	$ 72.05	$21,460.50		
		StdDev	4.4			2	8	10	5	3	10	7	4	7	56	$ 1,843.22	$ 77.86	$21,877.32		
	8-II	Mean	5.1	9.6	0.6	3	8	8	8	1	13	4	4	3	52	$ 1,865.18	$ 76.86	$22,728.48		
		StdDev	4.5			2	9	11	5	7	12	6	8	3	63	$ 1,772.30	$ 73.44	$20,577.29		
	7-II	Mean	10.5	15.1	5.9	3	8	5	1	5	12	8	4	2	48	$ 2,008.28	$ 81.18	$23,832.84		
		StdDev	4.6			2	8	5	7	4	7	3	5	8	49	$ 1,947.03	$ 81.85	$23,519.34		
	6	Mean	6.4	10.9	1.9	2	6	6	3	2	7	7	5	4	42	$ 2,108.72	$ 89.51	$25,698.82		
		StdDev	4.5			4	7	4	6	7	12	5	8	2	55	$ 1,888.55	$ 73.05	$22,115.11		
	5	Mean	5.8	9.2	2.4	4	8	3	9	2	11	10	3	2	52	$ 1,892.34	$ 74.98	$22,753.77		
		StdDev	3.4			2	3	5	6	3	7	10	3	2	41	$ 2,139.32	$ 90.37	$26,071.26		
	4	Mean	5.1	8.4	1.8	3	8	11	6	7	11	3	4	4	57	$ 1,808.06	$ 72.38	$21,645.62		
		StdDev	3.3			2	2	5	7	4	14	9	8	7	58	$ 1,906.92	$ 80.16	$21,567.07		
						2	1	9	1	6	8	8	9	7	51	$ 2,007.37	$ 83.58	$23,103.51		
						4	8	7	1	9	10	9	3	7	58	$ 1,870.52	$ 71.66	$21,522.16		
						2	2	10	6	3	8	5	9	2	47	$ 1,993.77	$ 84.22	$24,084.43		
	deck area	use 6600 sqft approx median				4	6	7	3	2	11	3	3	7	46	$ 2,008.88	$ 79.60	$24,368.82		
	New deck	$ 88.00	per sqft			4	2	10	2	3	9	4	6	2	42	$ 2,098.58	$ 82.75	$25,681.93		
	Median deck	$580,800.00				4	7	6	3	3	9	9	5	8	54	$ 1,907.65	$ 75.22	$22,340.24		
	i	4%				4	2	5	4	8	14	3	9	8	57	$ 1,924.96	$ 74.10	$21,764.24		
	Construction inflation	3.50%				2	5	8	3	5	7	5	8	5	48	$ 1,998.63	$ 83.62	$23,825.62		
	CO ($7/sqft)	$ 46,200.00	CO end of 6			3	5	3	6	9	7	5	8	8	54	$ 1,935.43	$ 76.74	$22,369.54		
	Seal cost	$ 1,980.00	seal when 7			4	3	8	2	7	11	2	9	4	50	$ 1,981.45	$ 76.64	$23,305.14		
						4	8	3	9	9	6	10	4	2	55	$ 1,861.44	$ 71.31	$22,086.26		
						4	2	5	6	9	9	5	7	6	53	$ 1,946.07	$ 74.55	$22,588.83		
						3	3	4	2	7	7	2	4	6	38	$ 2,251.36	$ 90.13	$27,311.07		
						4	6	11	6	6	7	3	5	2	50	$ 1,888.22	$ 73.39	$23,208.66		
						2	7	5	3	6	14	7	4	8	56	$ 1,915.67	$ 79.76	$21,951.67		
						4	7	5	7	7	10	10	6	7	63	$ 1,806.79	$ 69.89	$20,608.24		
						2	7	10	1	2	9	8	3	4	46	$ 2,008.88	$ 85.27	$24,374.49		
						2	1	11	7	4	12	4	7	5	53	$ 1,908.92	$ 80.25	$22,557.37		

Figure 5-3: Example simulation

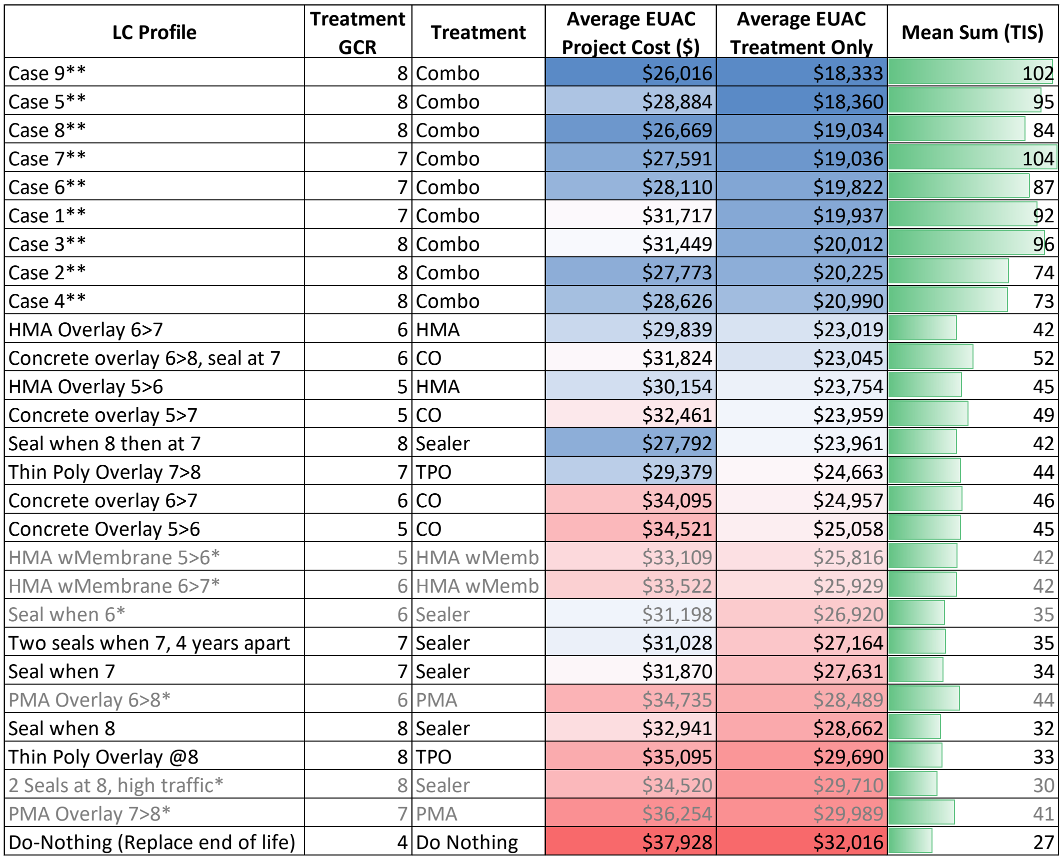


LC Profile	Treatment GCR	Treatment	Average EUAC Project Cost ($)	Average EUAC Treatment Only	Mean Sum (TIS)
Case 9**	8	Combo	$26,016	$18,333	102
Case 8**	8	Combo	$26,669	$19,034	84
Case 7**	7	Combo	$27,591	$19,036	104
Case 2**	8	Combo	$27,773	$20,225	74
Seal when 8 then at 7	8	Sealer	$27,792	$23,961	42
Case 6**	7	Combo	$28,110	$19,822	87
Case 4**	8	Combo	$28,626	$20,990	73
Case 5**	8	Combo	$28,884	$18,360	95
Thin Poly Overlay 7>8	7	TPO	$29,379	$24,663	44
HMA Overlay 6>7	6	HMA	$29,839	$23,019	42
HMA Overlay 5>6	5	HMA	$30,154	$23,754	45
Two seals when 7, 4 years apart	7	Sealer	$31,028	$27,164	35
Seal when 6*	6	Sealer	$31,198	$26,920	35
Case 3**	8	Combo	$31,449	$20,012	96
Case 1**	7	Combo	$31,717	$19,937	92
Concrete overlay 6>8, seal at 7	6	CO	$31,824	$23,045	52
Seal when 7	7	Sealer	$31,870	$27,631	34
Concrete overlay 5>7	5	CO	$32,461	$23,959	49
Seal when 8	8	Sealer	$32,941	$28,662	32
HMA wMembrane 5>6*	5	HMA wMemb	$33,109	$25,816	42
HMA wMembrane 6>7*	6	HMA wMemb	$33,522	$25,929	42
Concrete overlay 6>7	6	CO	$34,095	$24,957	46
2 Seals at 8, high traffic*	8	Sealer	$34,520	$29,710	30
Concrete Overlay 5>6	5	CO	$34,521	$25,058	45
PMA Overlay 6>8*	6	PMA	$34,735	$28,489	44
Thin Poly Overlay @8	8	TPO	$35,095	$29,690	33
PMA Overlay 7>8*	7	PMA	$36,254	$29,989	41
Do-Nothing (Replace end of life)	4	Do Nothing	$37,928	$32,016	27

*Limited data

**Life-cycle profile built based on most common treatments

Figure 5-4: Life-cycle profiles ranked by project costs



LC Profile	Treatment GCR	Treatment	Average EUAC Project Cost ($)	Average EUAC Treatment Only	Mean Sum (TIS)
Case 9**	8	Combo	$26,016	$18,333	102
Case 5**	8	Combo	$28,884	$18,360	95
Case 8**	8	Combo	$26,669	$19,034	84
Case 7**	7	Combo	$27,591	$19,036	104
Case 6**	7	Combo	$28,110	$19,822	87
Case 1**	7	Combo	$31,717	$19,937	92
Case 3**	8	Combo	$31,449	$20,012	96
Case 2**	8	Combo	$27,773	$20,225	74
Case 4**	8	Combo	$28,626	$20,990	73
HMA Overlay 6>7	6	HMA	$29,839	$23,019	42
Concrete overlay 6>8, seal at 7	6	CO	$31,824	$23,045	52
HMA Overlay 5>6	5	HMA	$30,154	$23,754	45
Concrete overlay 5>7	5	CO	$32,461	$23,959	49
Seal when 8 then at 7	8	Sealer	$27,792	$23,961	42
Thin Poly Overlay 7>8	7	TPO	$29,379	$24,663	44
Concrete overlay 6>7	6	CO	$34,095	$24,957	46
Concrete Overlay 5>6	5	CO	$34,521	$25,058	45
HMA wMembrane 5>6*	5	HMA wMemb	$33,109	$25,816	42
HMA wMembrane 6>7*	6	HMA wMemb	$33,522	$25,929	42
Seal when 6*	6	Sealer	$31,198	$26,920	35
Two seals when 7, 4 years apart	7	Sealer	$31,028	$27,164	35
Seal when 7	7	Sealer	$31,870	$27,631	34
PMA Overlay 6>8*	6	PMA	$34,735	$28,489	44
Seal when 8	8	Sealer	$32,941	$28,662	32
Thin Poly Overlay @8	8	TPO	$35,095	$29,690	33
2 Seals at 8, high traffic*	8	Sealer	$34,520	$29,710	30
PMA Overlay 7>8*	7	PMA	$36,254	$29,989	41
Do-Nothing (Replace end of life)	4	Do Nothing	$37,928	$32,016	27

*Limited data

**Life-cycle profile built based on most common treatments

Figure 5-5: Life-cycle profiles ranked by treatment costs only

The critical findings from the simulation analyses are summarized as follows:

- The “do nothing” treatment plan (replace the deck at the end of its life) results in the highest overall EUAC. Any treated deck has a lower life-cycle cost and provides value to the agency and road users.
- Treating decks as early as possible in their life cycles leads to lower EUACs.
- The data set included a limited number of epoxy overlay applications at GCR 8 (only 14 observations), and most were censored observations (11 of 14). It would be beneficial to revisit the TIS data for thin polymer overlays applied at GCR 8 to properly contrast sealers and polymer overlays at GCR 8.
- For an average deck, sealing the deck early, at GCR 8, followed by another seal at GCR 7 results in a lower life-cycle cost. For decks that carry high volumes of traffic, bridge owners should consider applying sealers more frequently than for decks that carry lower volumes of traffic, since the findings indicate that sealers perform significantly differently at high traffic volumes than at low traffic volumes.
- Due to the limited number of cases with various frequencies of sealers at different traffic volumes, an ideal frequency of sealers cannot be recommended at this time. Additionally, comparing the EUACs of sealers at high and low traffic volumes is not meaningful since maintenance decisions regarding decks in these two different environments are independent of each other. Therefore, we recommend that eligible concrete decks on bridges that carry an

AADT of 15,000 or higher be sealed every three years. While current WisDOT policy recommends sealing decks every three to five years regardless of AADT, we recommend that this frequency be determined based on the AADT carried by the structure.

- Due to the data limitations discussed above, it was not possible to properly contrast the cost-effectiveness of HMA overlays with membrane and PMA overlays with other treatment options. We recommend that decisions regarding these treatments take into account site conditions and funding eligibility. We also recommend that WisDOT continue collecting data on these treatments in order to revisit their performance and economic efficiency in the future.
- Some of the life-cycle profiles show decks that are in better condition overall throughout their life cycles. For example, thin polymer overlays are typically applied at GCR 8 or 7, while HMA overlays are typically considered for decks at lower GCRs. Therefore, the life-cycle cost findings presented here should be considered in conjunction with the asset performance measure targets of the agency. The treatment efficiency findings can be incorporated into agency bridge management systems and other decision support tools to facilitate bridge-level decisions.
- Overall, Case 9 (sealing a deck at GCR 8, then at GCR 7, followed by two thin polymer overlays when GCR drops to 7, a concrete overlay at GCR 6, and a seal at GCR 7) provides the most cost-effective option regardless of whether project or treatment costs are considered. We recommend the sequence of treatments in Case 9 as the deck preservation policy for Wisconsin decks, with more frequent seals at GCR 8 for high-AADT corridors when possible.
- Based on project costs, Case 8 (sealing a deck at GCR 8, then at GCR 7, followed by one thin polymer overlay when the GCR drops to 7, a concrete overlay at GCR 6, and a seal at GCR 7) is the second most cost-effective option. Therefore, if a second thin polymer overlay cannot be applied at GCR 7, we recommend a concrete overlay at GCR 6 followed by a seal at GCR 8 (frequency determined based on AADT). Based on treatments costs only, Case 5 (sealing a deck at GCR 8, then at GCR 7 and GCR 6, a concrete overlay at GCR 6, and a seal at GCR 7, followed by a second concrete overlay at GCR 5) is the second most cost-effective option. In cases where a thin polymer overlay cannot be applied, we recommend that decks be sealed at GCRs 8, 7, and 6, before applying a concrete overlay at GCR 6 and then a seal at GCR 8 (frequency determined based on AADT).

6. CONCLUSION

The main objective of this research project was to develop a cost-effective life-cycle treatment plan for the preservation of Wisconsin bridge decks. The research team identified a comprehensive list of strategies through a review of current practice and DOT policies and provided data-driven estimates of the performance and ideal timing of treatments with respect to condition by analyzing historic bridge condition data from WisDOT and other state DOTs and by considering engineering economics principles. To the authors' knowledge, the work presented is the most comprehensive data analysis on deck preservation treatment performance by a state agency.

The main findings from the study can be summarized as follows:

- The "do nothing" treatment plan (replace the deck at the end of its life) results in the highest overall EUAC. Any treated deck has a lower life-cycle cost and provides value to the agency and road users.
- Treating decks as early as possible in their life cycles leads to lower EUACs.
- The data set included a limited number of epoxy overlay applications at GCR 8. It would be beneficial to revisit the TIS data for thin polymer overlays applied at GCR 8 to properly contrast sealers and polymer overlays at GCR 8.
- For an average deck, sealing the deck early, at GCR 8, followed by another seal at GCR 7 results in a lower life-cycle cost. For decks that carry high volumes of traffic, bridge owners should consider applying sealers more frequently than for decks that carry lower volumes of traffic, since the findings indicate that sealers perform significantly differently at high traffic volumes than at low traffic volumes.
- Due to the limited number of cases with various frequencies of sealers at different traffic volumes, an ideal frequency of sealers cannot be recommended at this time. Additionally, comparing the EUACs of sealers at high and low traffic volumes is not meaningful, since maintenance decisions regarding decks in these two different environments are independent of each other. Therefore, we recommend that eligible concrete decks on bridges that carry an AADT of 15,000 or higher be sealed every three years. While current WisDOT policy recommends sealing decks every three to five years regardless of AADT, we recommend that this frequency be determined based on the AADT carried by the structure.
- Due to the data limitations discussed above, it was not possible to properly contrast the cost-effectiveness of HMA overlays with membrane and PMA overlays with other treatment options.
- Some of the life-cycle profiles show decks that are in better condition overall throughout their life cycles. For example, thin polymer overlays are typically applied at GCR 8 or 7, while HMA overlays are typically considered for decks at lower GCRs. Therefore, the life-cycle cost findings presented here should be considered in conjunction with the asset performance measure targets of the agency. The treatment efficiency findings can be incorporated into agency bridge management systems and other decision support tools to facilitate bridge-level decisions.
- Overall, Case 9 (sealing a deck at GCR 8, then at GCR 7, followed by two thin polymer overlays when GCR drops to 7, a concrete overlay at GCR 6, and a seal at GCR 7) provides the most cost-effective option regardless of whether project or treatment costs are considered.

We recommend the sequence of treatments in Case 9 as the deck preservation policy for Wisconsin decks, with more frequent seals at GCR 8 for high-AADT corridors when possible.

- Based on project costs, Case 8 (sealing a deck at GCR 8, then at GCR 7, followed by one thin polymer overlay when the GCR drops to 7, a concrete overlay at GCR 6, and a seal at GCR 7) is the second most cost-effective option. Therefore, if a second thin polymer overlay cannot be applied at GCR 7, we recommend a concrete overlay at GCR 6 followed by a seal at GCR 8 (frequency determined based on AADT). Based on treatments costs only, Case 5 (sealing a deck at GCR 8, then at GCR 7 and GCR 6, a concrete overlay at GCR 6, and a seal at GCR 7, followed by a second concrete overlay at GCR 5) is the second most cost-effective option. In cases where a thin polymer overlay cannot be applied, we recommend that decks be sealed at GCRs 8, 7, and 6, before applying a concrete overlay at GCR 6 and then a seal at GCR 8 (frequency determined based on AADT).

While limited data were available for some treatment options, the work described in this report yielded data-driven estimates of treatment efficiency for deck overlays and sealers. The simulated life-cycle costs for various life-cycle plans give insight into the most cost-effective strategies that could be adapted by WisDOT and potentially other Midwest agencies. The data analysis was enabled by the rich work history data collected by the WisDOT Bureau of Structures and the individual regions. Continuation of this data collection effort at WisDOT is paramount for improving asset management practice and refining the bridge preservation policy further in future.

REFERENCES

ACI Committee 548. 2016. *Guide for Polymer Concrete Overlays*. American Concrete Institute, Farmington Hills, MI.

Bektas, B. A. 2011. Bridge Management from Data to Policy. PhD dissertation, Iowa State University, Ames, IA.

Chamberlain, D. A. and L. F. Boswell. 2005. The Use of Pavix CCC100 as a Reinforced Concrete Impregnate and as an Alternative to Silane. CONREPNET: Performance Based Rehabilitation of Reinforced Concrete Structures Conference, June 23, Prague. http://www.pavix.co.uk/uploads/docs/PAVIX_TECHNICAL_PAPER_AT_CONREP_Conference_CZECH_REPUBLIC.pdf.

DeRuyver, J. and P. Schiefer 2016. *Thin Epoxy Overlay/Healer Sealer Treatments on Bridge Decks*. Michigan Department of Transportation, Region Bridge Support Unit Bridge Field Services, Lansing, MI. https://www.michigan.gov/documents/mdot/Thin_Epoxy_Overlay_and_Healer_Sealer_Treatments_on_Bridge_Decks_395120_7.pdf.

ElBatanouny, M. K., E. I. Nadelman, J. C. Kurth, and P. D. Krauss. 2017. *Use of Polymer Overlays or Sealers on New Bridges*. Iowa Highway Research Board, Ames, IA. http://publications.iowa.gov/26124/.

Evans, J. 2010. *Making Roads and Bridges Resistant to Frost and Ice*. Minnesota Department of Transportation, St. Paul, MN. https://www.lrrb.org/pdf/201013TS.pdf.

FHWA 2018. *Bridge Preservation Guide: Maintaining a Resilient Infrastructure to Preserve Mobility*. FHWA-HIF-18-022. Federal Highway Administration, Office of Bridges and Structures, Washington, DC. https://www.fhwa.dot.gov/bridge/preservation/guide/guide.pdf.

Fowler, D. W. and D. W. Whitney. 2011. *NCHRP Synthesis 423: Long-Term Performance of Polymer Concrete for Bridge Decks*. National Cooperative Highway Research Program, Washington, DC. https://www.nap.edu/download/14623.

Habbouche, J., E. Hajj, and P. Sebaaly 2016. Laboratory and Economic Evaluations of Thin Lift Asphalt Overlay for Pavement Preservation. *Advances in Civil Engineering Materials,* Vol. 5, No. 1, pp. 303–324.

Hydro-Technologies, Inc. and Modified Concrete Suppliers, LLC. 2014. *Maintaining and Preserving Bridge Decks Using Fast Track Hydrodemolition Surface Preparation and Latex Modified Concrete Overlays*. 2014 National Bridge Preservation Partnership, April, 25, Orlando, FL. https://pavementvideo.s3.amazonaws.com/2014_NBPPC/PDF/Tracks/2%20-%20Hydrodemolition%20and%20LMC%20Overlays%20-%20Liberati.pdf.

Illinois DOT. 2011. *Bridge Condition Report Procedures & Practices.* Division of Highways Bureau of Bridges and Structures, Illinois Department of Transportation, Springfield, IL. http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Planning/BCR%20Procedures%20and%20Practices%20.pdf.

Indiana DOT. 2013. *2013 Design Manual: Chapter 412: Bridge Preservation*. Indiana Department of Transportation, Indianapolis, IN https://www.in.gov/indot/design_manual/files/Ch_412_2013.pdf.

Iowa DOT. 2014. *Bridge Maintenance Manual*. Iowa Department of Transportation, Office of Bridges and Structures, Ames, IA. http://publications.iowa.gov/16345/1/Iowa_DOT_TR-646_Bridge_Maintenance_Manual_2014.pdf.

Krauss, P. D., J. S. Lawler, and K. A. Steiner 2009. *Guidelines for Selection of Bridge Deck Overlays, Sealers, and Treatments*. NCHRP Project: 20-07, Task 234. National Cooperative Highway Research Program, Washington, DC. https://www.tsp2.org/library-tsp2/uploads/698/FINAL_NCHRP_Guidelines_20-07_Task234_WJE__Comments_5-19-09.pdf.

Krauss, P. D. and E. A. Rogalla. 1996. *NCHRP Report 380: Transverse Cracking in Newly Constructed Bridge Decks*. National Cooperative Highway Research Program, Washington, DC. http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_380.pdf.

KwikBond Polymers. 2020. PPC 1121: Polyester Polymer Concrete. Product Specification. http://www.kwikbondpolymers.com/products/ppc1121-polyester-polymer-concrete/.

Liu, M. and D. M. Frangopol 2004. Optimal Bridge Maintenance Planning Based on Probabilistic Performance Prediction. *Engineering Structures*, Vol. 26, No. 7, pp. 991–1002.

Mathur, S. 2003. *Effect of High Reactivity Metakaolin (HRM) on Mechanical, Chemical, and Optical Properties of Cement-based Systems*. Society for Mining, Metallurgy & Exploration, Englewood, CO. https://www.onemine.org/document/abstract.cfm?docid=29157&title=Effect-of-High-Reactivity-Metakaolin-HRM-on-Mechanical-Chemical-and-Optical-Properties-of-Cementbased-Systems.

Michigan DOT. 2011. *Bridge Deck Preservation Matrix – Decks with Epoxy Coated Rebar*. Michigan Department of Transportation, Lansing, MI. https://www.michigan.gov/documents/mdot/MDOT_BridgeDeckMatrix_withEpoxyCoatedRebar_355086_7.pdf.

Michigan DOT. 2016. *Special Provision for Thin Epoxy Polymer Bridge Deck Overlay*. Michigan Department of Transportation, Lansing, MI. https://www.atssa.com/Portals/0/12SP-712B-01.pdf.

Minnesota DOT. 2015. *Fiscal Year 2016 through 2020 Bridge Preservation and Improvement Guidelines*. Bridge Office, Minnesota Department of Transportation, St. Paul, MN. http://www.dot.state.mn.us/bridge/pdf/bridge-preservation-and-improvement-guidelines-2016-2020.pdf.

Nabar, S. and P. Mendis. 1997. *Experience with Epoxy Polymer Concrete Bridge Deck Thin Overlays in Service for Over 10 Years*. Special publication/symposium paper, Vol. 169, pp. 1–17. https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/5928.

Oman, M. S. 2014. *Concrete Bridge Deck Crack Sealant Evaluation and Implementation*. Minnesota Department of Transportation, St. Paul, MN. http://www.dot.state.mn.us/research/TS/2014/201434.pdf.

Scherer, W. T. and D. M. Glagola 1994. Markovian Models for Bridge Maintenance Management. *Journal of Transportation Engineering*, Vol. 120, No. 1, pp. 37–51.

Sprinkel, M. 1997. *Nineteen Year Performance of Polymer Concrete Bridge*. Special publication/symposium paper, Vol. 169, pp. 42–74. https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/5930.

Sprinkel, M. 2003. *Twenty-Five-Year Experience with Polymer Concrete Bridge Deck Overlays*. Special publication/symposium paper, Vol. 214, pp. 51–62. https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/12760.

Sprinkel, M. M. 2016. Bond Strength between Shotcrete Overlay and Reinforced Concrete Base of the Saint Johns River Power Park Cooling Tower. *Concrete Repair Bulletin*, January/February 2016, pp. 8–13. https://cdn.ymaws.com/www.icri.org/resource/resmgr/CRB/2016JanFeb/BondStrengthSprinkel.pdf.

Sritharan, S., G. Doiron, D. Bierwagen, B. Keierleber, and A. Abu-Hawash. 2018. First Application of UHPC Bridge Deck Overlay in North America. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2672, No. 26, pp. 40-47. https://journals.sagepub.com/doi/abs/10.1177/0361198118755665.

Tabatabai, H., M. Tabatabai, and C-W. Lee 2010. Reliability of Bridge Decks in Wisconsin. *Journal of Bridge Engineering,* Vol. 16, No. 1, pp. 53–62.

Tabatabai, H., K. Sobolev, A. Ghorbanpoor, A. Nabizadeh, C-W. Lee, and M. Lind. 2016. *Evaluation of Thin Polymer Overlays for Bridge Decks*. Wisconsin Highway Research Program, Madison, WI. https://wisconsindot.gov/documents2/research/12-06-2nd-final-report.pdf.

Thompson, P. D., K. M. Ford, M. H. R. Arman, S. Labi, K. C. Sinha, and A. M. Shirole. 2012. *NCHRP Report 713: Estimating Life Expectancies of Highway Assets: Volume 1: Guidebook*. National Cooperative Highway Research Program, Washington, DC. https://www.nap.edu/download/22782.

Uhlmeyer, J. S., L. M. Pierce, and J. T. Weston. 2003. *NOVACHIP®: SR-17, City of Soap Lake, Milepost 75.44 to Milepost 76.15*. Washington State Department of Transportation, Olympia, WA. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.369.8484&rep=rep1&type=pdf

Wisconsin DOT. 2016. *Bridge Preservation Policy Guide, Version 1.02*. Wisconsin Department of Transportation, Bureau of Structures, Madison, WI. https://wisconsindot.gov/dtsdManuals/strct/manuals/preservation/wisdot-prsv-pol.pdf.

Wisconsin DOT. 2018. *WisDOT Bridge Manual*. Wisconsin Department of Transportation, Madison, WI. https://wisconsindot.gov/dtsdManuals/strct/manuals/bridge/ch-all.pdf.

Wisconsin DOT. 2020. *Structure Inspection Field Manual*. Wisconsin Department of Transportation, Madison, WI. https://wisconsindot.gov/dtsdManuals/strct/inspection/insp-fm-2020.pdf.

APPENDIX A: POLICIES AND PERFORMANCE EXPECTATIONS FOR DECK SEALERS AND OVERLAYS

Overlays Used in Wisconsin

Thin Polymer Overlay

Thin polymer overlays (TPOs) are categorized into three types: multi-layer, slurry, and premixed system. They are typically 1 inch or less in thickness. TPO provides a minimal dead load to a pre-existing bridge as well as an impermeable surface to prevent chlorides from infiltrating the deck. TPOs may also be used to improve surface friction. They are expected to extend the bridge deck service life by 7 to 15 years. TPOs may be used on decks with a National Bridge Inventory (NBI) rating of more than 7. The deck must be in good condition with a distressed area of less than 2% of the total deck area. Less than 10 years of chloride exposure is required. In the case of 10 to 15 year old decks with above-average deck condition, traffic volume must be considered. TPOs must be placed on decks and patches older than 21 days. Patches must be compatible with the overlay material. In the case of active large (> 0.04 inches) cracks, TPOs are not recommended. Use of TPOs on concrete approaches must be avoided due to moisture issues. Reapplication of thin polymer overlays may be considered if the deck meets the above specifications and the original TPO has performed well (Wisconsin DOT 2018).

Low-Slump Concrete Overlay (Concrete Overlay)

Concrete overlays use low-slump Grade E concrete. The thickness varies between 1.5 to 4.5 inches. Concrete overlays are expected to extend the bridge deck service life by 15 to 20 years. Concrete overlays require certain specifications, such as equipment, consolidation, and curing requirements. Upon the application of concrete overlays, any cracks must be sealed to minimize deck deterioration. Delaminated, structurally sound decks may be rehabilitated using concrete overlays instead of being replaced. The distressed surface must not exceed 25%. In cases where this percentage is exceeded, a cost analysis is required. If the underside of the deck or slab shows more than 5% distress, the deck must be replaced in the future. With a pre-existing overlay, the deck condition should be evaluated. The pre-existing overlay must be removed to the original deck surface prior to placement of the new overlay. Complete removal and replacement of the overlay is an option if the deck remains structurally sound (Wisconsin DOT 2018).

Polyester Polymer Concrete Overlay

Polyester polymer concrete (PPC) overlays are considered thin polymer overlays. Their recommended thickness should not exceed 1 inch (> 1 inch is cost prohibitive). PPC overlays are expected to extend the service life of the bridge deck by 20 to 30 years. They are applied using conventional concrete mixing and placement equipment that is exclusively intended for PPC usage. PPC overlays provide an impermeable surface while minimizing any traffic disruptions due to its quick curing time (2 to 4 hours). Prior to the overlay application, high molecular weight methacrylate (HMWM) binder is used to prepare the deck. HMWM also serves in sealing any existing cracks. PPC must be used on decks in good condition that require shorter traffic disruptions. The deck must have a wearing distress of 5% or less, have an NBI rating greater than 7, and be less than 15 years old. If the deck is older, it must be previously protected by a

TPO or have an acceptable chloride level. In the case of chloride exposure of more than 10 years, 0.75 inches of scarification is required. Chloride content should not exceed 5 lb/yd^3 for epoxy-coated reinforcement. PPC is not recommended on decks with an uncoated top mat reinforcement. Unless approved, PPC must not be applied on concrete decks or patches that are less than 28 days old. The patch crack repair and overlay material must be compatible. PPC is expensive and relatively new and must not be used for structural repairs due to cost and performance concerns. PPC is limited mainly for preservation projects and must be approved by the Bureau of Structures (Wisconsin DOT 2018).

Polymer-Modified Asphaltic Overlay

Polymer-modified asphaltic (PMA) overlays use aggregates, asphalt content, and a thermoplastic polymer modifier additive. The added polymer makes the overlay impermeable to water and chloride infiltration. The choice of aggregates is also very important because the aggregates selected and permeability are highly dependent. Moreover, limestone aggregates are not to be used. To achieve the protection that this type of overlay offers, proper mix control and placement procedures are crucial. PMA overlays have a minimum thickness of 2 inches. They extend the deck service life by 10 to 15 years and accommodate both profile and cross-slope differences. PMA overlays may also be used on flexible structures. PMA product availability and its ability to maintain an acceptable temperature in a given location should be considered by designers ahead of application (Wisconsin DOT 2018).

Asphaltic Overlay

Asphaltic overlays use asphaltic pavement with a mixture of aggregates and asphaltic material. Conventional asphaltic and placement equipment is typically used for overlay application. Without a waterproofing membrane, asphaltic overlays extend the deck service life by 3 to 7 years. The waterproofing membrane prevents the overlay from trapping moisture at the deck's surface, thus decelerating deterioration. The thickness of asphaltic overlays is 2 inches minimum. They can accommodate profile and cross-slope differences. Asphaltic overlays may need to be monitored for distress because distresses easily reflect through the surface. If a deck or bridge is lightly used and is to be replaced within four years, asphaltic overlays may be used to provide a smooth riding surface. Asphaltic overlays without a waterproofing membrane are not eligible for federal funds (Wisconsin DOT 2018).

Asphaltic Overlay with Waterproofing Membrane

Asphaltic overlays with a waterproofing membrane decelerate deck deterioration through creating an impermeable surface for water and chloride movement into the concrete. They extend the bridge deck service life by 5 to 15 years. Asphaltic overlays with a waterproofing membrane were more commonly used in the 1990s. They were phased out in 2009 due to performance concerns and difficulties in deck inspection. This overlay type is currently being studied for further improvements. If a deck or bridge is scheduled for replacement, low-slump concrete or PMA are usually recommended over an asphaltic overlay with waterproofing membrane unless approved otherwise. The use of this type of overlay requires prior approval by the Bureau of Structures (Wisconsin DOT 2018).

Other Overlays

Various overlays used in previous projects are currently no longer used. They require approval by the Bureau of Structures.

Microsilica (Silica Fume) Modified Concrete Overlay

Commonly used for improving durability, this overlay has very low permeability and therefore high resistance to chloride penetration.

Latex-Modified Concrete Overlay

This long-lasting overlay is used when minimal traffic disruption is required. It is also being used in multiple states when deck preparation includes hydrodemolition.

Reinforced Concrete Overlay

This overlay can be either thin or thick. Thin reinforced concrete overlays are less than 4.5 inches in thickness. To reduce cracks and crack diameters, this overlay uses superplasticizers or fiber enforcements that are either steel or synthetic for added crack control. Thick reinforced concrete overlays are 4.5 inches in thickness or more. For new structural decks, this overlay uses steel reinforcement, weld wire fabric, or rebar. This overlay type includes at least one layer of reinforcement per direction for crack control. In general, rehabilitation overlays more than 4.5 inches in thickness do not require steel reinforcements. When using steel reinforcements, low-slump Grade E concrete should not be used. Thick reinforced concrete overlays are currently being recommended for prestressed concrete box girder superstructures (Wisconsin DOT 2018).

Overlays Used in Neighboring States

Concrete Overlays

Concrete overlays are widely used in states neighboring Wisconsin, including Minnesota, Iowa, Illinois, Michigan, Indiana, Kansas, North Dakota, and South Dakota.

The Iowa DOT refers to concrete overlays as the most used overlay type on bridge decks in Iowa. Portland cement concrete overlay (PCC), the traditional low-slump overlay, with an estimated lifespan of 25 to 30 or more years, is commonly used by the Iowa DOT. High-performance concrete (HPC) overlays are regarded as an alternative with the same lifespan.

In Minnesota, reportedly, the use of HPC overlays and synthetic fibers has reduced bridge deck cracking. However, the Minnesota Department of Transportation (MnDOT) believes that the performance of decks with fibers should be studied for a longer period of time to estimate how long fibers extend deck service life. Recent experience in Minnesota also indicates that monolithic decks develop fewer cracks than bridge decks with low-slump overlays. In Indiana, low-slump concrete overlays are not recommended because their performance is comparable to that of latex-modified concrete (LMC) overlays, but they are more expensive. North Dakota also names low-slump concrete overlays as the only overlay type currently used on the state’s bridges.

Reinforced concrete overlays for closely spaced PPC box beams are being utilized in Illinois, along with hot-mix asphalt (HMA) overlays with sheet membranes. One of the overlays used most by the Michigan DOT is rigid concrete (deep and shallow). Besides these, HMA with membrane and HMA cap are also listed as deck preservation overlays (Michigan DOT 2011). The Washington State DOT (WSDOT) applies three modified concrete overlays: LMC, microsilica concrete (MSC), and fly ash-modified concrete (FAMC). The Kansas DOT (KDOT) has previously used dense PCC overlays (1½ inches). However, recent information from KDOT indicates that it currently uses PCC overlays (1½ inches). WSDOT also does not use low-slump dense concrete (LSDC) overlays anymore because they performed poorly on the state's network. Unlike Kansas, South Dakota still uses LSDC overlays. Information from the South Dakota DOT (SDDOT), however, indicates that the state is trying a modified Class A concrete to replace LSDC overlays. Only a couple have been placed so far.

Epoxy/Polymer and Polyester Polymer Concrete Overlays

Epoxy overlays are one of the most commonly used overlays by state DOTs. MnDOT has been using epoxy overlays since 2007 on satisfactory- to good-condition decks (Minnesota DOT 2015). Information from MnDOT indicates that although epoxy overlays have a life expectancy of 10 years, there have been some premature failures with some systems. Epoxy and rigid concrete overlays are the most commonly used overlays by the Michigan DOT (MDOT). MDOT has experienced great success with epoxy overlays and will continue to use them for deck protection. MDOT has developed a special provision on thin epoxy polymer bridge deck overlay implementation that includes specifications on materials, equipment, and construction of two-coat epoxy overlay systems (Michigan DOT 2016). North Dakota is also considering using epoxy overlays on a limited basis. Currently, this treatment is used minimally in South Dakota. South Dakota has also recently started experimenting with polymer chip seal overlays.

The second most frequently used overlays in the region neighboring Wisconsin are PPC overlays. Iowa uses a multi-layer polymer (MLP) overlay with an estimated lifespan of 15 to 20 years. The state is currently considering KwikBond polyester polymer (thick polymer) concrete overlays for testing purposes. MnDOT notes some benefit to thin polymer overlays, such as the fact that it is not subject to shrinkage cracking (no cement), is impermeable, and cures quickly, which allows accelerated construction. MnDOT also uses PPC overlays with a life expectancy of 30 to 40 years. The Illinois DOT lists polymer-modified overlays among its currently used overlays, with an estimated life of 10 years. In recent years, flexible overlays, also known as polymer or thin overlays, have been used for bridge decks by the Indiana DOT (INDOT), with an average service life of 10 years. However, according to INDOT policy, those bridge decks that have previously received a concrete overlay are not suitable for a flexible overlay. On the other hand, bridge decks with small amounts of delamination are more appropriate for flexible overlays. KDOT has recently started using polymer overlays (polyesters) ¾ inches or more in thickness. This is the newest overlay the state is using, and a total of four polymer overlays have been applied, with some placement and cost issues. KDOT estimates the life expectancy of polymer overlays to be 10 to 15 years for major urban areas and 20 to 25 years for others. The Virginia DOT (VDOT) allows the use of polymer-modified concrete (PMC) overlays only under special provisions. PMC overlays are used on both new and existing bridges in Tennessee. Information from the North Dakota DOT (NDDOT) indicates that the state may also consider using a PPC overlay in specific cases. The South Dakota DOT is currently using polymer chip seal overlays. MDOT conducted a project in 2018 to experiment with a polyester overlay.

Latex Concrete Overlays

Latex concrete overlays are some of the most popular concrete overlays among the Midwest states. Although KDOT is not using latex-modified concrete deck overlays anymore, there are other states that use it frequently. IDOT includes latex concrete overlays in its list of alternative preservation treatments, and it is currently being used with an estimated lifespan of 20 or more years (Illinois DOT 2011). Ohio's *Bridge Design Manual* also specifies LMC for bridge deck overlays. Washington State DOT uses LMC, but the use of rapid set latex-modified concrete (RSLMC) has been discontinued due to poor performance. Since the 1970s, INDOT has been successfully using LMC overlays. Based on the traffic and site conditions, an LMC overlay is expected to protect the bridge deck for approximately 15 years.

INDOT uses fast track hydrodemolition with LMC overlays for bridge decks because the combination provides an economical, long-lasting, and very fast bridge deck preservation method (Hydro-Technologies 2014). Hydrodemolition minimizes the residual cracking around patched areas caused by manual methods such as jackhammers. INDOT uses hydrodemolition on bridge rehabilitation projects requiring deck patching when cost-effective (Hydro-Technologies 2014). Hydrodemolition may not be cost-effective for small bridge decks or in isolated locations.

Silica Fume (Microsilica) Concrete Overlays

These overlays are no longer used by the Wisconsin DOT (WisDOT) but were used in the past. KDOT has used 1½ inch silica fume concrete deck overlays in the past. Microsilica concrete overlays are also currently being used by the Illinois and Ohio DOTs. MnDOT uses silica fume overlays with fibers. INDOT has been using microsilica concrete overlays since the early 1990s to provide a low-diffusivity concrete overlay, but they are still considered experimental and must be approved before use.

Ultra-High Performance Concrete Overlays

In recent projects and related research, Iowa has explored the use of ultra-high performance concrete (UHPC) with fiber reinforcement (UHPFRC) as a durable option to combat wide-ranging bridge deck deterioration problems (Sritharan et al. 2018). Although durability is known to be the best benefit of UHPC overlays in comparison to other alternatives, recent research from Iowa (Sritharan et al. 2018) indicates that more quantifiable benefits for UHPC overlays are required to outweigh the additional expense of using the new technology. However, that research also concludes that a 1½ inch UHPC overlay is an ideal choice to provide an impermeable surface for a bridge deck. Also, a UHPC layer in conjunction with a rebar mat can increase the deck's load capacity. This system is suggested as an alternative to full deck replacement (Sritharan et al. 2018).

Asphalt Overlay with Membrane

An asphalt overlay with waterproofing membrane is the primary deck protection system used in Nebraska. It is anticipated that most Nebraska bridges will have this treatment. Expected performance depends on overlay depth and membrane type. If a bridge's rail height and load rating are sufficient for a 3-inch overlay, then the membrane's service life is considered indefinite and the future asphalt surface would be replaced with a 2-inch mill/fill at the frequency that the roadway needs (about 15 years). If a 2-inch overlay is placed, then it is considered unlikely that the membrane will survive a milling operation and would be replaced when the asphalt overlay pavement needs replacement. Asphalt overlays with waterproofing membrane seem to have a longer service life than asphalt pavement on most roadway surfaces due to the stability of the bridge deck as a subgrade. Nebraska has a couple of bridges where the original 1974 asphalt is still on the deck (these decks have required a lot of crack sealing but have held up well). The Nebraska DOT (NDOT) has an element (9512) to collect element condition data for these overlays. Most membranes are a preformed fabric-backed bituminous type; 241 are in service now. Spray-on polyurea (cold liquid-applied) membranes are also used in high-traffic areas; 33 are in service now and another 18 or so are being placed.

The Illinois DOT also uses HMA with sheet membrane.

High-Reactivity Metakaolin Overlays

According to Mathur (2003), high-reactivity metakaolin (HRM) "is manufactured with selected naturally occurring kaolin crudes, carefully processed under stringent conditions to result in a reproducible product." IDOT is currently using HRM overlays as an effective overlay for its bridges. There are multiple benefits to using HRM, including but not limited to workability enhancement, increased strength, and reduced permeability (Mathur 2003).

SafeLane Overlays

SafeLane overlays are among the preferred overlays for Illinois bridges due to their anti-icing properties. Research by the University of Minnesota that studied materials designed to prevent frost and ice from building up on its roads and bridges, showed that while the SafeLane overlay significantly increased traction and reduced crash rates, it was subject to rapid wearing caused by traffic and snowplows (Evans 2010). Further research was suggested in the future when more data are available to investigate performance and effectiveness.

NovaChip Overlays

MDOT uses NovaChip overlays on bridges with less than 2% patching and new expansion joints. MDOT gives an estimate of 10 years for NovaChip's expected life. NovaChip is a pavement rehabilitation, preventive maintenance, or surface treatment overlay that is known for surface durability and improved skid resistance, rut resistance, and wear resistance. NovaChip consists of a thin (3/8- to 3/4-inch), gap-graded coarse aggregate hot mix over a Novabond membrane (polymer-modified asphalt emulsion seal coat) (Uhlmeyer et al. 2003).

Epoxy Injection in Rigid Overlays

During an interim meeting for this project on January 12, 2018, members of the project oversight committee (POC) requested that the project team ask Midwest states whether they used epoxy injection in rigid overlays. This question was included in the emails or phone calls to the agency contacts described in the main report. Injecting epoxy into localized delaminations between the interface of a structural bridge deck and a concrete overlay is a common practice for the Iowa DOT (Iowa DOT 2014). The Michigan DOT has used epoxy injection on shallow concrete overlays that had debonded from the original deck. A shallow overlay is a latex- or silica fume-modified concrete where the top mat of rebar is not exposed (typically involving around 2 inches of removal, with replacement in kind). This work has been done using state maintenance crews and has had good success. MDOT notes that ideal candidates for this treatment can be difficult to find because the bottom surface must be in fair to good condition to prevent the epoxy from flowing out the bottom of the deck. KDOT implemented one epoxy injection in a rigid pavement overlay 20 years ago, but the state is reconsidering using it as an option.

Sealers Used by Neighboring States

WisDOT's 2016 *Bridge Preservation Manual* indicates sealing 25% of the bridge deck area of eligible concrete decks and slabs in good or fair condition with waterproofing penetrating sealant every four years as a cyclical objective.

IDOT also recommends that sealers be used every four years. Based on research done by IDOT, using a protective coat, penetrating sealers, and laminates deters the ingress of chloride ions into PCC (Illinois DOT 2011). IDOT has proposed a policy that all new bridge deck construction, new overlays, and existing bridge decks for which the state would like to buy more service time should be protected from the ingress of chloride ions by a sealant or laminate.

Crack sealants are typically reapplied by MnDOT crews at a three- to five-year frequency (five years for life-cycle cost). MnDOT completed a research study in 2014 that evaluated 12 concrete bridge deck crack sealants and changed the agency's product qualification process accordingly (Oman 2014).

Sealers currently used by state DOTs, as gathered from agency documents and information gathered during Task B of this project, are described in the following sections.

Saline

The Iowa DOT uses saline with two different mixtures and expects three to four years of life:

- 100% saline, MasterProtect H 100, manufactured by BASF
- 90% saline and 10% mineral spirits concrete sealer, TK-590-90, manufactured by TK Products

Saline is also being considered by the Michigan DOT and will be used in the near future (the DOT is currently in search of a product maintenance crews to use).

Water-Based Sealers

The Iowa DOT is using two different water-based sealers with three to four years of life expectancy, as described below. However, the results from penetration tests show that none of the sealants are effective, and the Iowa DOT has not received good results from these sealants.

Star Macro-Deck

Star Macro-Deck is supposed to protect concrete bridge decks against salt and damage from chemicals. Its claimed features include inhibiting chloride deicing chemicals, salt, and damage from chemicals to concrete and maintaining the flexural and tensile strength of the concrete.

Pavix CCC100

Chem-Crete Pavix CCC100 is a unique water-based chemical product for the protection of large-scale concrete layers against problems associated with temperature and water, such as thermal cracking, repeated freeze and thaw cycles, chloride ion penetration, and alkali silica reaction. Pavix CCC100 is designed to achieve the same benefits as saline sealers and deliver additional benefits for structures, construction workers, and the environment (Chamberlain and Boswell 2005).

Healer-Sealers

Healer-sealer is commonly used as a sealant by the Michigan DOT. According to DeRuyver and Schiefer (2016), a healer-sealer is "a crack penetrating sealer with a much lower viscosity than thin overlay materials."

Methyl Methacrylate Resin Crack Sealers

Methyl methacrylate (MMA) is a crack sealer for concrete structures. MMA allows an ultra-fast cure time and super-tough physical characteristics. MnDOT uses MMA as a sealer for concrete bridges.

Polymer Sealers

KDOT has been using polymer sealers (two courses, 3/8 inches or less in total) with a life expectancy of 10 to 15 years for urban areas and 25 years for others. However, the experience has not been consistent, and the KDOT materials department does not allow using sealers because it is not deemed cost-effective.

Epoxy Sealers

North Dakota uses epoxy crack sealers. These sealers use a crack chasing method different from that of healer-sealers. So far, North Dakota has experienced good performance with epoxy sealers. The agency recommends resealing on a three-year cycle. INDOT also recommends the use of epoxy sealants with a service life of three years to prevent the ingress of chloride ions into concrete bridge decks. MnDOT uses two different types of epoxy sealers: high-elongation epoxy crack sealers and high-strength epoxy crack sealers.

Silane

Silane is a commonly used surface treatment to reduce water entry into concrete. All bridge decks in North Dakota are treated with silane at the time of construction. NDDOT has guidance to re-treat the decks with silane on a six-year cycle, but the agency has only started actually retreating them in the last couple of years. INDOT also recommends the use of silane with a service life of three years to prevent the ingress of chloride ions into concrete bridge decks. Minnesota uses 40% and 100% silane for bridge penetrating sealers.

A summary of sealants used by states neighboring Wisconsin is provided in Table A-1.

Table A-1: Sealants used by states neighboring Wisconsin

State	Sealer	Expected Performance (years)	Application Details
Iowa	Saline Star Macro-Deck Pavix CCC100	3–4 3–4 3–4	Iowa DOT is not satisfied with the results from its sealants.
Michigan	Saline Healer-Sealer	8–10	
Indiana	Epoxy Silane		
Kansas	Polymer (two courses)	10–15	Temperature must be above 40°F. Must remove shallow voids in the deck. Epoxies must be compatible with patching materials. Contamination must be avoided. Not to be placed directly over a new concrete deck without allowing for adequate cure time.
North Dakota	Epoxy Silane	3 6	Getting the surface prepped, particularly for crack sealing, is important to get a good result.
Minnesota	MMA Epoxy Silane	3–5 3–5 3–5	For sealants, air-blown test sections perform better than sand-blasted test sections.

Implementation Specifications for Overlays Used by WisDOT

An Excel file, detailing various implementation specifications for the types of overlays currently used by WisDOT, was submitted to the POC with an intermediary report. For each type of overlay, a worksheet within that file details the identified implementation specifications or information gathered from agencies. Additional information is presented below.

Research conducted for the Iowa DOT listed the following recommendations for implementation of polyester polymer concrete overlays (ElBatanouny et al. 2017):

- Uneven surfaces should be corrected prior to the application of the overlay (Nabar and Mendis 1997).
- Avoid rapid changes in overlay thickness (Nabar and Mendis 1997).
- Maximum temperatures for placement are commonly limited to 95°F (ACI 2016).

- Minimum temperatures for placement are commonly set by DOTs in the range of 50°F to 60°F (Fowler and Whitney 2011).
- The substrate tensile strength and overlay bond strength should be evaluated based on ASTM C1583 or the test methods described in ACI 503R or CA55.
- Minimum bond strength values have been specified for the overlay materials, often ranging between 100 and 250 psi (Sprinkel 1997, Sprinkel 2016).
- A minimum direct pull strength of 250 psi should be readily achieved.
- In a relatively recent survey, material suppliers recommended that a surface roughness of ICRI CSP 7 is desirable, with a minimum roughness of ICRI CSP 6 (Fowler and Whitney 2011).
- Curing (Sprinkel 2003):
  - Two hours at 90°F
  - Three hours at 75°F
  - Five to six hours at 60°F

Overlay Policies from Neighboring States

Available policy documents from neighboring states were examined to develop the following notes covering Minnesota, Illinois, and Indiana.

Minnesota DOT Policies

- Decisions to overlay or re-overlay a bridge deck should consider life-cycle costs and benefits. A decision to remove and replace a bridge deck will generally extend the “repair-free” service life to the 75-year design life of a bridge. A decision to provide a protective overlay on a bridge deck will generally extend the service life another 10 to 30 years, depending on the prior condition of the deck. Placing bituminous overlays may help maintain rideability in the deck’s last few years of life.
- In locations with high traffic volumes and high levels of deicing chemical usage, special emphasis should be given to the programming of protective systems for bridge decks (Minnesota DOT 2015).
- Grade separation bridges with no access to mainline roadways generally should not be programmed for protective overlays unless high traffic volumes (average daily traffic [ADT] > 2,000), frequent use of deicing chemicals, or evidence of deck deterioration warrant overlays (Minnesota DOT 2015).
- Where overlays are not warranted but leakage through existing joints is damaging the superstructure or substructure, waterproof joint installation should be considered (Minnesota DOT 2015).
- Bridges with high levels of existing deck cracking, high levels of anti-icing chemical use, and accident-prone conditions are good candidates for an epoxy overlay. Epoxy overlays are recommended for box girder bridges or for bridges with limited load capacity. In addition, due to this overlay type’s quick curing and application times, bridges with limited or time-sensitive construction access can make good candidates for epoxy overlays (Minnesota DOT 2015).
- It is recommended that epoxy overlays be applied on satisfactory- to good-condition decks (Minnesota DOT 2015).

- Where it is necessary to maintain rideability or minimize the need for surface repairs, short-term overlays are frequently used to extend the service life of bridge decks. Service life can be extended up to 5 years when bituminous overlays of 2 to 4 inches are used, while concrete overlays of up to 3 inches over deteriorated concrete may provide up to 10 to 15 years of additional service life (Minnesota DOT 2015).
- Districts should pay particular attention to monitoring the condition of in-place concrete overlays and monolithic decks on box girder bridges and other structures for which deck replacement is cost prohibitive or presents significant constructability problems. Structures of this type should be monitored to determine the chloride content at various depths of the overlay at intervals not exceeding 5 years. The bridge should be programmed for overlay replacement before the concrete at the level of the top rebar reaches half of the corrosion threshold (Minnesota DOT 2015).

Illinois DOT Policies

- If the wearing surface shows significant deterioration such as cracking, debonding, and spalling, it should be considered for repair or replacement. An evaluation survey is mainly performed on the top deck for this decision, although a survey of the bottom of the deck can also be useful (Illinois DOT 2011).
- Life-cycle cost analysis is utilized to study various percentages of deck repair verse deck replacement to determine whether repair or replacement is more economical. Table A-2 was developed to assist in making such decisions. The numbers listed in the table represent the estimated total percentage of the deck area that will be repaired (total repair percentage = partial-depth repair percentage + full-depth repair percentage). A maximum limit of 13% for full-depth deck repairs is recommended when repairing the deck for economic considerations and to ensure long-term soundness (the percentage of full-depth repairs includes deck removal at transverse joints).

Table A-2: Deck repair versus replacement assessment

Equal Width Decks	Decks Requiring Widening	Recommendation
≤ 25%	≤ 15%	Deck repair cost-effective
26%–35%	16%–25%	Deck repair cost-effective only in well-documented cases
> 35%	> 25%	Deck replacement appropriate

Source: Illinois DOT 2011

- If a recommended repair method results in dead load in excess of the existing conditions, approval must be obtained from the Bureau of Bridges and Structures (Illinois DOT 2011).
- The B-SMART Program allows for the quick approval of low-cost bridge deck preservation projects. The program is intended to extend the life of the deck by 12 to 20 years (depending on overlay type and location) on structures with good superstructures and substructures (Illinois DOT 2011).

Indiana DOT Policies

- Attaining a minimum of 75 years of service life from a bridge deck is considered cost-effective. This service life is reached by INDOT through the placement of latex-modified

concrete overlays and the use of fast track hydrodemolition. A service life of 75 years or more can be achieved as follows:
  - Year 1 – Construct new bridge deck
  - Year 25 – Place LMC overlay #1 and use hydrodemolition
  - Year 50 – Place LMC overlay #2 and use hydrodemolition
  - Year 75 – Replace bridge deck
- INDOT practice is to use hydrodemolition on bridge rehabilitation projects requiring deck patching when cost-effective.
- It is acceptable to remove an existing overlay and replace it with a new one.
- A new overlay should not be placed over an existing bridge deck overlay.
- LMC overlays have been successfully used by INDOT since the 1970s.
- Asphalt overlays over sheet membranes were used in the past with limited success. However, new research is revealing positive impacts of using this treatment (Indiana DOT 2013).
- Polymeric or thin overlays have been utilized more frequently in recent years. While these types of overlays have been found not to be appropriate for bridge decks that have previously received a concrete overlay yet, they could be used for bridge decks with small amounts of delamination (Indiana DOT 2013).

APPENDIX B: TIS ANALYSIS RESULTS

Impacting Treatment Type	(NEW)							
% of Obs. In Treatment	**Previous NBI Rating**							
GCR Increase	**3**	**4**	**5**	**6**	**7**	**8**	**x**	**Grand Total**
1	0.00%	0.00%	0.00%	0.34%	0.21%	0.07%	0.00%	0.62%
2	0.00%	0.00%	0.48%	1.58%	0.07%	0.00%	0.00%	2.13%
3	0.00%	0.14%	2.06%	1.72%	0.00%	0.00%	0.00%	3.91%
4	0.00%	1.92%	2.26%	0.00%	0.00%	0.00%	0.00%	4.19%
5	0.48%	1.85%	0.00%	0.00%	0.00%	0.00%	0.00%	2.33%
Unknown	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	86.82%	86.82%
Grand Total	0.48%	3.91%	4.80%	3.64%	0.27%	0.07%	86.82%	100.00%

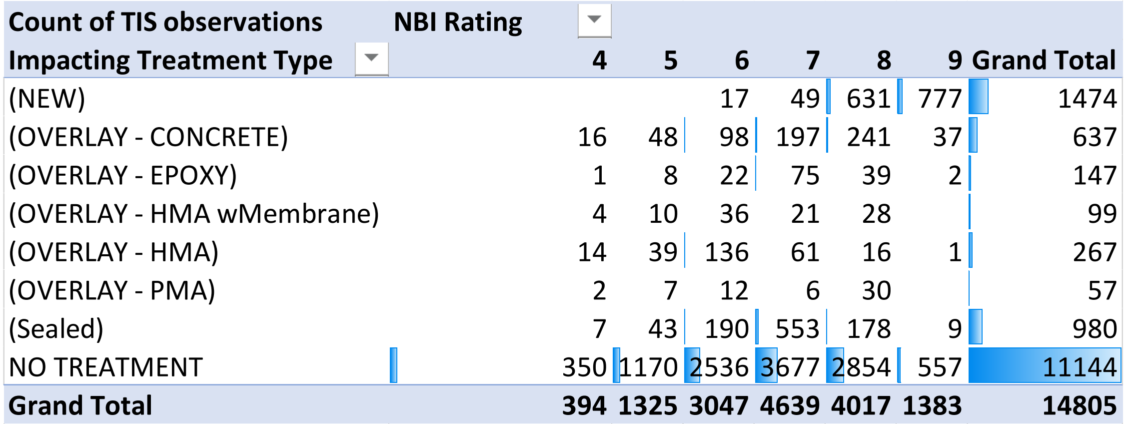
Impacting Treatment Type	(OVERLAY - EPOXY)				
% of Obs. In Treatment	**Previous NBI Rating**				
GCR Increase	**4**	**5**	**6**	**7**	**x**	**Grand Total**
1	1.96%	5.88%	33.33%	31.37%	0.00%	72.55%
2	0.00%	3.92%	1.96%	0.00%	0.00%	5.88%
4	0.00%	1.96%	0.00%	0.00%	0.00%	1.96%
Unknown	0.00%	0.00%	0.00%	0.00%	19.61%	19.61%
Grand Total	1.96%	11.76%	35.29%	31.37%	19.61%	100.00%

Impacting Treatment Type	(OVERLAY - HMA with Membrane)					
% of Obs. In Treatment	**Previous NBI Rating**					
GCR Increase	**4**	**5**	**6**	**7**	**x**	**Grand Total**
1	1.35%	6.76%	8.11%	13.51%	0.00%	29.73%
2	1.35%	2.70%	6.76%	0.00%	0.00%	10.81%
3	0.00%	8.11%	0.00%	0.00%	0.00%	8.11%
Unknown	0.00%	0.00%	0.00%	0.00%	51.35%	51.35%
Grand Total	2.70%	17.57%	14.86%	13.51%	51.35%	100.00%

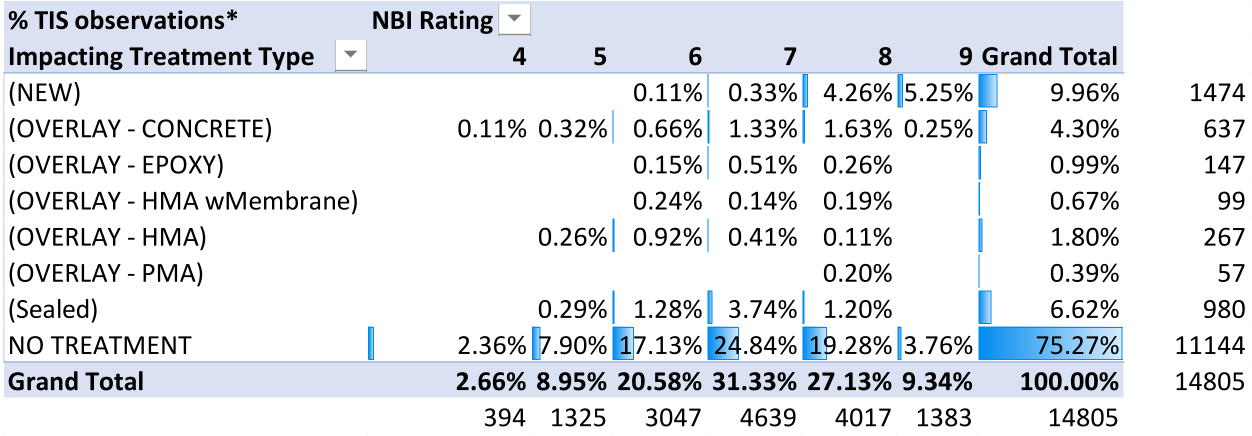
Impacting Treatment Type	(OVERLAY - HMA)							
% of Obs. In Treatment	Previous NBI Rating							
GCR Increase	2	3	4	5	6	7	x	Grand Total
1	0.00%	1.12%	2.23%	15.08%	17.32%	3.91%	0.00%	39.66%
2	0.56%	0.00%	2.79%	3.91%	2.23%	0.00%	0.00%	9.50%
3	0.00%	0.56%	1.12%	1.68%	0.56%	0.00%	0.00%	3.91%
Unknown	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	46.93%	46.93%
Grand Total	0.56%	1.68%	6.15%	20.67%	20.11%	3.91%	46.93%	100.00%

Impacting Treatment Type	(OVERLAY - PMA)					
% of Obs. In Treatment	Previous NBI Rating					
GCR Increase	4	5	6	7	x	Grand Total
1	2.22%	13.33%	6.67%	33.33%	0.00%	55.56%
2	0.00%	0.00%	26.67%	0.00%	0.00%	26.67%
Unknown	0.00%	0.00%	0.00%	0.00%	17.78%	17.78%
Grand Total	2.22%	13.33%	33.33%	33.33%	17.78%	100.00%

Impacting Treatment Type	(Sealed)						
% of Obs. In Treatment	Previous NBI Rating						
Increase in CR	4	5	6	7	8	x	Grand Total
1	0.00%	2.56%	23.08%	12.82%	1.28%	0.00%	39.74%
2	0.00%	4.49%	1.92%	0.00%	0.00%	0.00%	6.41%
3	0.64%	4.49%	1.28%	0.00%	0.00%	0.00%	6.41%
4	0.00%	0.64%	0.00%	0.00%	0.00%	0.00%	0.64%
Unknown	0.00%	0.00%	0.00%	0.00%	0.00%	46.79%	46.79%
Grand Total	0.64%	12.18%	26.28%	12.82%	1.28%	46.79%	100.00%

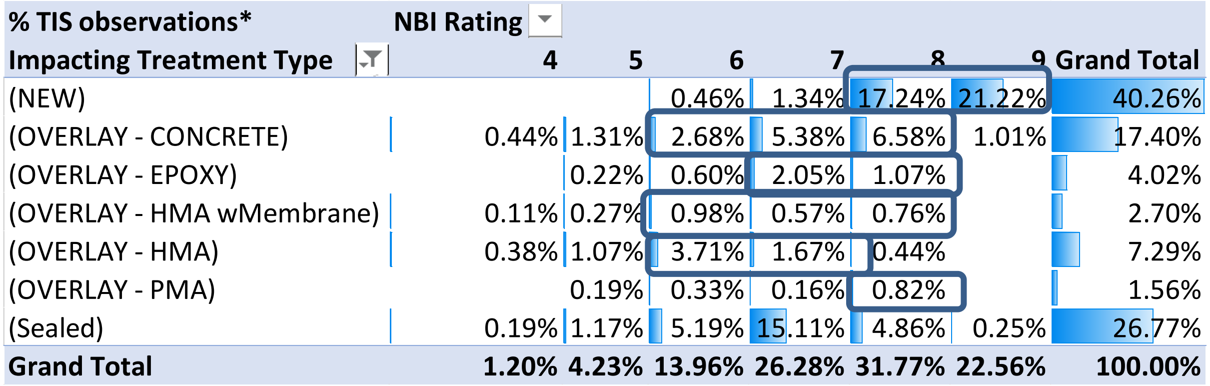


Count of TIS observations	NBI Rating						
Impacting Treatment Type	4	5	6	7	8	9	Grand Total
(NEW)			17	49	631	777	1474
(OVERLAY - CONCRETE)	16	48	98	197	241	37	637
(OVERLAY - EPOXY)	1	8	22	75	39	2	147
(OVERLAY - HMA wMembrane)	4	10	36	21	28		99
(OVERLAY - HMA)	14	39	136	61	16	1	267
(OVERLAY - PMA)	2	7	12	6	30		57
(Sealed)	7	43	190	553	178	9	980
NO TREATMENT	350	1170	2536	3677	2854	557	11144
Grand Total	**394**	**1325**	**3047**	**4639**	**4017**	**1383**	**14805**



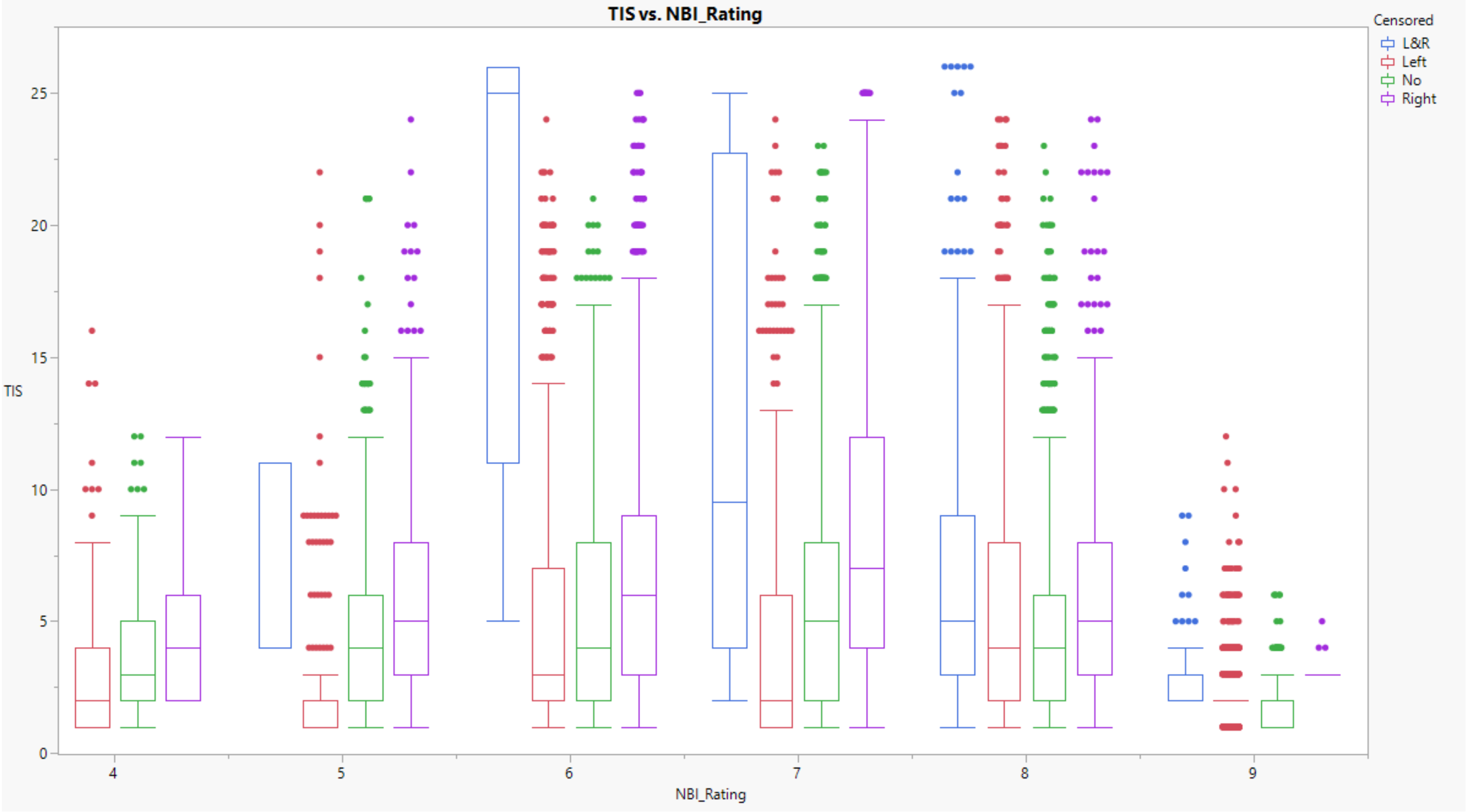
% TIS observations*	NBI Rating							
Impacting Treatment Type	4	5	6	7	8	9	Grand Total	
(NEW)			0.11%	0.33%	4.26%	5.25%	9.96%	1474
(OVERLAY - CONCRETE)	0.11%	0.32%	0.66%	1.33%	1.63%	0.25%	4.30%	637
(OVERLAY - EPOXY)			0.15%	0.51%	0.26%		0.99%	147
(OVERLAY - HMA wMembrane)			0.24%	0.14%	0.19%		0.67%	99
(OVERLAY - HMA)		0.26%	0.92%	0.41%	0.11%		1.80%	267
(OVERLAY - PMA)					0.20%		0.39%	57
(Sealed)		0.29%	1.28%	3.74%	1.20%		6.62%	980
NO TREATMENT	2.36%	7.90%	17.13%	24.84%	19.28%	3.76%	75.27%	11144
Grand Total	**2.66%**	**8.95%**	**20.58%**	**31.33%**	**27.13%**	**9.34%**	**100.00%**	14805
	394	1325	3047	4639	4017	1383	14805	

* Excludes less than 0.1% of observations by treatment and rating

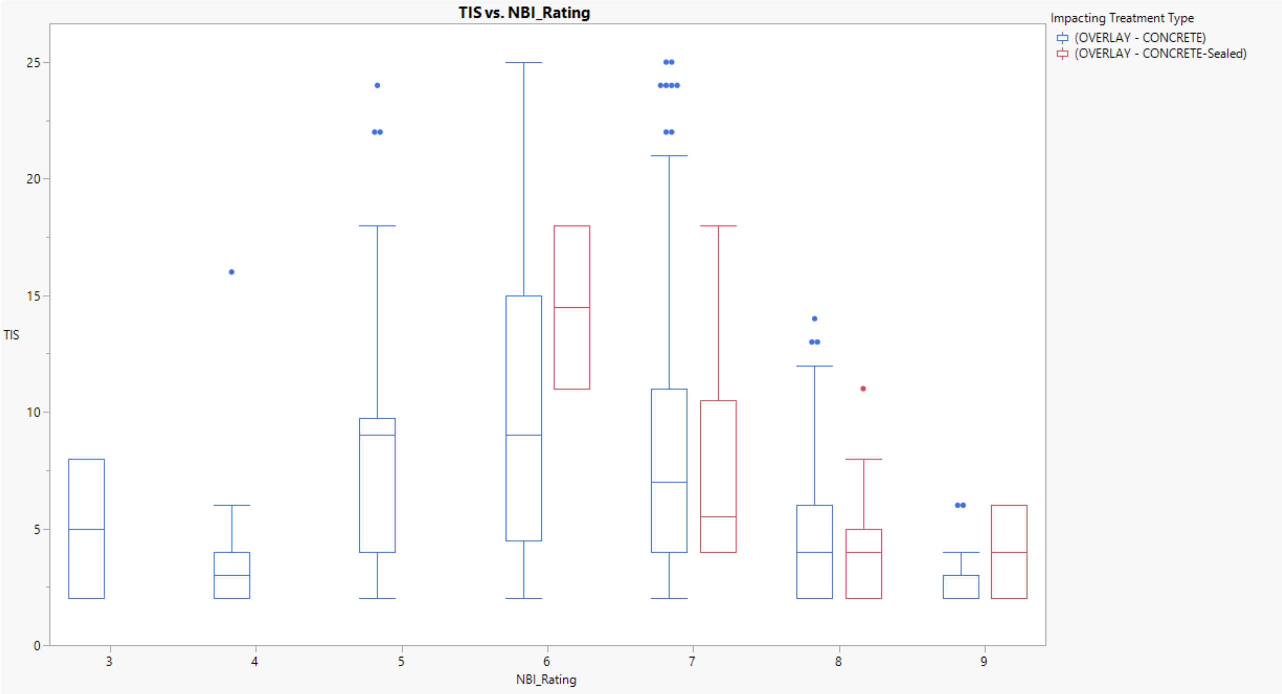


% TIS observations*	NBI Rating						
Impacting Treatment Type	4	5	6	7	8	9	Grand Total
(NEW)			0.46%	1.34%	17.24%	21.22%	40.26%
(OVERLAY - CONCRETE)	0.44%	1.31%	2.68%	5.38%	6.58%	1.01%	17.40%
(OVERLAY - EPOXY)		0.22%	0.60%	2.05%	1.07%		4.02%
(OVERLAY - HMA wMembrane)	0.11%	0.27%	0.98%	0.57%	0.76%		2.70%
(OVERLAY - HMA)	0.38%	1.07%	3.71%	1.67%	0.44%		7.29%
(OVERLAY - PMA)		0.19%	0.33%	0.16%	0.82%		1.56%
(Sealed)	0.19%	1.17%	5.19%	15.11%	4.86%	0.25%	26.77%
Grand Total	**1.20%**	**4.23%**	**13.96%**	**26.28%**	**31.77%**	**22.56%**	**100.00%**

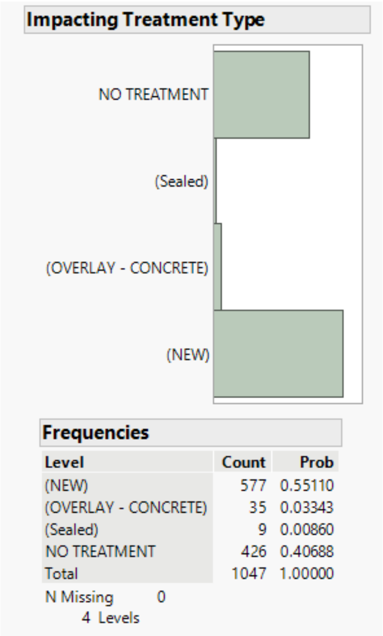
The figure below was prepared to check for the impact of censoring on the TIS values. If any, the impact was found to be minimal and therefore was ignored, with the exception of right-censoring after 2010.



The analyses that resulted in the chart below investigated the impact of sealing immediately after an overlay or new construction. No statistically significant difference was observed, but the average TIS is higher for ratings 6 and 9 when a seal follows a concrete overlay.



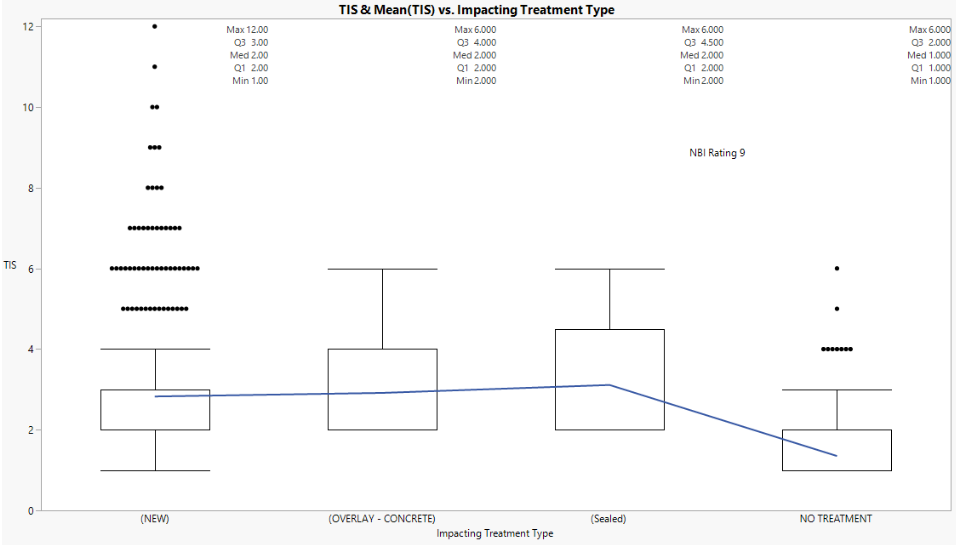
GCR 9

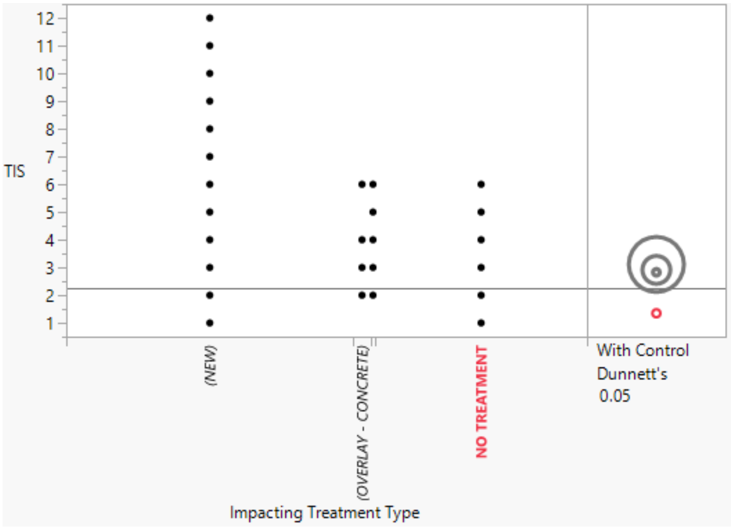


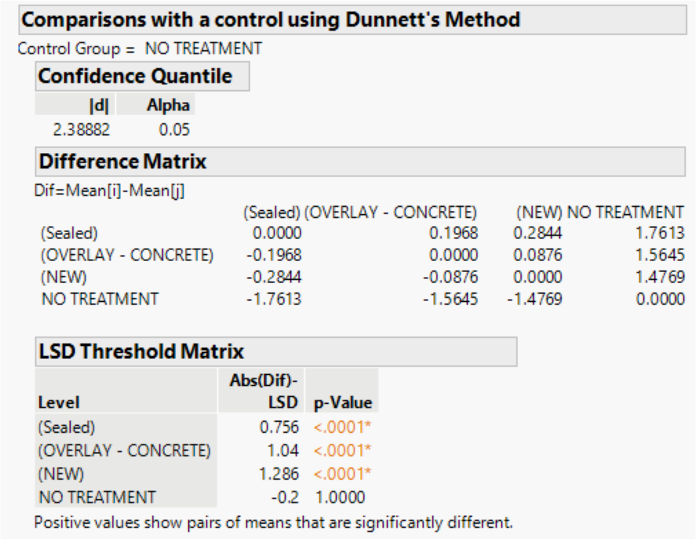
Frequencies

Level	Count	Prob
(NEW)	577	0.55110
(OVERLAY - CONCRETE)	35	0.03343
(Sealed)	9	0.00860
NO TREATMENT	426	0.40688
Total	1047	1.00000

N Missing 0
4 Levels







Comparisons with a control using Dunnett's Method

Control Group = NO TREATMENT

Confidence Quantile

|d|	Alpha
2.38882	0.05

Difference Matrix

Dif=Mean[i]-Mean[j]

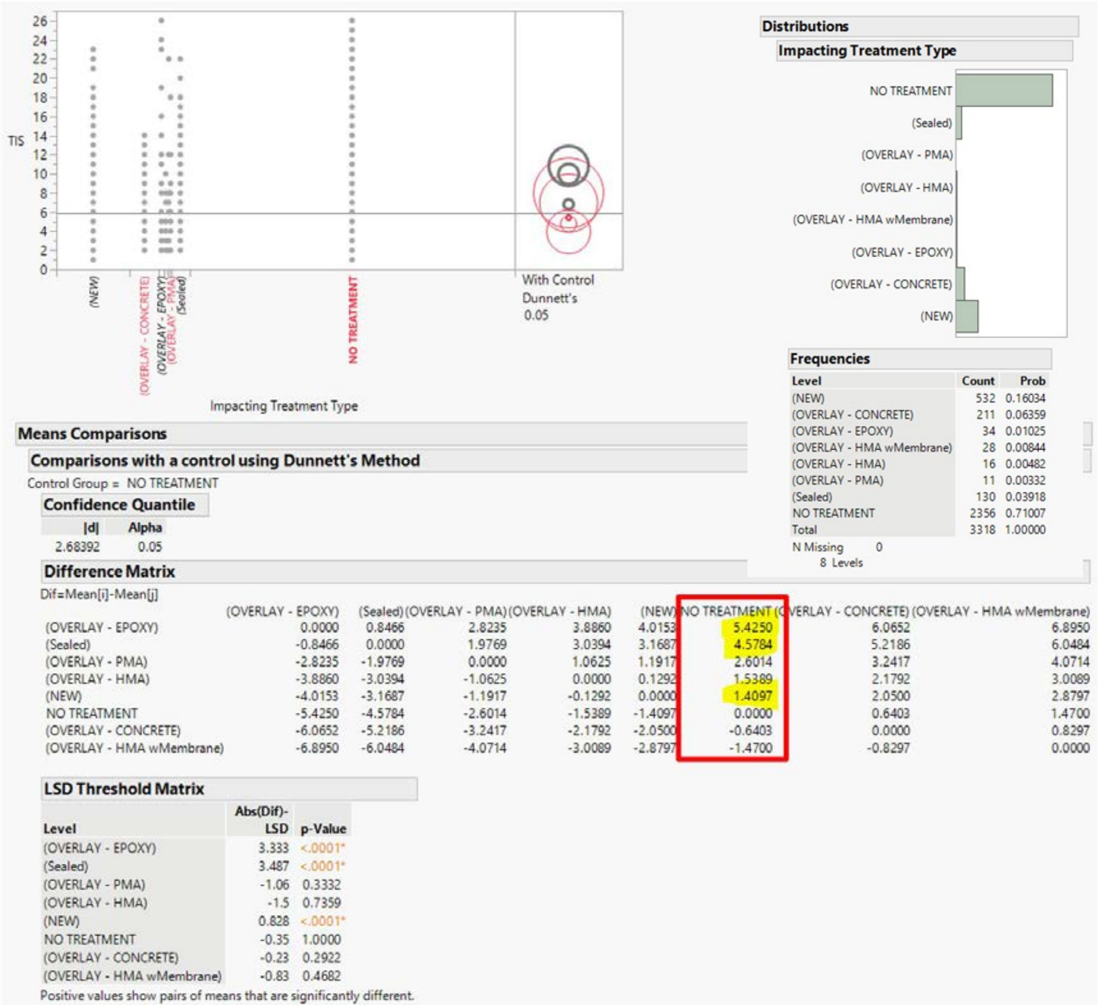
	(Sealed)	(OVERLAY - CONCRETE)	(NEW)	NO TREATMENT
(Sealed)	0.0000	0.1968	0.2844	1.7613
(OVERLAY - CONCRETE)	-0.1968	0.0000	0.0876	1.5645
(NEW)	-0.2844	-0.0876	0.0000	1.4769
NO TREATMENT	-1.7613	-1.5645	-1.4769	0.0000

LSD Threshold Matrix

Level	Abs(Dif)-LSD	p-Value
(Sealed)	0.756	<.0001*
(OVERLAY - CONCRETE)	1.04	<.0001*
(NEW)	1.286	<.0001*
NO TREATMENT	-0.2	1.0000

Positive values show pairs of means that are significantly different.

GCR 8



Distributions

Impacting Treatment Type

Frequencies

Level	Count	Prob
(NEW)	532	0.16034
(OVERLAY - CONCRETE)	211	0.06359
(OVERLAY - EPOXY)	34	0.01025
(OVERLAY - HMA wMembrane)	28	0.00844
(OVERLAY - HMA)	16	0.00482
(OVERLAY - PMA)	11	0.00332
(Sealed)	130	0.03918
NO TREATMENT	2356	0.71007
Total	3318	1.00000

N Missing 0
8 Levels

Means Comparisons

Comparisons with a control using Dunnett's Method

Control Group = NO TREATMENT

Confidence Quantile

|d|	Alpha
2.68392	0.05

Difference Matrix

Dif=Mean[i]-Mean[j]

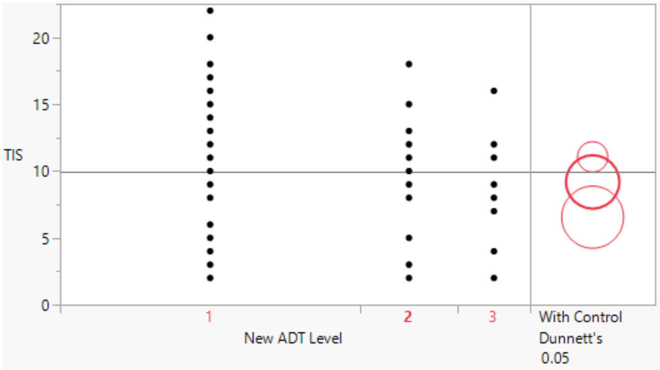
	(OVERLAY - EPOXY)	(Sealed)	(OVERLAY - PMA)	(OVERLAY - HMA)	(NEW)	NO TREATMENT	(OVERLAY - CONCRETE)	(OVERLAY - HMA wMembrane)
(OVERLAY - EPOXY)	0.0000	0.8466	2.8235	3.8860	4.0153	5.4250	6.0652	6.8950
(Sealed)	-0.8466	0.0000	1.9769	3.0394	3.1687	4.5784	5.2186	6.0484
(OVERLAY - PMA)	-2.8235	-1.9769	0.0000	1.0625	1.1917	2.6014	3.2417	4.0714
(OVERLAY - HMA)	-3.8860	-3.0394	-1.0625	0.0000	0.1292	1.5389	2.1792	3.0089
(NEW)	-4.0153	-3.1687	-1.1917	-0.1292	0.0000	1.4097	2.0500	2.8797
NO TREATMENT	-5.4250	-4.5784	-2.6014	-1.5389	-1.4097	0.0000	0.6403	1.4700
(OVERLAY - CONCRETE)	-6.0652	-5.2186	-3.2417	-2.1792	-2.0500	-0.6403	0.0000	0.8297
(OVERLAY - HMA wMembrane)	-6.8950	-6.0484	-4.0714	-3.0089	-2.8797	-1.4700	-0.8297	0.0000

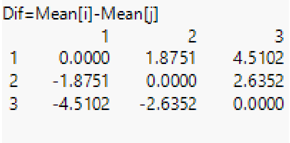
LSD Threshold Matrix

Level	Abs(Dif)-LSD	p-Value
(OVERLAY - EPOXY)	3.333	<.0001*
(Sealed)	3.487	<.0001*
(OVERLAY - PMA)	-1.06	0.3332
(OVERLAY - HMA)	-1.5	0.7359
(NEW)	0.828	<.0001*
NO TREATMENT	-0.35	1.0000
(OVERLAY - CONCRETE)	-0.23	0.2922
(OVERLAY - HMA wMembrane)	-0.83	0.4682

Positive values show pairs of means that are significantly different.

Sealed decks perform differently at three levels of traffic: L1 (AADT < 6,500), L2 (6,500 < AADT < 15,000), L3 (AADT > 15,000).

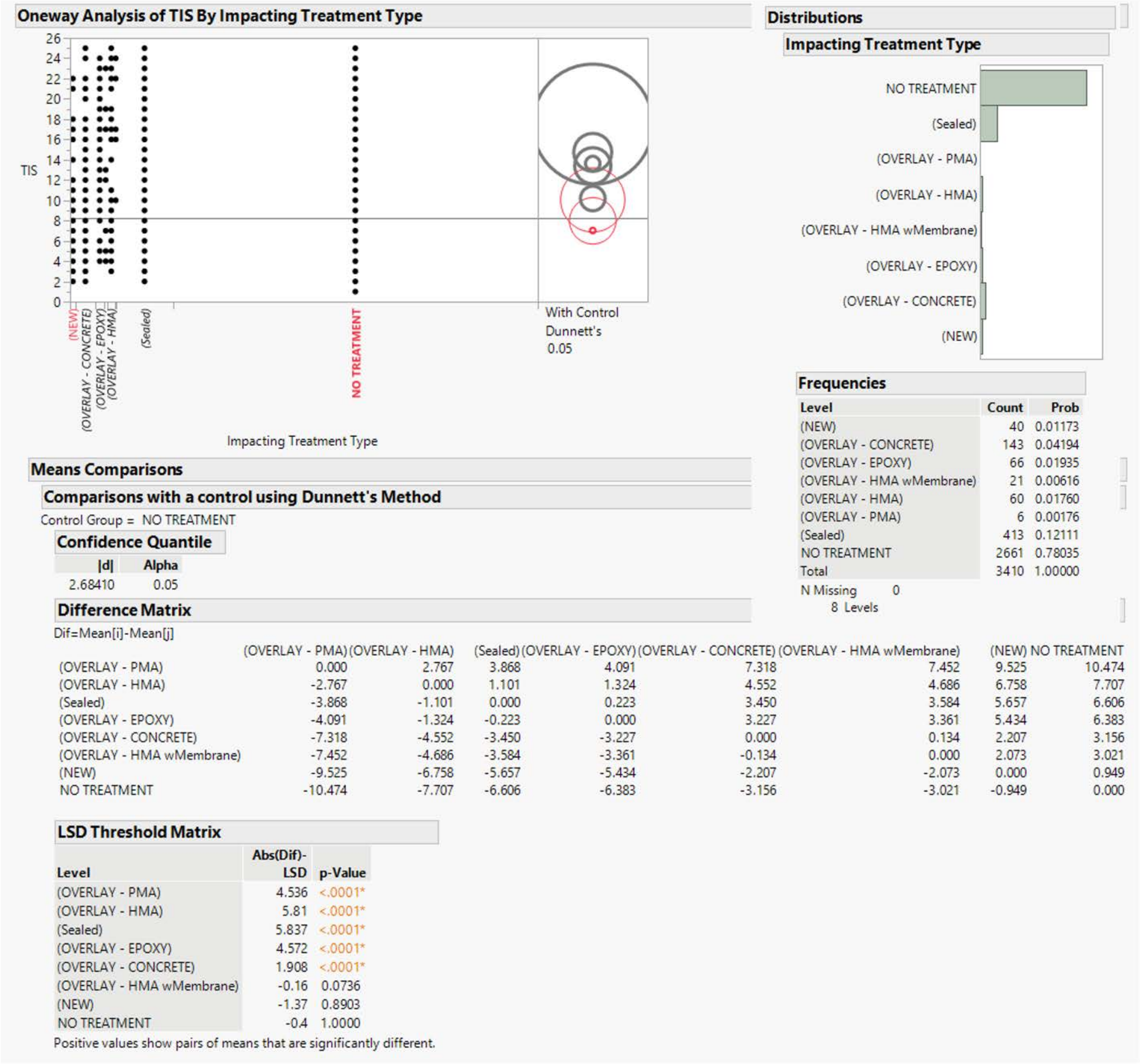




Dif=Mean[i]-Mean[j]

	1	2	3
1	0.0000	1.8751	4.5102
2	-1.8751	0.0000	2.6352
3	-4.5102	-2.6352	0.0000

GCR 7



Oneway Analysis of TIS By Impacting Treatment Type

Distributions

Impacting Treatment Type

Frequencies

Level	Count	Prob
(NEW)	40	0.01173
(OVERLAY - CONCRETE)	143	0.04194
(OVERLAY - EPOXY)	66	0.01935
(OVERLAY - HMA wMembrane)	21	0.00616
(OVERLAY - HMA)	60	0.01760
(OVERLAY - PMA)	6	0.00176
(Sealed)	413	0.12111
NO TREATMENT	2661	0.78035
Total	3410	1.00000

N Missing 0
8 Levels

Means Comparisons

Comparisons with a control using Dunnett's Method

Control Group = NO TREATMENT

Confidence Quantile

|d|	Alpha
2.68410	0.05

Difference Matrix

Dif=Mean[i]-Mean[j]

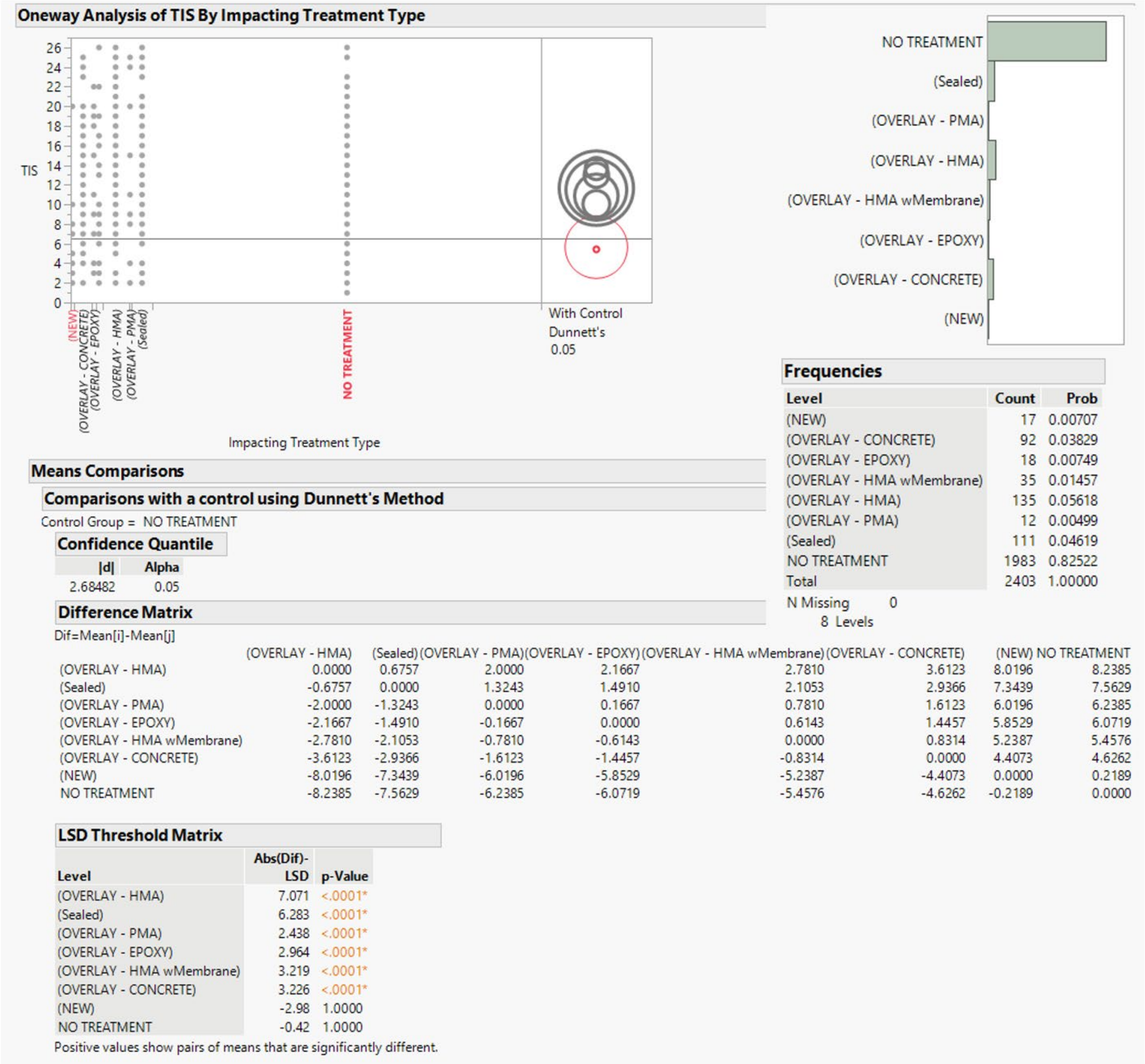
	(OVERLAY - PMA)	(OVERLAY - HMA)	(Sealed)	(OVERLAY - EPOXY)	(OVERLAY - CONCRETE)	(OVERLAY - HMA wMembrane)	(NEW)	NO TREATMENT
(OVERLAY - PMA)	0.000	2.767	3.868	4.091	7.318	7.452	9.525	10.474
(OVERLAY - HMA)	-2.767	0.000	1.101	1.324	4.552	4.686	6.758	7.707
(Sealed)	-3.868	-1.101	0.000	0.223	3.450	3.584	5.657	6.606
(OVERLAY - EPOXY)	-4.091	-1.324	-0.223	0.000	3.227	3.361	5.434	6.383
(OVERLAY - CONCRETE)	-7.318	-4.552	-3.450	-3.227	0.000	0.134	2.207	3.156
(OVERLAY - HMA wMembrane)	-7.452	-4.686	-3.584	-3.361	-0.134	0.000	2.073	3.021
(NEW)	-9.525	-6.758	-5.657	-5.434	-2.207	-2.073	0.000	0.949
NO TREATMENT	-10.474	-7.707	-6.606	-6.383	-3.156	-3.021	-0.949	0.000

LSD Threshold Matrix

Level	Abs(Dif)-LSD	p-Value
(OVERLAY - PMA)	4.536	<.0001*
(OVERLAY - HMA)	5.81	<.0001*
(Sealed)	5.837	<.0001*
(OVERLAY - EPOXY)	4.572	<.0001*
(OVERLAY - CONCRETE)	1.908	<.0001*
(OVERLAY - HMA wMembrane)	-0.16	0.0736
(NEW)	-1.37	0.8903
NO TREATMENT	-0.4	1.0000

Positive values show pairs of means that are significantly different.

GCR 6



Oneway Analysis of TIS By Impacting Treatment Type

Frequencies

Level	Count	Prob
(NEW)	17	0.00707
(OVERLAY - CONCRETE)	92	0.03829
(OVERLAY - EPOXY)	18	0.00749
(OVERLAY - HMA wMembrane)	35	0.01457
(OVERLAY - HMA)	135	0.05618
(OVERLAY - PMA)	12	0.00499
(Sealed)	111	0.04619
NO TREATMENT	1983	0.82522
Total	2403	1.00000

N Missing 0
8 Levels

Means Comparisons

Comparisons with a control using Dunnett's Method

Control Group = NO TREATMENT

Confidence Quantile

|d|	Alpha
2.68482	0.05

Difference Matrix

Dif=Mean[i]-Mean[j]

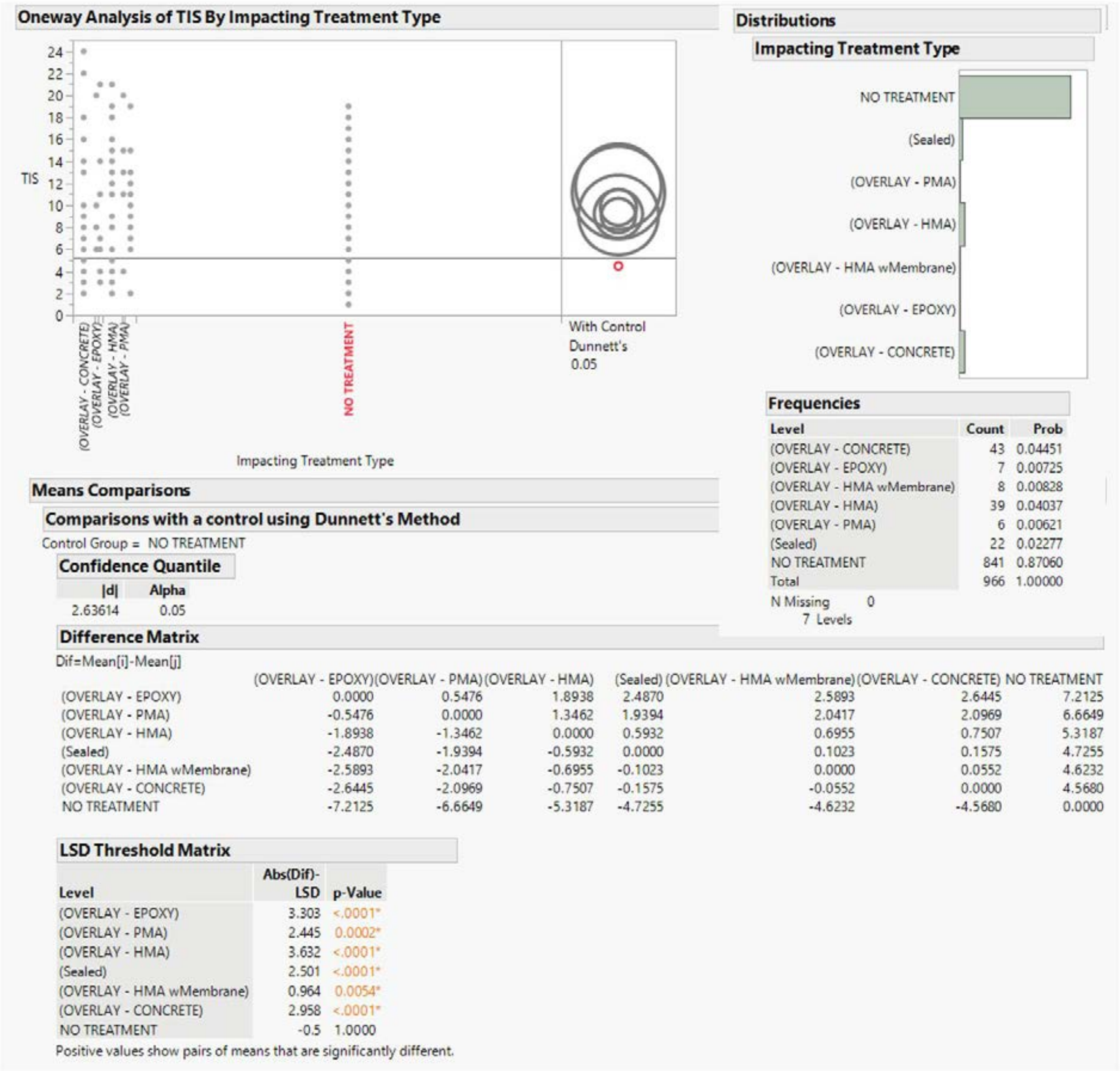
	(OVERLAY - HMA)	(Sealed)	(OVERLAY - PMA)	(OVERLAY - EPOXY)	(OVERLAY - HMA wMembrane)	(OVERLAY - CONCRETE)	(NEW)	NO TREATMENT
(OVERLAY - HMA)	0.0000	0.6757	2.0000	2.1667	2.7810	3.6123	8.0196	8.2385
(Sealed)	-0.6757	0.0000	1.3243	1.4910	2.1053	2.9366	7.3439	7.5629
(OVERLAY - PMA)	-2.0000	-1.3243	0.0000	0.1667	0.7810	1.6123	6.0196	6.2385
(OVERLAY - EPOXY)	-2.1667	-1.4910	-0.1667	0.0000	0.6143	1.4457	5.8529	6.0719
(OVERLAY - HMA wMembrane)	-2.7810	-2.1053	-0.7810	-0.6143	0.0000	0.8314	5.2387	5.4576
(OVERLAY - CONCRETE)	-3.6123	-2.9366	-1.6123	-1.4457	-0.8314	0.0000	4.4073	4.6262
(NEW)	-8.0196	-7.3439	-6.0196	-5.8529	-5.2387	-4.4073	0.0000	0.2189
NO TREATMENT	-8.2385	-7.5629	-6.2385	-6.0719	-5.4576	-4.6262	-0.2189	0.0000

LSD Threshold Matrix

Level	Abs(Dif)-LSD	p-Value
(OVERLAY - HMA)	7.071	<.0001*
(Sealed)	6.283	<.0001*
(OVERLAY - PMA)	2.438	<.0001*
(OVERLAY - EPOXY)	2.964	<.0001*
(OVERLAY - HMA wMembrane)	3.219	<.0001*
(OVERLAY - CONCRETE)	3.226	<.0001*
(NEW)	-2.98	1.0000
NO TREATMENT	-0.42	1.0000

Positive values show pairs of means that are significantly different.

GCR 5



Oneway Analysis of TIS By Impacting Treatment Type

Distributions

Impacting Treatment Type

Frequencies

Level	Count	Prob
(OVERLAY - CONCRETE)	43	0.04451
(OVERLAY - EPOXY)	7	0.00725
(OVERLAY - HMA wMembrane)	8	0.00828
(OVERLAY - HMA)	39	0.04037
(OVERLAY - PMA)	6	0.00621
(Sealed)	22	0.02277
NO TREATMENT	841	0.87060
Total	966	1.00000

N Missing 0
7 Levels

Means Comparisons

Comparisons with a control using Dunnett's Method

Control Group = NO TREATMENT

Confidence Quantile

|d|	Alpha
2.63614	0.05

Difference Matrix

Dif=Mean[i]-Mean[j]

	(OVERLAY - EPOXY)	(OVERLAY - PMA)	(OVERLAY - HMA)	(Sealed)	(OVERLAY - HMA wMembrane)	(OVERLAY - CONCRETE)	NO TREATMENT
(OVERLAY - EPOXY)	0.0000	0.5476	1.8938	2.4870	2.5893	2.6445	7.2125
(OVERLAY - PMA)	-0.5476	0.0000	1.3462	1.9394	2.0417	2.0969	6.6649
(OVERLAY - HMA)	-1.8938	-1.3462	0.0000	0.5932	0.6955	0.7507	5.3187
(Sealed)	-2.4870	-1.9394	-0.5932	0.0000	0.1023	0.1575	4.7255
(OVERLAY - HMA wMembrane)	-2.5893	-2.0417	-0.6955	-0.1023	0.0000	0.0552	4.6232
(OVERLAY - CONCRETE)	-2.6445	-2.0969	-0.7507	-0.1575	-0.0552	0.0000	4.5680
NO TREATMENT	-7.2125	-6.6649	-5.3187	-4.7255	-4.6232	-4.5680	0.0000

LSD Threshold Matrix

Level	Abs(Dif)-LSD	p-Value
(OVERLAY - EPOXY)	3.303	<.0001*
(OVERLAY - PMA)	2.445	0.0002*
(OVERLAY - HMA)	3.632	<.0001*
(Sealed)	2.501	<.0001*
(OVERLAY - HMA wMembrane)	0.964	0.0054*
(OVERLAY - CONCRETE)	2.958	<.0001*
NO TREATMENT	-0.5	1.0000

Positive values show pairs of means that are significantly different.

APPENDIX C: DATA ANALYSES FOR MINNESOTA AND SOUTH DAKOTA

Minnesota Data Analysis

The project team worked with the Minnesota Department of Transportation (MnDOT) Bridge Office to analyze the time in state (TIS) of bridge decks at different National Bridge Inventory (NBI) General Condition Ratings (GCRs). MnDOT does not have data resources that we could query regarding their sealants, but they have a data field for wearing surface type (NBI 108, Table C-1) and record the year of deck protection (wearing surface) installation. However, when overlaid with the TIS observations we created using the application described in the main report and using past Minnesota NBI files, more than 16 of the TIS observations could not be matched to a wearing surface due to missing data entries.

Table C-1: Minnesota deck surface types

CODE	DISPLAY	DESCRIPTION
1	MONOLITHIC CONC	Concrete (concurrently placed with structural deck)
2	INTEGRAL CONC	Integral Concrete (separate non-modified layer of concrete added to structural deck)
3	LATEX CONC	Latex Concrete
4	LOW-SLUMP CONC	Low-Slump Concrete
5	EPOXY OVERLAY	Epoxy Overlay
6	BITUMINOUS	Bituminous
7	TIMBER	Timber
8	GRAVEL	Gravel
9	OTHER	Other
0	NONE	No additional concrete thickness or wearing surface is included in the bridge deck.
N	N/A	Not Applicable (Structures with no Deck)

TIS observations were first classified under three categories (Figure C-1): decreasing (DEC, the next GCR in the time series is lower), increasing (INC, the next GCR in the time series is higher, potentially due to a treatment), and unknown (X, censored due to the next GCR being unknown and outside of data availability).

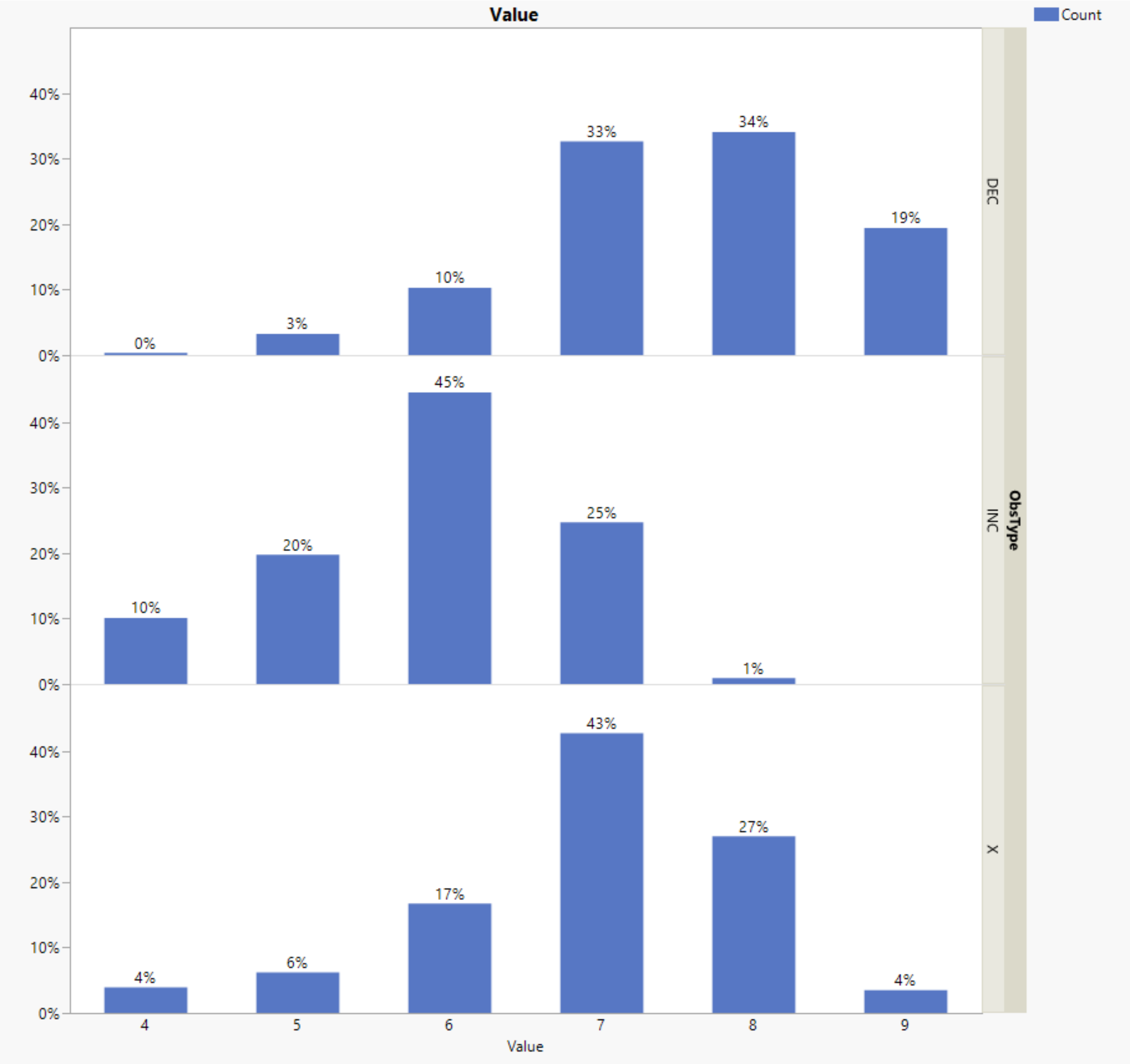


Figure C-1: Frequency of TIS observation types by GCR (Minnesota)

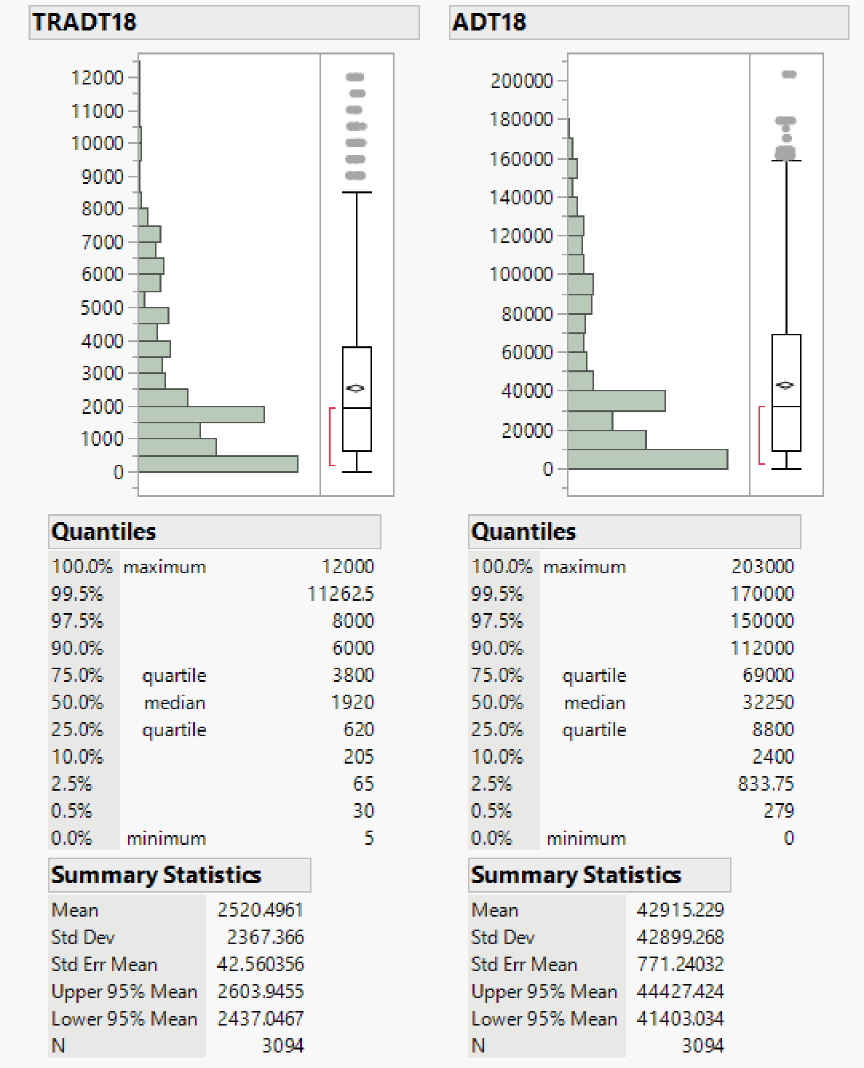
For typical deterioration models, the DEC observations would have been used since they are the monotonically decreasing TIS observations. Since we are interested in treatment efficiency for this project, all of these observations were included in the initial data set but included this classification as a variable. The share of observations between DEC and X observations are quite close at approximately 40% and 39%, while the INC observations constitute 21% of the data set (Table C-2).

Table C-2: Frequency of TIS observation types by GCR

GCR	DEC		INC		X		TOTAL	
4	13	0.14%	193	2.14%	138	1.53%	344	3.82%
5	116	1.29%	377	4.18%	219	2.43%	712	7.90%
6	368	4.08%	850	9.43%	591	6.55%	1,809	20.06%
7	1,166	12.93%	471	5.22%	1,508	16.72%	3,145	34.88%
8	1,218	13.51%	18	0.20%	953	10.57%	2,189	24.28%
9	694	7.70%		0.00%	124	1.38%	818	9.07%
TOTAL	3,575	39.65%	1,909	21.17%	3533	39.18%	9,017	100.00%

GCRs 6 to 9 are well represented in the DEC data set, while the INC data set has the greatest number of observations for GCRs 5 to 7, the GCRs preferred for deck overlays. Most X observations are for GCRs 6, 7, and 8.

As with Wisconsin bridges, traffic volume (ADT in Figure C-2) and truck traffic volume (TRADT in Figure C-2) are highly correlated, with a correlation ratio of 78% (Figure C-2).



TRADT18

Quantiles

100.0%	maximum	12000
99.5%		11262.5
97.5%		8000
90.0%		6000
75.0%	quartile	3800
50.0%	median	1920
25.0%	quartile	620
10.0%		205
2.5%		65
0.5%		30
0.0%	minimum	5

Summary Statistics

Mean	2520.4961
Std Dev	2367.366
Std Err Mean	42.560356
Upper 95% Mean	2603.9455
Lower 95% Mean	2437.0467
N	3094

ADT18

Quantiles

100.0%	maximum	203000
99.5%		170000
97.5%		150000
90.0%		112000
75.0%	quartile	69000
50.0%	median	32250
25.0%	quartile	8800
10.0%		2400
2.5%		833.75
0.5%		279
0.0%	minimum	0

Summary Statistics

Mean	42915.229
Std Dev	42899.268
Std Err Mean	771.24032
Upper 95% Mean	44427.424
Lower 95% Mean	41403.034
N	3094

Figure C-2: ADT and TRADT distribution for the Minnesota state bridge network

ADT was preferred as a variable since the observations were more complete in the data set.

MnDOT overlay history data also include a variable for wearing surface thickness, WS DEPTH. A simple regression model was fit to explore strong correlations among variables of interest, as shown in Table C-3.

Table C-3: Regression parameter estimates for TIS

RATING	DKSURFTYPE	WS DEPTH	RATING WHEN	ADT
4	NS	NS	After Ovly (Shorter TIS)	NS
5	NS	NS	Before Ovly (Higher TIS)	NS
6	BITUMINOUS (TIS=8.6 years) Epoxy: 5.14, LS Conc: 6.51, Mono Conc: 7.9	NS	After Ovly (Shorter TIS)	NS
7	LS CONC (TIS=15 years) Bit: 9.9, Epoxy: 10.4, Mono: 10.3, None: 2	Deeper WS, Shorter TIS	After Ovly (Shorter TIS)	NS
8	LS CONC (TIS=8.5 years) Bit: 7.6, Epoxy: 5.9, Mono: 7, None: 3.3	NS	After Ovly (Shorter TIS) Before Ovly (Longer TIS)	High Traffic: TIS=3.9 yrs Medium Traffic: TIS= 4.9 yrs Low Traffic: TIS= 6.5 yrs
9	BITUMINOUS (TIS=4.6 yrs) Epoxy: 2.6, LS Conc: 4.2, Mono: 3.4, None: 2.4	NS	After Ovly (Shorter TIS)	Medium Traffic: TIS is 0.7 yrs shorter compared to low traffic.

All TIS observations were classified with respect to an overlay they were associated with. The RATING WHEN variable identifies TIS observations to indicate whether the TIS duration is before (Before Ovly) or after (After Ovly). The parameter estimates are significant at a 95% confidence level. The RATING WHEN variable was significant across all GCRs and typically indicated shorter TIS after an overlay. Investigation of the data due to this unexpected relationship showed that TIS observations after an overlay were newer TIS observations and were typically right-censored (cut off after 2018). The issue is due to data availability, and the findings may be different in future. Deck surface type was significant for ratings 6 to 9. For GCR 6, bituminous overlays had significantly higher TIS (8.6 years) than other deck surface types, while low-slump concrete overlays had significantly higher TIS for GCRs 7 and 8 (15 and 8.5 years, respectively). Bituminous overlays also had a significantly higher TIS for GCR 9, but the TIS was very close to that of low-slump concrete overlays.

A closer look at the Minnesota TIS data sample and the number of observation by GCR and deck surface type (Table C-4) shows that bituminous overlays constitute a very small portion of the observations at 1%.

Low-slump concrete overlays constitute 57% of the data set, followed by monolithic concrete at 21% and unknown wearing surface at 16%. Therefore, the findings on these frequently used overlays present a potential reference point for this study. In Table C-5, median and average TIS values by deck GCR with at least 20 observations are reported for comparison.

For Table C-5, overlays older than 1990 are also indicated with the Before 1990 variable. The number of TIS observations for the After Ovly group, which indicates the data for newer overlays, is smaller, as was also found in the regression analysis. The values for the Before Ovl and Before 1990 groups provide more reasonable values. The median TIS for GCR 7 is seven years longer for decks with low-slump concrete overlays with respect to their median TIS before the deck overlay. This is the most relevant finding, which is also supported by 806 observations for After Ovly TIS values (Before 1990) and 236 observations of Before Ovl TIS values.

In this data set, only 0.4% of the decks had bare wearing surfaces (Table C-4). Therefore, the project team did not have a good reference to estimate and discuss the TIS added by a particular overlay type and could only contrast a few overlay types with respect to each other.

Table C-4: Count and descriptive statistics of TIS by GCR and deck surface type

	4						5						6						7						8						9							
DKSURFTYPE	N	Mean	Min	Max	Median	Sum	N	Mean	Min	Max	Median	Sum	N	Mean	Min	Max	Median	Sum	N	Mean	Min	Max	Median	Sum	N	Mean	Min	Max	Median	Sum	N	Mean	Min	Max	Median	Sum	Grand Total	Grand %
BITUMINOUS	7	4.4	1	9	5	31	9	8.0	1	24	6	72	26	12.8	1	29	10	334	20	10.3	1	29	8.5	206	14	6.4	1	29	3	90	17	3.8	1	8	4	65	93	1.0%
EPOXY OVLY	4	4.8	3	6	5	19	13	5.3	1	15	4	69	64	8.2	1	23	6	525	100	10.0	1	29	9	1001	59	4.1	1	15	3	240	23	2.2	1	6	1	50	263	2.9%
GRAVEL	1	4.0	4	4	4	4	1	5.0	5	5	5	5	2	11.5	1	22	11.5	23	1	15.0	15	15	15	15	0	.	.	.	.	.	0	.	.	.	.	.	5	0.1%
INTG CONC	0	.	.	.	.	.	2	12.0	5	19	12	24	5	2.4	1	4	2	12	5	3.8	1	8	3	19	7	3.9	1	8	3	27	4	1.5	1	2	1.5	6	23	0.3%
LATEX CONC	0	.	.	.	.	.	5	7.0	2	12	8	35	13	9.1	1	27	10	118	18	15.2	1	29	15	274	14	6.9	1	18	9	97	2	5.0	5	5	5	10	52	0.6%
LOW SLUMP CONC	48	3.7	1	11	3	177	227	6.1	1	26	4	1383	935	8.7	1	30	6	8141	2058	13.3	1	30	12	27331	1319	5.4	1	29	4	7145	559	3.0	1	24	2	1692	5146	57.1%
MONO CONC	34	5.8	1	29	4.5	198	96	7.3	1	29	6	699	321	9.8	1	29	9	3156	579	12.2	1	29	10	7057	643	6.2	1	29	3	4005	183	3.1	1	19	2	562	1856	20.6%
NO DECK	1	16.0	16	16	16	16	2	2.0	1	3	2	4	3	3.7	1	9	1	11	17	4.8	1	27	2	81	8	5.6	2	8	6.5	45	4	7.0	1	13	7	28	35	0.4%
NONE	**0**	**.**	**.**	**.**	**.**	**.**	**0**	**.**	**.**	**.**	**.**	**.**	**5**	**5.0**	**1**	**11**	**5**	**25**	**8**	**4.5**	**1**	**17**	**3**	**36**	**15**	**3.3**	**1**	**7**	**3**	**49**	**12**	**2.5**	**1**	**6**	**2.5**	**30**	**40**	**0.4%**
OTHER	0	.	.	.	.	.	1	23.0	23	23	23	23	4	9.3	5	14	9	37	8	7.5	1	27	3	60	6	3.3	1	9	2.5	20	0	.	.	.	.	.	19	0.2%
TIMBER	0	.	.	.	.	.	2	10.0	1	19	10	20	3	13.7	6	29	6	41	2	10.0	1	19	10	20	0	.	.	.	.	.	1	4.0	4	4	4	4	8	0.1%
UNKNOWN	249	13.0	1	29	11	3248	354	10.6	1	29	9	3738	428	9.8	1	29	7	4191	329	9.7	1	29	6	3180	104	4.6	1	29	3	480	13	3.7	1	28	2	48	1477	16.4%

Table C-5: Average and median TIS by GCR and deck surface type

	AfterOvly			Before1990			BeforeOvl			Unknown						
CR	Average of MEDTIS	Average of AVGTIS	Sum of count	Average of MEDTIS	Average of AVGTIS	Sum of count	Average of MEDTIS	Average of AVGTIS	Sum of count	Average of MEDTIS	Average of AVGTIS	Sum of count	Total Average of MEDTIS	Total Average of AVGTIS	Total Sum of count	% of count
4							**4.0**	**4.9**	**25.0**	**8.0**	**9.7**	**274**	**6.7**	**8.1**	**299**	**1.3%**
LOW SLUMP							4.0	4.9	25.0				4.0	4.9	25	0.1%
MONO CONC										5.0	6.3	25	5.0	6.3	25	0.1%
UNKNOWN										11.0	13.0	249	11.0	13.0	249	1.1%
5	**1.0**	**2.1**	**38.0**	**5.0**	**6.7**	**93.0**	**6.0**	**8.4**	**102.0**	**7.3**	**8.7**	**401**	**5.4**	**7.1**	**634**	**2.8%**
LOW SLUMP	1.0	2.1	38.0	5.0	6.7	93.0	6.0	8.0	75.0				4.0	5.6	206	0.9%
MONO CONC							6.0	8.7	27.0	5.5	6.8	48	5.8	7.7	75	0.3%
UNKNOWN										9.0	10.6	353	9.0	10.6	353	1.6%
6	**1.7**	**3.6**	**197.0**	**10.5**	**11.1**	**505.0**	**9.7**	**10.2**	**255.0**	**8.5**	**10.2**	**649**	**7.2**	**8.4**	**1606**	**7.2%**
EPOXY OVLY	2.0	3.1	22.0				12.0	10.8	39.0				7.0	7.0	61	0.3%
LOW SLUMP	2.0	5.5	151.0	9.0	10.8	474.0	7.0	9.1	180.0				6.0	8.5	805	3.6%
MONO CONC	1.0	2.1	24.0	12.0	11.4	31.0	10.0	10.7	36.0	10.0	10.6	222	8.3	8.7	313	1.4%
UNKNOWN										7.0	9.7	427	7.0	9.7	427	1.9%
7	**5.5**	**6.8**	**613.0**	**14.0**	**15.1**	**855.0**	**9.7**	**12.4**	**338.0**	**9.0**	**11.5**	**756**	**9.2**	**11.1**	**2562**	**11.5%**
EPOXY OVLY	1.0	3.1	22.0				10.0	12.4	70.0				5.5	7.7	92	0.4%
LOW SLUMP	12.0	12.2	545.0	18.0	17.7	806.0	11.0	14.4	236.0				13.7	14.7	1587	7.1%
MONO CONC	3.5	5.0	46.0	10.0	12.6	49.0	8.0	10.4	32.0	12.0	13.4	429	8.4	10.4	556	2.5%
UNKNOWN										6.0	9.6	327	6.0	9.6	327	1.5%
8	**2.0**	**3.2**	**719.0**	**9.0**	**11.4**	**342.0**	**6.5**	**7.1**	**94.0**	**3.5**	**5.9**	**545**	**4.9**	**6.5**	**1700**	**7.6%**
EPOXY OVLY	1.0	1.9	24.0				5.0	5.7	31.0				3.0	3.8	55	0.2%
LOW SLUMP	3.0	4.8	574.0	8.0	9.4	316.0	8.0	8.6	63.0				6.3	7.6	953	4.3%
MONO CONC	2.0	2.7	121.0	10.0	13.5	26.0				4.0	7.3	442	5.3	7.8	589	2.6%
UNKNOWN										3.0	4.6	103	3.0	4.6	103	0.5%
9	**1.5**	**2.7**	**464.0**				**2.0**	**3.1**	**54.0**	**3.0**	**3.6**	**101**	**2.0**	**3.1**	**619**	**2.8%**
EPOXY OVLY							1.0	2.1	20.0				1.0	2.1	20	0.1%
LOW SLUMP	2.0	3.2	396.0				3.0	4.1	34.0				2.5	3.6	430	1.9%
MONO CONC	1.0	2.3	68.0							3.0	3.6	101	2.0	3.0	169	0.8%
Grand Total	**2.6**	**4.0**	**2031.0**	**10.3**	**11.7**	**1795.0**	**7.0**	**8.5**	**868.0**	**6.9**	**8.7**	**2726**	**6.3**	**7.8**	**7420**	**33.3%**
															22260	

South Dakota Analysis

The project team acquired deck overlay history and condition data from the South Dakota Department of Transportation (SDDOT) Office of Bridge Design. Data for external variables were also acquired from the SDDOT for deicer usage and regular and truck traffic volume (annual average daily traffic [AADT] and truck AADT, respectively). TIS values were produced using an approach similar to that used for the Wisconsin NBI condition data analysis, and all variables were combined within geographic information systems (GIS) software. The data sample for South Dakota contained 1,224 state bridges, as shown in Figure C-3.

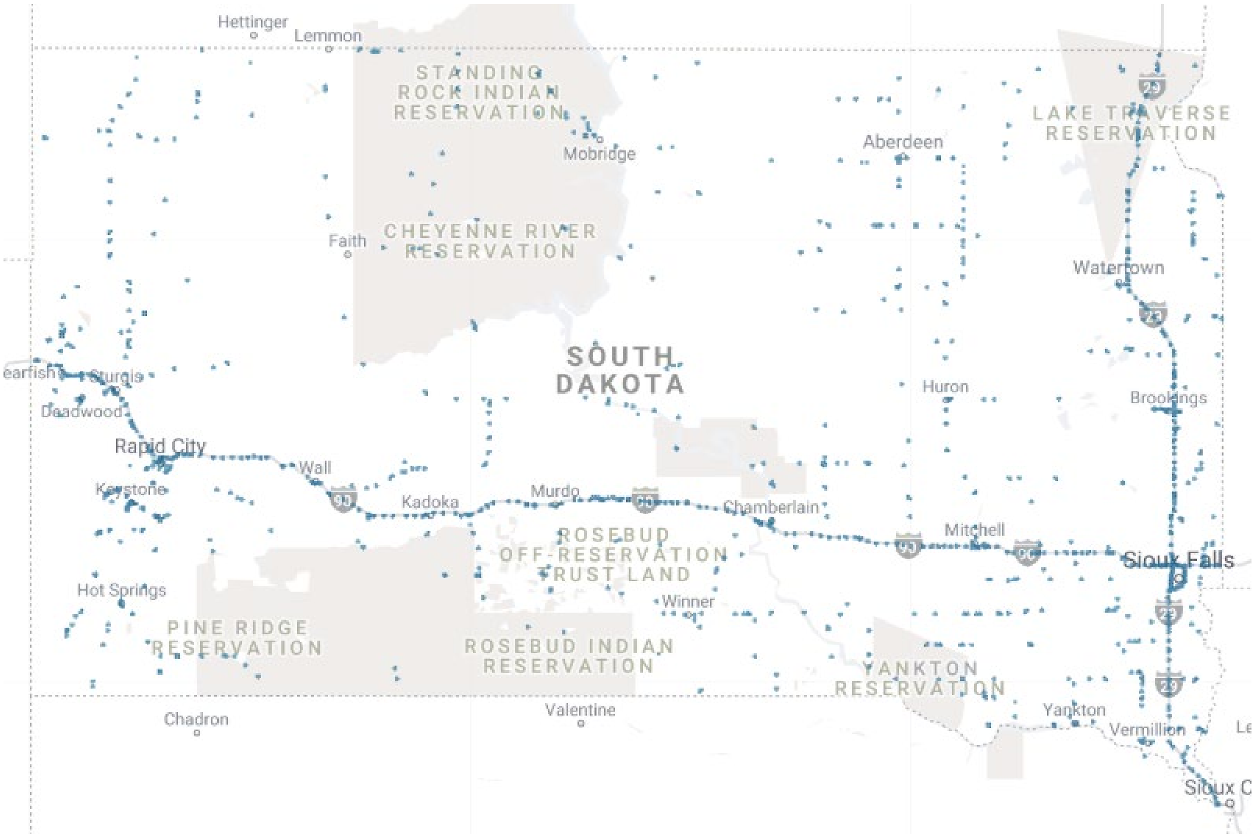


Figure C-3: South Dakota state bridge locations in the sample

An initial comparison of TIS values for treated and untreated decks indicates slightly higher values for treated decks (Figure C-4).

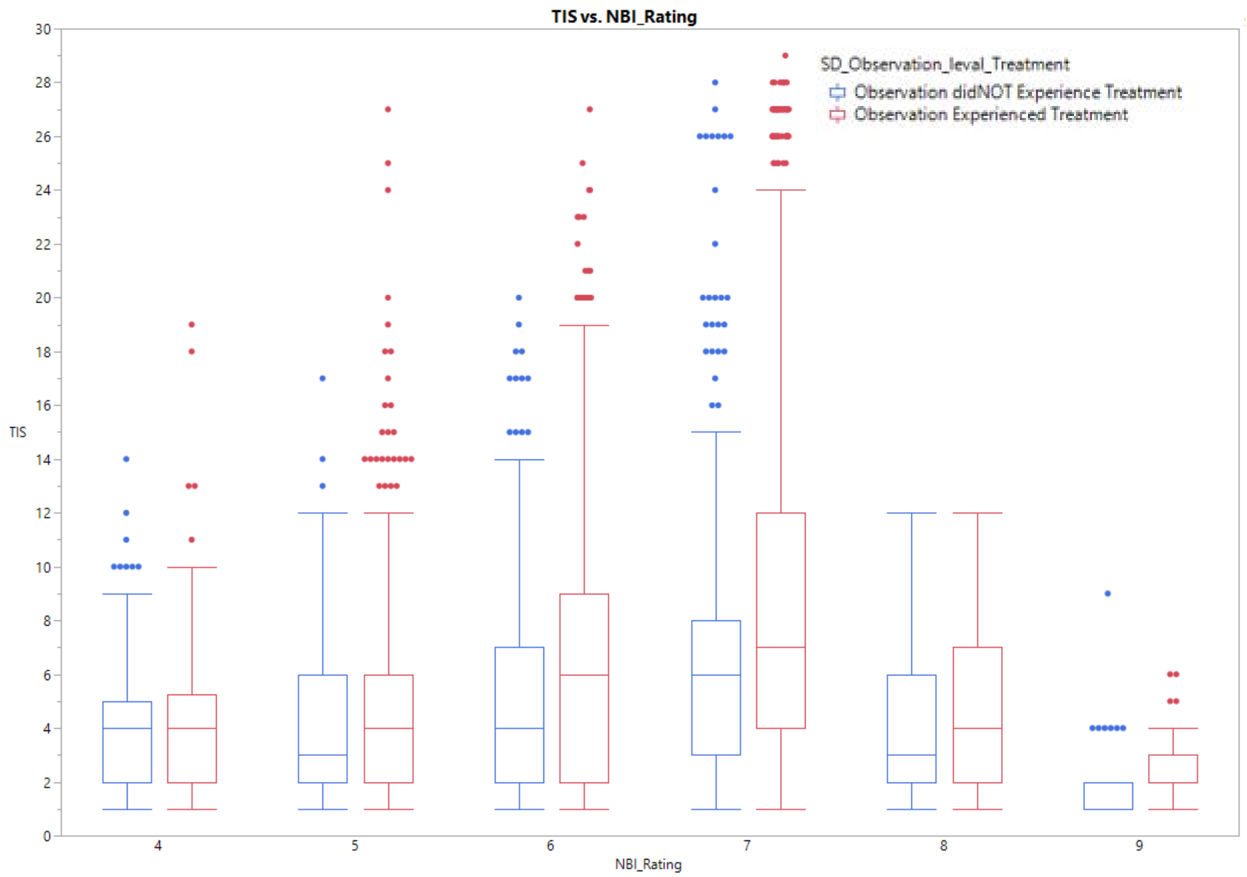
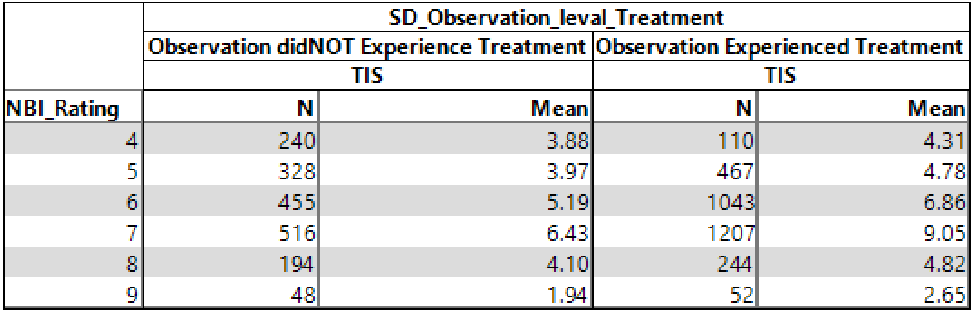


Figure C-4: TIS distribution by GCR and treatment presence

Table C-6 provides average TIS values by GCR for both cases.

Table C-6: Mean TIS by GCR for treated and untreated deck observations



	SD_Observation_leval_Treatment			
	Observation didNOT Experience Treatment		Observation Experienced Treatment	
	TIS		TIS	
NBI_Rating	N	Mean	N	Mean
4	240	3.88	110	4.31
5	328	3.97	467	4.78
6	455	5.19	1043	6.86
7	516	6.43	1207	9.05
8	194	4.10	244	4.82
9	48	1.94	52	2.65

After the initial analysis, the project team investigated the changes in TIS by overlay type. Concrete and epoxy overlays were most common and typically provided a one-point increase in GCR (Figure C-5).

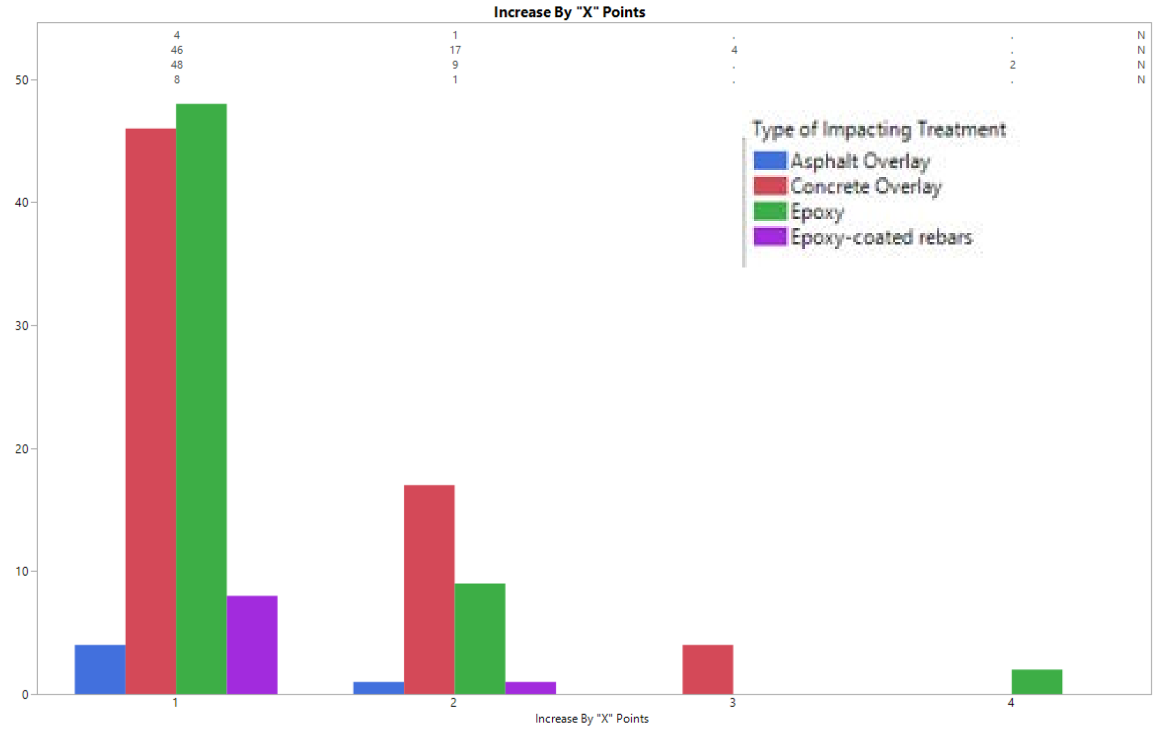


Figure C-5: GCR increase by overlay type

Asphalt overlays and epoxy-coated rebars were other common improvements noted in South Dakota's deck construction history data. For only GCR 7, the existence of an overlay increased TIS by a notable magnitude, 2.5 years (Figure C-6).

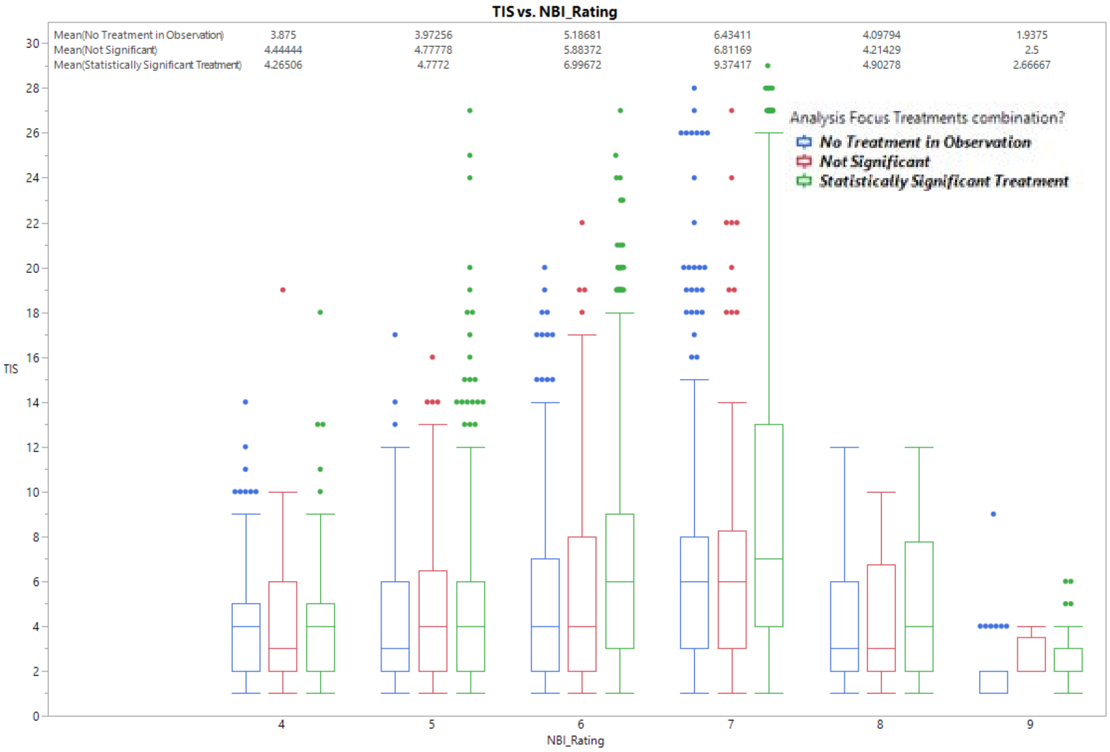
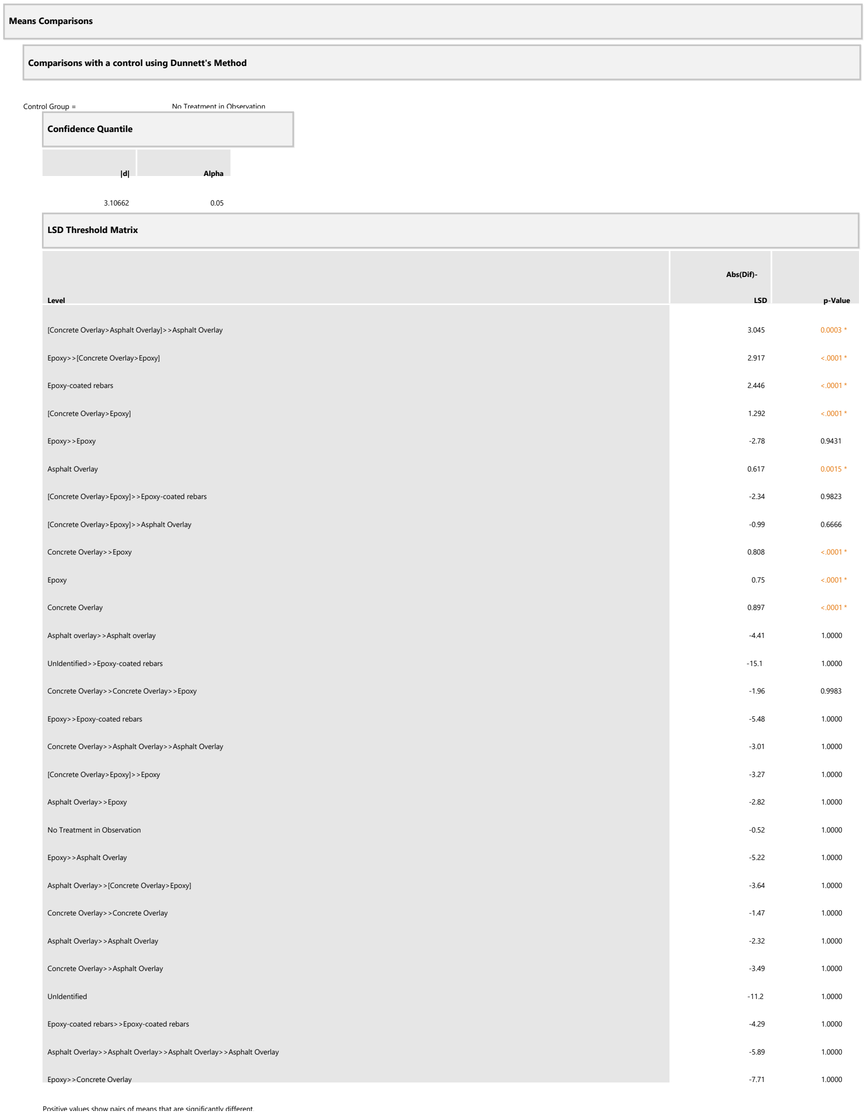


Figure C-6: TIS by GCR and presence of significant treatment

The differences in TIS for other GCRs were quite minimal.

Using Dunnett’s method, mean TIS values were compared for different treatment combinations. Eight combinations (noted with orange p-values, Figure C-7) were significantly different at the 95% confidence level.



Means Comparisons

Comparisons with a control using Dunnett's Method

Control Group = No Treatment in Observation

Confidence Quantile

|d|	Alpha
3.10662	0.05

LSD Threshold Matrix

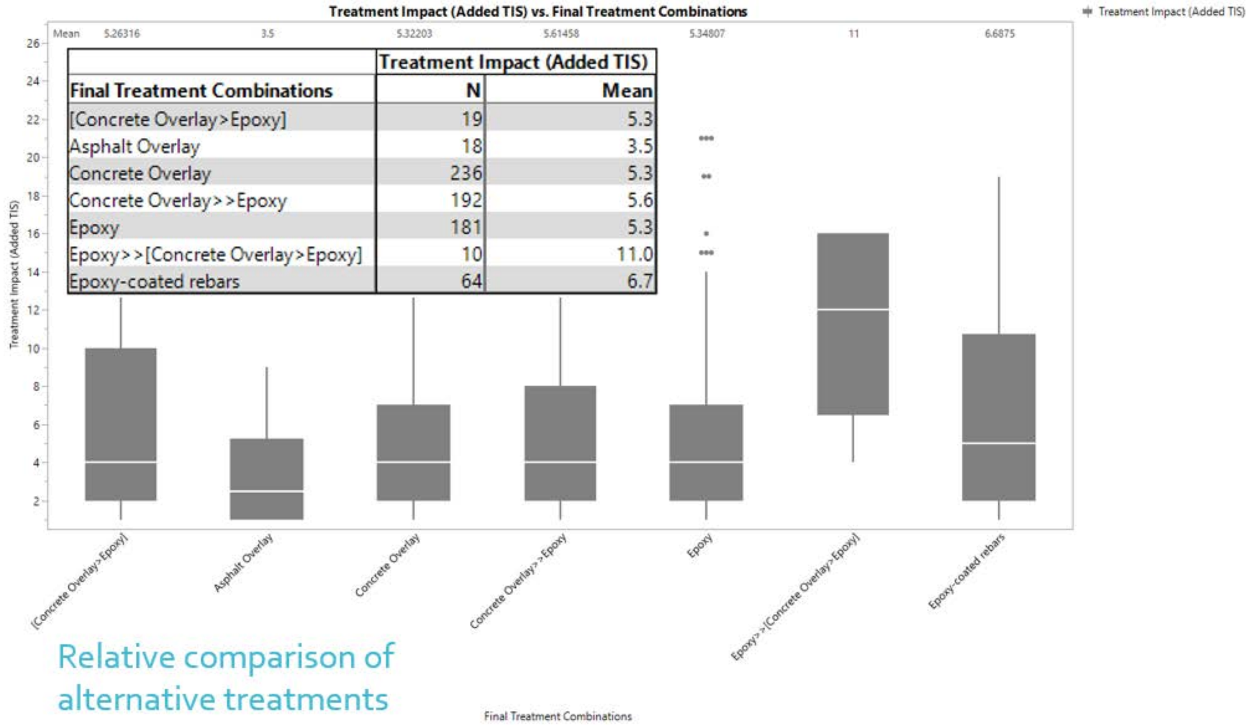
Level	Abs(Dif)-LSD	p-Value
[Concrete Overlay>Asphalt Overlay]>>Asphalt Overlay	3.045	0.0003 *
Epoxy>>[Concrete Overlay>Epoxy]	2.917	<.0001 *
Epoxy-coated rebars	2.446	<.0001 *
[Concrete Overlay>Epoxy]	1.292	<.0001 *
Epoxy>>Epoxy	-2.78	0.9431
Asphalt Overlay	0.617	0.0015 *
[Concrete Overlay>Epoxy]>>Epoxy-coated rebars	-2.34	0.9823
[Concrete Overlay>Epoxy]>>Asphalt Overlay	-0.99	0.6666
Concrete Overlay>>Epoxy	0.808	<.0001 *
Epoxy	0.75	<.0001 *
Concrete Overlay	0.897	<.0001 *
Asphalt overlay>>Asphalt overlay	-4.41	1.0000
UnIdentified>>Epoxy-coated rebars	-15.1	1.0000
Concrete Overlay>>Concrete Overlay>>Epoxy	-1.96	0.9983
Epoxy>>Epoxy-coated rebars	-5.48	1.0000
Concrete Overlay>>Asphalt Overlay>>Asphalt Overlay	-3.01	1.0000
[Concrete Overlay>Epoxy]>>Epoxy	-3.27	1.0000
Asphalt Overlay>>Epoxy	-2.82	1.0000
No Treatment in Observation	-0.52	1.0000
Epoxy>>Asphalt Overlay	-5.22	1.0000
Asphalt Overlay>>[Concrete Overlay>Epoxy]	-3.64	1.0000
Concrete Overlay>>Concrete Overlay	-1.47	1.0000
Asphalt Overlay>>Asphalt Overlay	-2.32	1.0000
Concrete Overlay>>Asphalt Overlay	-3.49	1.0000
UnIdentified	-11.2	1.0000
Epoxy-coated rebars>>Epoxy-coated rebars	-4.29	1.0000
Asphalt Overlay>>Asphalt Overlay>>Asphalt Overlay>>Asphalt Overlay	-5.89	1.0000
Epoxy>>Concrete Overlay	-7.71	1.0000

Positive values show pairs of means that are significantly different.

Figure C-7: Comparison of means for change in TIS by treatment combination

The best performing combinations were (1) a concrete and an asphalt overlay followed by an asphalt overlay, (2) an epoxy overlay with a concrete overlay and another epoxy overlay, and (3) epoxy-coated rebars. The differences, while significant, are within three years.

An investigation of the number of observations by treatment combination showed that concrete overlays were most common in the data set, followed by a concrete overlay and an epoxy overlay, and finally a single epoxy overlay. The TIS values added by these treatments are virtually equal, between 5.3 and 5.6 years (Figure C-8).

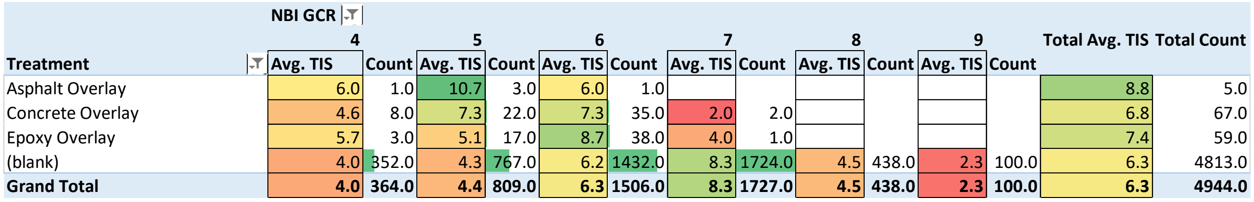


	Treatment Impact (Added TIS)	
Final Treatment Combinations	**N**	**Mean**
[Concrete Overlay>Epoxy]	19	5.3
Asphalt Overlay	18	3.5
Concrete Overlay	236	5.3
Concrete Overlay>>Epoxy	192	5.6
Epoxy	181	5.3
Epoxy>>[Concrete Overlay>Epoxy]	10	11.0
Epoxy-coated rebars	64	6.7

Relative comparison of alternative treatments

Figure C-8: Added TIS by treatment

Figure C-9 presents average TIS values by treatment and GCR for South Dakota bridges.



	NBI GCR													
	4		5		6		7		8		9		Total Avg. TIS	Total Count
Treatment	**Avg. TIS**	**Count**	**Avg. TIS**	**Count**	**Avg. TIS**	**Count**	**Avg. TIS**	**Count**	**Avg. TIS**	**Count**	**Avg. TIS**	**Count**		
Asphalt Overlay	6.0	1.0	10.7	3.0	6.0	1.0							8.8	5.0
Concrete Overlay	4.6	8.0	7.3	22.0	7.3	35.0	2.0	2.0					6.8	67.0
Epoxy Overlay	5.7	3.0	5.1	17.0	8.7	38.0	4.0	1.0					7.4	59.0
(blank)	4.0	352.0	4.3	767.0	6.2	1432.0	8.3	1724.0	4.5	438.0	2.3	100.0	6.3	4813.0
Grand Total	**4.0**	**364.0**	**4.4**	**809.0**	**6.3**	**1506.0**	**8.3**	**1727.0**	**4.5**	**438.0**	**2.3**	**100.0**	**6.3**	**4944.0**

Figure C-9: Average TIS by GCR and treatment (South Dakota)

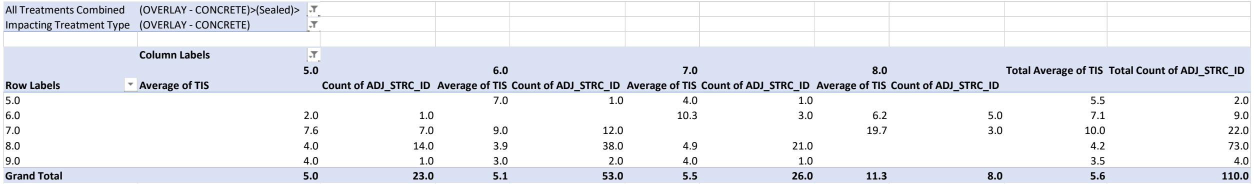
These values are contrasted with those for Wisconsin in Section 4.1.

APPENDIX D: STATISTICAL ANALYSIS OF TIS RANGES

Detailed Analysis of TIS for Life-Cycle Profiles

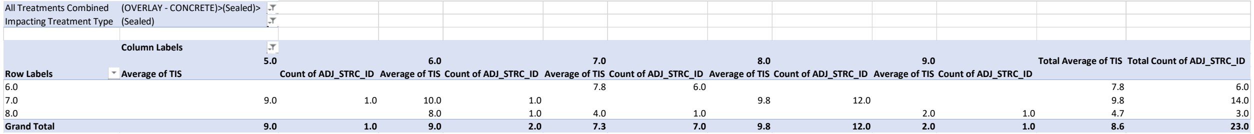
Impacting Treatment Type **(Sealed)**

NBI Rating	% of Obs. In Treatment	Average of TIS	
4	0.7%	6.0	
5	4.4%	7.2	
6	19.4%	9.6	94%
7	56.4%	11.5	
8	18.2%	8.5	
9	0.9%	3.1	
Total	100.0%	10.3	



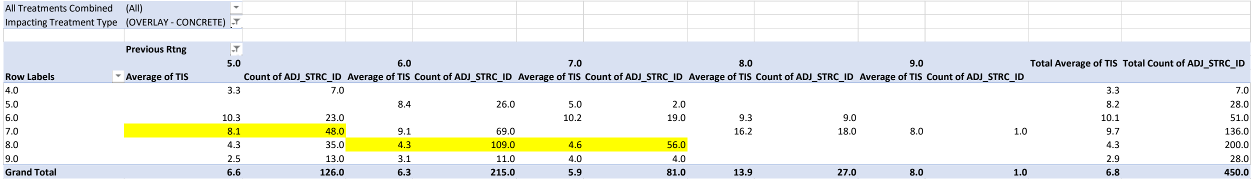
All Treatments Combined (OVERLAY - CONCRETE)>(Sealed)>
Impacting Treatment Type (OVERLAY - CONCRETE)

	Column Labels									
	5.0		6.0		7.0		8.0		Total Average of TIS	Total Count of ADJ_STRC_ID
Row Labels	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID		
5.0			7.0	1.0	4.0	1.0			5.5	2.0
6.0	2.0	1.0			10.3	3.0	6.2	5.0	7.1	9.0
7.0	7.6	7.0	9.0	12.0			19.7	3.0	10.0	22.0
8.0	4.0	14.0	3.9	38.0	4.9	21.0			4.2	73.0
9.0	4.0	1.0	3.0	2.0	4.0	1.0			3.5	4.0
Grand Total	**5.0**	**23.0**	**5.1**	**53.0**	**5.5**	**26.0**	**11.3**	**8.0**	**5.6**	**110.0**



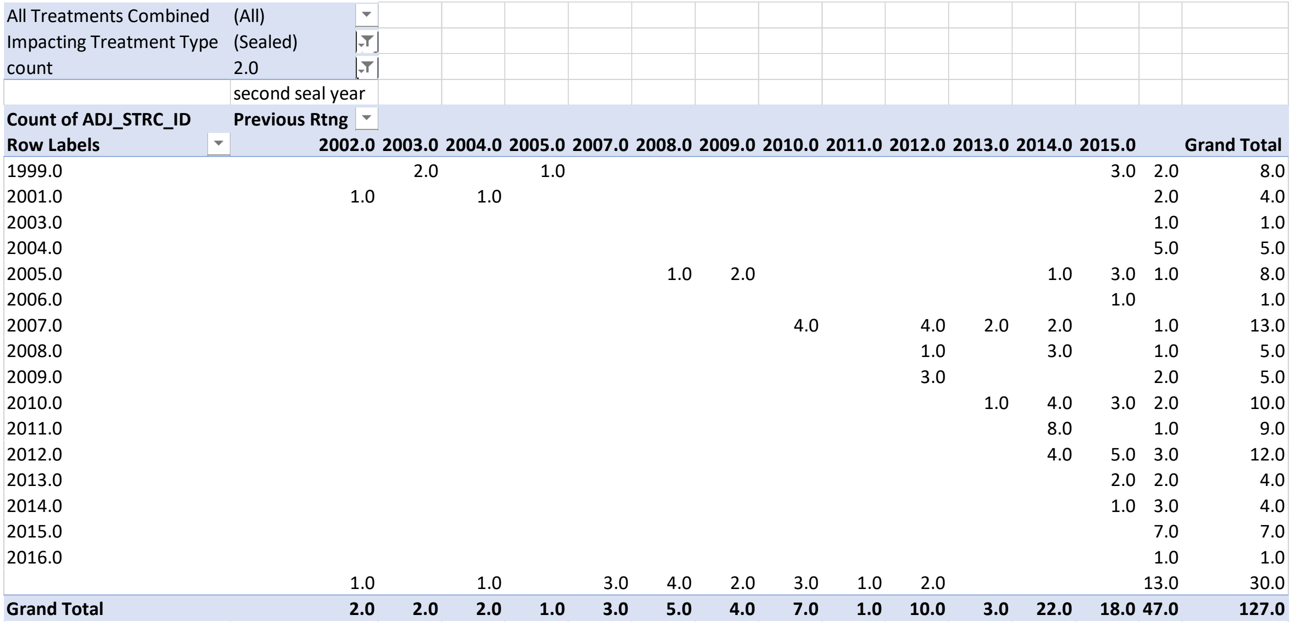
All Treatments Combined (OVERLAY - CONCRETE)>(Sealed)>
Impacting Treatment Type (Sealed)

	Column Labels											
	5.0		6.0		7.0		8.0		9.0		Total Average of TIS	Total Count of ADJ_STRC_ID
Row Labels	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID		
6.0					7.8	6.0					7.8	6.0
7.0	9.0	1.0	10.0	1.0			9.8	12.0			9.8	14.0
8.0			8.0	1.0	4.0	1.0			2.0	1.0	4.7	3.0
Grand Total	**9.0**	**1.0**	**9.0**	**2.0**	**7.3**	**7.0**	**9.8**	**12.0**	**2.0**	**1.0**	**8.6**	**23.0**



All Treatments Combined (All)
Impacting Treatment Type (OVERLAY - CONCRETE)

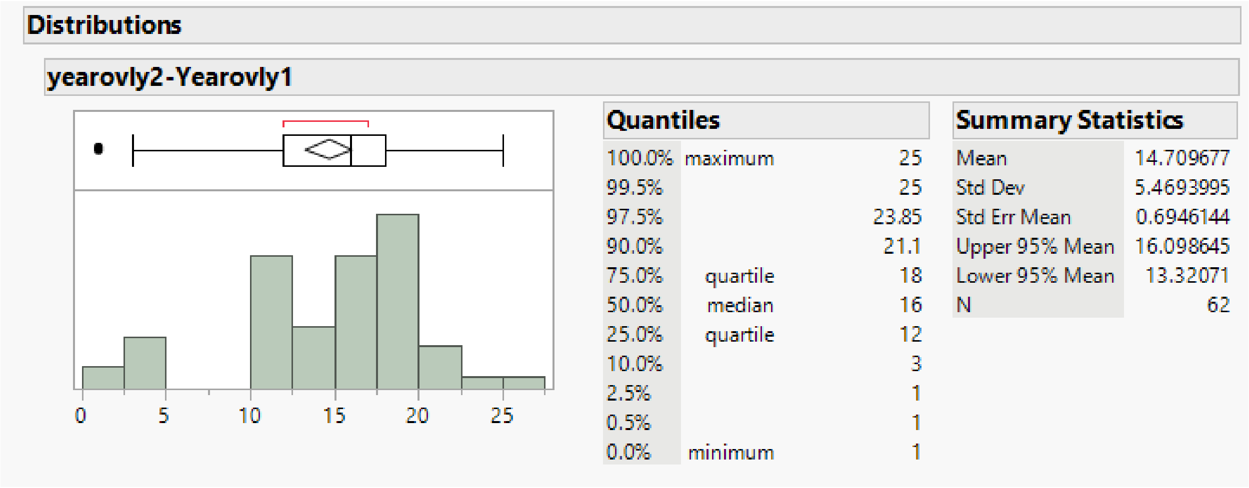
	Previous Rtng											
	5.0		6.0		7.0		8.0		9.0		Total Average of TIS	Total Count of ADJ_STRC_ID
Row Labels	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID	Average of TIS	Count of ADJ_STRC_ID		
4.0	3.3	7.0									3.3	7.0
5.0			8.4	26.0	5.0	2.0					8.2	28.0
6.0	10.3	23.0			10.2	19.0	9.3	9.0			10.1	51.0
7.0	8.1	48.0	9.1	69.0			16.2	18.0	8.0	1.0	9.7	136.0
8.0	4.3	35.0	4.3	109.0	4.6	56.0					4.3	200.0
9.0	2.5	13.0	3.1	11.0	4.0	4.0					2.9	28.0
Grand Total	**6.6**	**126.0**	**6.3**	**215.0**	**5.9**	**81.0**	**13.9**	**27.0**	**8.0**	**1.0**	**6.8**	**450.0**



All Treatments Combined (All)
Impacting Treatment Type (Sealed)
count 2.0

Count of ADJ_STRC_ID	Previous Rtng second seal year														
Row Labels	2002.0	2003.0	2004.0	2005.0	2007.0	2008.0	2009.0	2010.0	2011.0	2012.0	2013.0	2014.0	2015.0		Grand Total
1999.0		2.0		1.0									3.0	2.0	8.0
2001.0	1.0		1.0											2.0	4.0
2003.0														1.0	1.0
2004.0														5.0	5.0
2005.0						1.0	2.0					1.0	3.0	1.0	8.0
2006.0													1.0		1.0
2007.0								4.0		4.0	2.0	2.0		1.0	13.0
2008.0										1.0		3.0		1.0	5.0
2009.0										3.0				2.0	5.0
2010.0											1.0	4.0	3.0	2.0	10.0
2011.0												8.0		1.0	9.0
2012.0												4.0	5.0	3.0	12.0
2013.0													2.0	2.0	4.0
2014.0													1.0	3.0	4.0
2015.0														7.0	7.0
2016.0														1.0	1.0
	1.0		1.0		3.0	4.0	2.0	3.0	1.0	2.0				13.0	30.0
Grand Total	**2.0**	**2.0**	**2.0**	**1.0**	**3.0**	**5.0**	**4.0**	**7.0**	**1.0**	**10.0**	**3.0**	**22.0**	**18.0**	**47.0**	**127.0**

Two concrete overlays are most commonly placed 15 years apart, as shown in the figure below. We could not capture before-after ratings for all of these double overlays due to the limited number of years available in the data set.



Quantiles

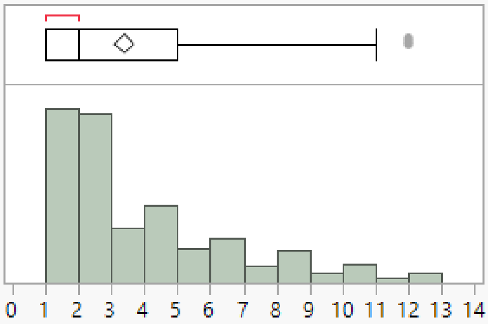
100.0%	maximum	25
99.5%		25
97.5%		23.85
90.0%		21.1
75.0%	quartile	18
50.0%	median	16
25.0%	quartile	12
10.0%		3
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	14.709677
Std Dev	5.4693995
Std Err Mean	0.6946144
Upper 95% Mean	16.098645
Lower 95% Mean	13.32071
N	62

Distributions NBI_Rating=4, Impacting Treatment Type=NO TREATMENT

TIS



Quantiles

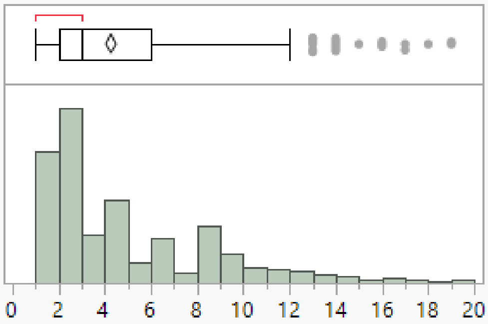
100.0%	maximum	12
99.5%		12
97.5%		10
90.0%		8
75.0%	quartile	5
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	3.4018692
Std Dev	2.6546886
Std Err Mean	0.1481703
Upper 95% Mean	3.6933801
Lower 95% Mean	3.1103582
N	321

Distributions NBI_Rating=5, Impacting Treatment Type=NO TREATMENT

TIS



Quantiles

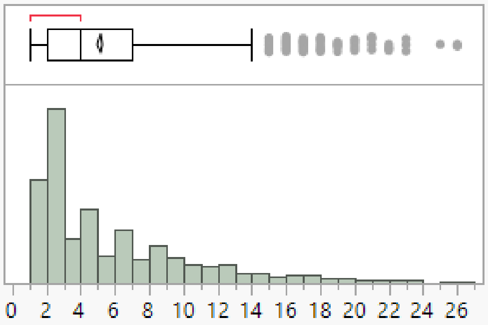
100.0%	maximum	19
99.5%		17
97.5%		13
90.0%		9
75.0%	quartile	6
50.0%	median	3
25.0%	quartile	2
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	4.2612802
Std Dev	3.4831439
Std Err Mean	0.1128301
Upper 95% Mean	4.4827046
Lower 95% Mean	4.0398557
N	953

Distributions NBI_Rating=6, Impacting Treatment Type=NO TREATMENT

TIS



Quantiles

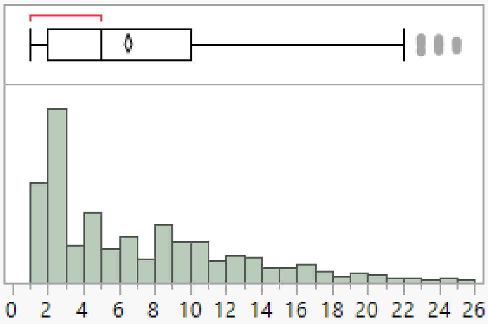
100.0%	maximum	26
99.5%		22
97.5%		17
90.0%		12
75.0%	quartile	7
50.0%	median	4
25.0%	quartile	2
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	5.1182109
Std Dev	4.4355549
Std Err Mean	0.0947604
Upper 95% Mean	5.3040405
Lower 95% Mean	4.9323812
N	2191

Distributions NBI_Rating=7, Impacting Treatment Type=NO TREATMENT

TIS



Quantiles

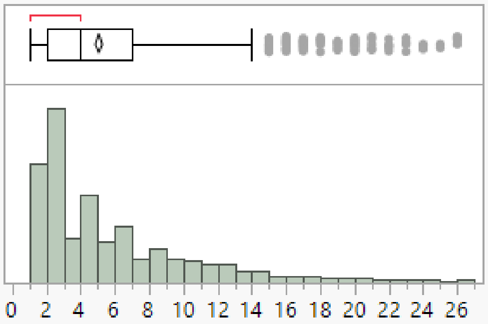
100.0%	maximum	25
99.5%		24
97.5%		20
90.0%		14
75.0%	quartile	10
50.0%	median	5
25.0%	quartile	2
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	6.4899464
Std Dev	5.2982675
Std Err Mean	0.0969917
Upper 95% Mean	6.6801237
Lower 95% Mean	6.299769
N	2984

Distributions NBI_Rating=8, Impacting Treatment Type=NO TREATMENT

TIS



Quantiles

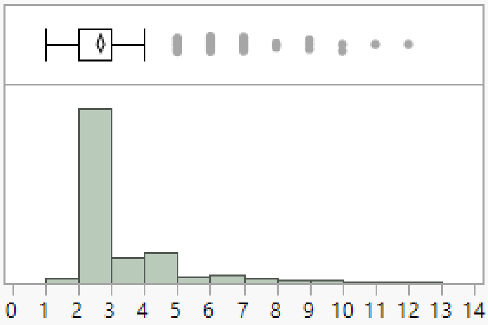
100.0%	maximum	26
99.5%		23
97.5%		17
90.0%		11
75.0%	quartile	7
50.0%	median	4
25.0%	quartile	2
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	5.0754573
Std Dev	4.4580931
Std Err Mean	0.0870296
Upper 95% Mean	5.246111
Lower 95% Mean	4.9048036
N	2624

Distributions NBI_Rating=9, Impacting Treatment Type=(NEW)

TIS

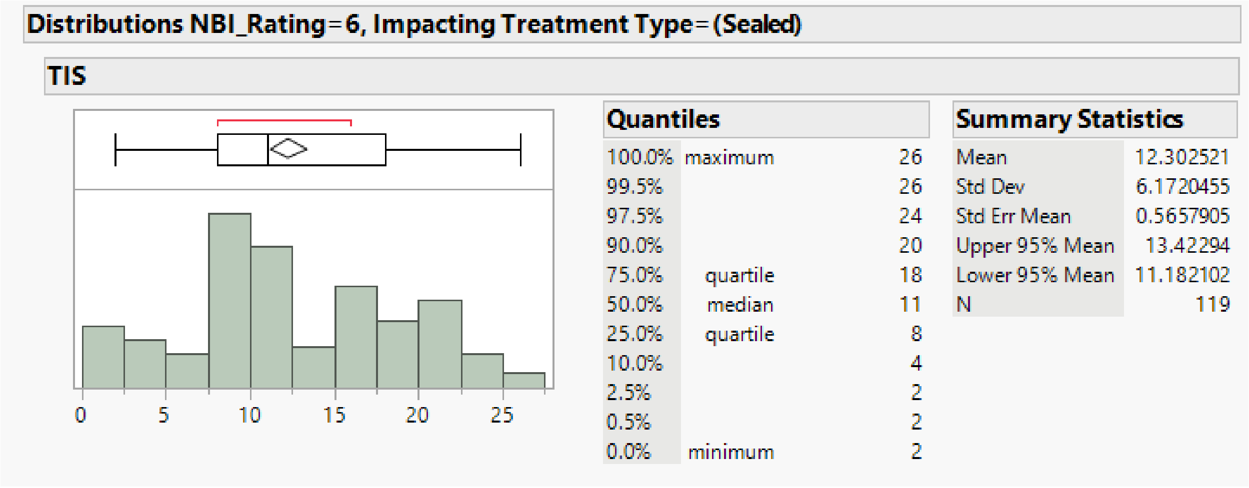


Quantiles

100.0%	maximum	12
99.5%		10
97.5%		7
90.0%		4
75.0%	quartile	3
50.0%	median	2
25.0%	quartile	2
10.0%		2
2.5%		2
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	2.6640523
Std Dev	1.3808059
Std Err Mean	0.0499231
Upper 95% Mean	2.7620551
Lower 95% Mean	2.5660495
N	765



Distributions NBI_Rating=6, Impacting Treatment Type=(Sealed)

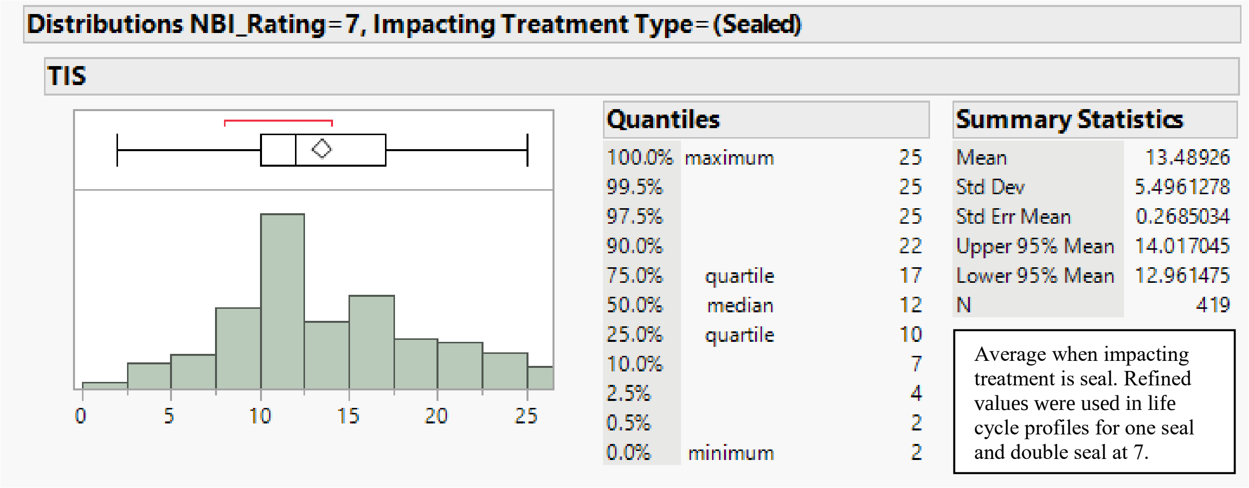
TIS

Quantiles

100.0%	maximum	26
99.5%		26
97.5%		24
90.0%		20
75.0%	quartile	18
50.0%	median	11
25.0%	quartile	8
10.0%		4
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	12.302521
Std Dev	6.1720455
Std Err Mean	0.5657905
Upper 95% Mean	13.42294
Lower 95% Mean	11.182102
N	119



Distributions NBI_Rating=7, Impacting Treatment Type=(Sealed)

TIS

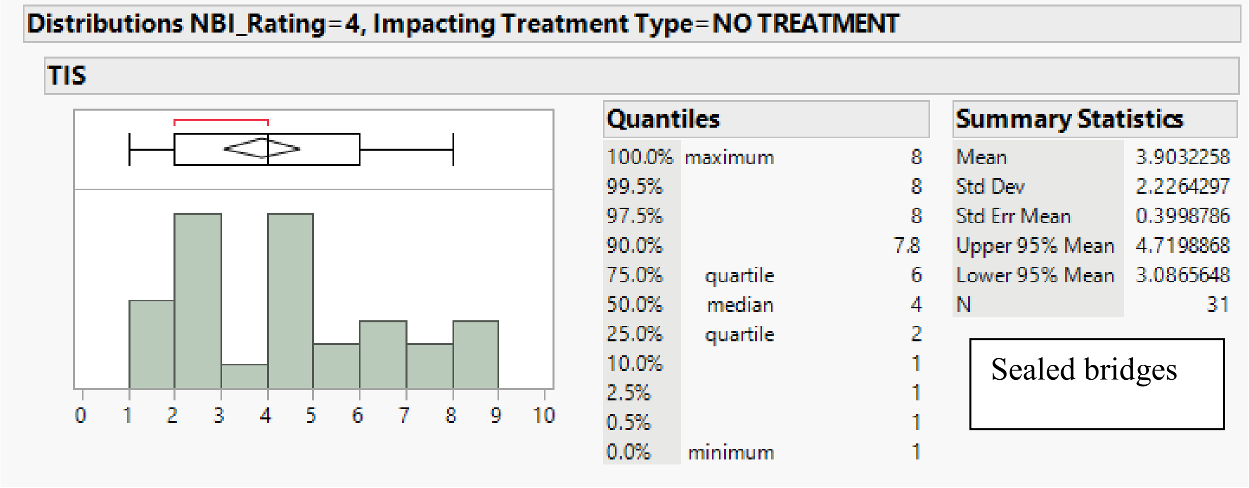
Quantiles

100.0%	maximum	25
99.5%		25
97.5%		25
90.0%		22
75.0%	quartile	17
50.0%	median	12
25.0%	quartile	10
10.0%		7
2.5%		4
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	13.48926
Std Dev	5.4961278
Std Err Mean	0.2685034
Upper 95% Mean	14.017045
Lower 95% Mean	12.961475
N	419

Average when impacting treatment is seal. Refined values were used in life cycle profiles for one seal and double seal at 7.



Distributions NBI_Rating=4, Impacting Treatment Type=NO TREATMENT

TIS

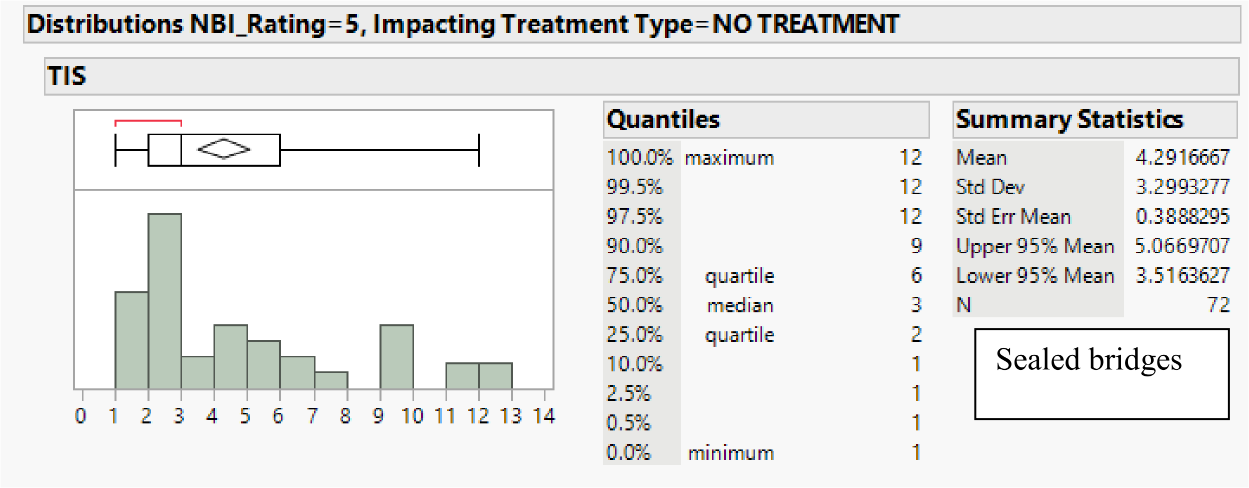
Quantiles

100.0%	maximum	8
99.5%		8
97.5%		8
90.0%		7.8
75.0%	quartile	6
50.0%	median	4
25.0%	quartile	2
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	3.9032258
Std Dev	2.2264297
Std Err Mean	0.3998786
Upper 95% Mean	4.7198868
Lower 95% Mean	3.0865648
N	31

Sealed bridges



Distributions NBI_Rating=5, Impacting Treatment Type=NO TREATMENT

TIS

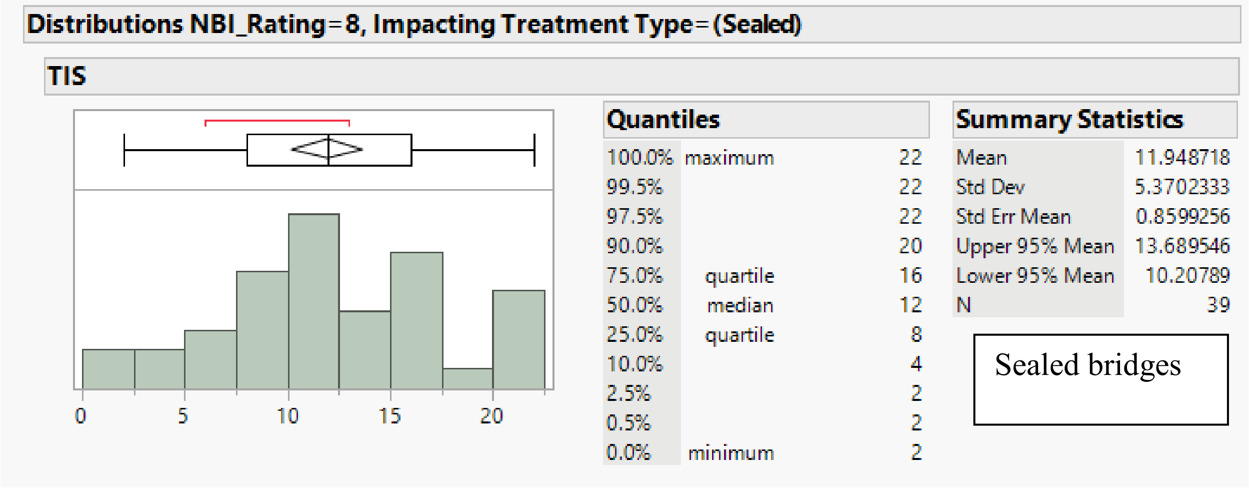
Quantiles

100.0%	maximum	12
99.5%		12
97.5%		12
90.0%		9
75.0%	quartile	6
50.0%	median	3
25.0%	quartile	2
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	4.2916667
Std Dev	3.2993277
Std Err Mean	0.3888295
Upper 95% Mean	5.0669707
Lower 95% Mean	3.5163627
N	72

Sealed bridges



Distributions NBI_Rating=8, Impacting Treatment Type=(Sealed)

TIS

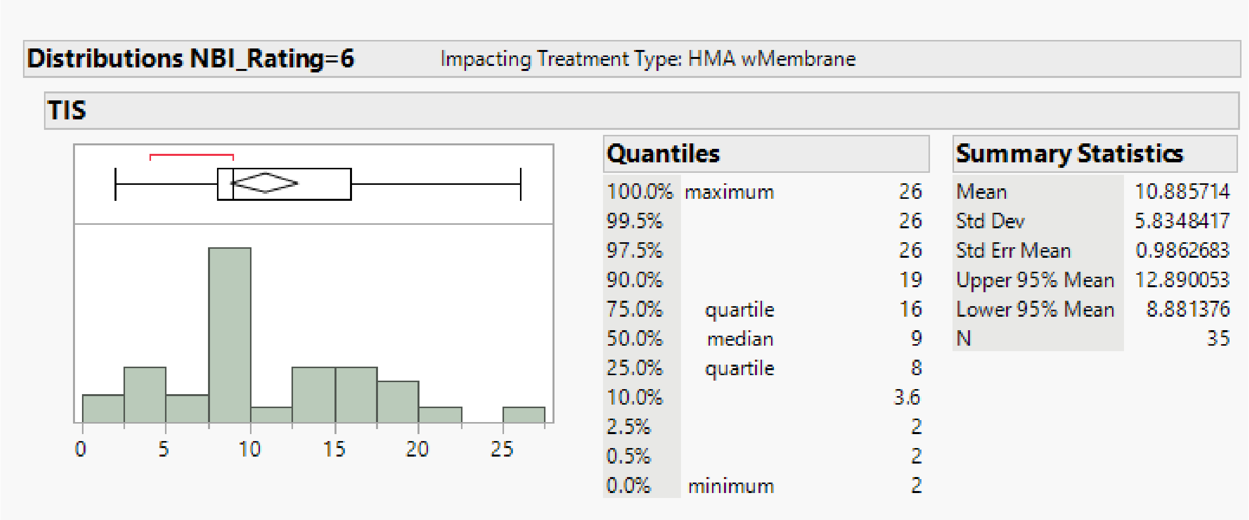
Quantiles

100.0%	maximum	22
99.5%		22
97.5%		22
90.0%		20
75.0%	quartile	16
50.0%	median	12
25.0%	quartile	8
10.0%		4
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	11.948718
Std Dev	5.3702333
Std Err Mean	0.8599256
Upper 95% Mean	13.689546
Lower 95% Mean	10.20789
N	39

Sealed bridges



Distributions NBI_Rating=6 Impacting Treatment Type: HMA wMembrane

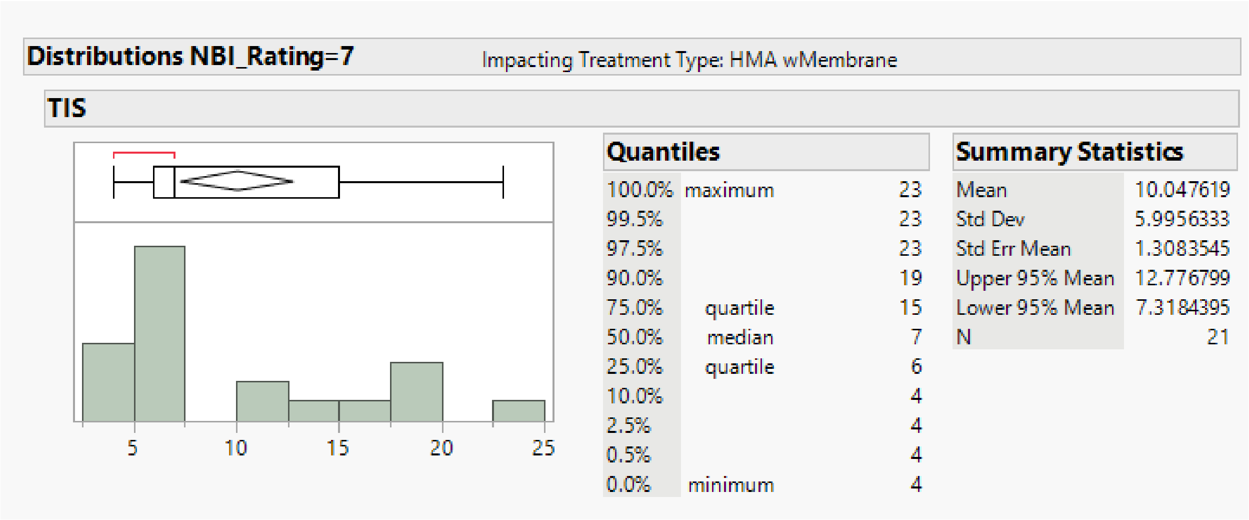
TIS

Quantiles

100.0%	maximum	26
99.5%		26
97.5%		26
90.0%		19
75.0%	quartile	16
50.0%	median	9
25.0%	quartile	8
10.0%		3.6
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	10.885714
Std Dev	5.8348417
Std Err Mean	0.9862683
Upper 95% Mean	12.890053
Lower 95% Mean	8.881376
N	35



Distributions NBI_Rating=7 Impacting Treatment Type: HMA wMembrane

TIS

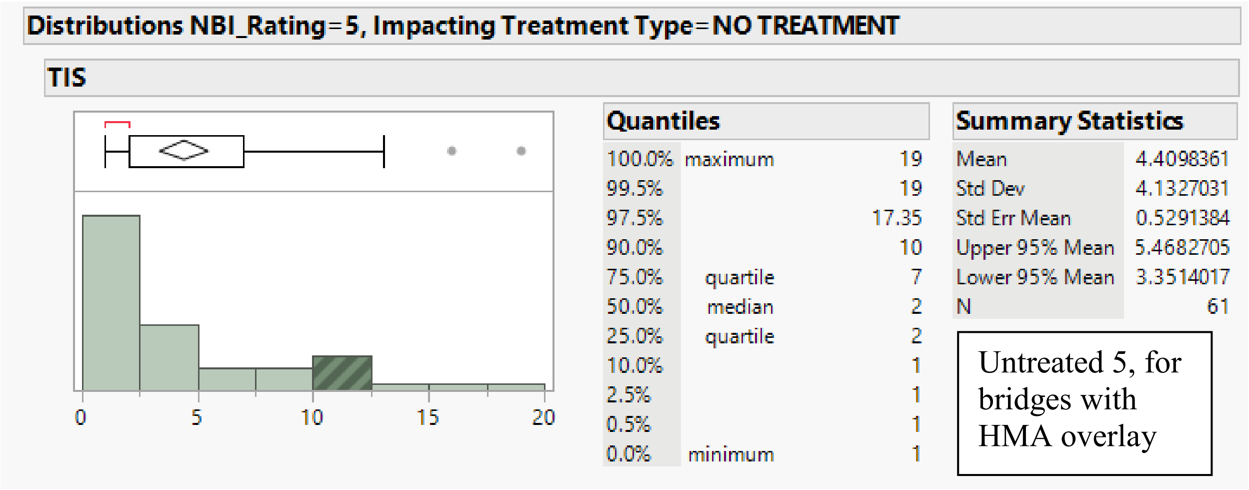
Quantiles

100.0%	maximum	23
99.5%		23
97.5%		23
90.0%		19
75.0%	quartile	15
50.0%	median	7
25.0%	quartile	6
10.0%		4
2.5%		4
0.5%		4
0.0%	minimum	4

Summary Statistics

Mean	10.047619
Std Dev	5.9956333
Std Err Mean	1.3083545
Upper 95% Mean	12.776799
Lower 95% Mean	7.3184395
N	21

The mean and standard deviation of the TIS for GCR 7 > 8 with hot-mix asphalt (HMA) with membrane (mean of 3.92, standard deviation of 2, 28 observations) was low and not included in the life-cycle profiles.



Distributions NBI_Rating=5, Impacting Treatment Type=NO TREATMENT

TIS

Quantiles

100.0%	maximum	19
99.5%		19
97.5%		17.35
90.0%		10
75.0%	quartile	7
50.0%	median	2
25.0%	quartile	2
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	4.4098361
Std Dev	4.1327031
Std Err Mean	0.5291384
Upper 95% Mean	5.4682705
Lower 95% Mean	3.3514017
N	61

Untreated 5, for bridges with HMA overlay


Data from bridges with PMA overlay

Distributions NBI_Rating=6

TIS

Quantiles		
100.0%	maximum	25
99.5%		25
97.5%		25
90.0%		24.7
75.0%	quartile	18.75
50.0%	median	10
25.0%	quartile	5
10.0%		2
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics	
Mean	11.666667
Std Dev	7.8893868
Std Err Mean	2.2774698
Upper 95% Mean	16.679344
Lower 95% Mean	6.6539894
N	12

Distributions NBI_Rating=7

TIS

Quantiles		
100.0%	maximum	24
99.5%		24
97.5%		24
90.0%		24
75.0%	quartile	22.5
50.0%	median	16.5
25.0%	quartile	14.5
10.0%		10
2.5%		10
0.5%		10
0.0%	minimum	10

Summary Statistics	
Mean	17.5
Std Dev	4.9699095
Std Err Mean	2.028957
Upper 95% Mean	22.7156
Lower 95% Mean	12.2844
N	6

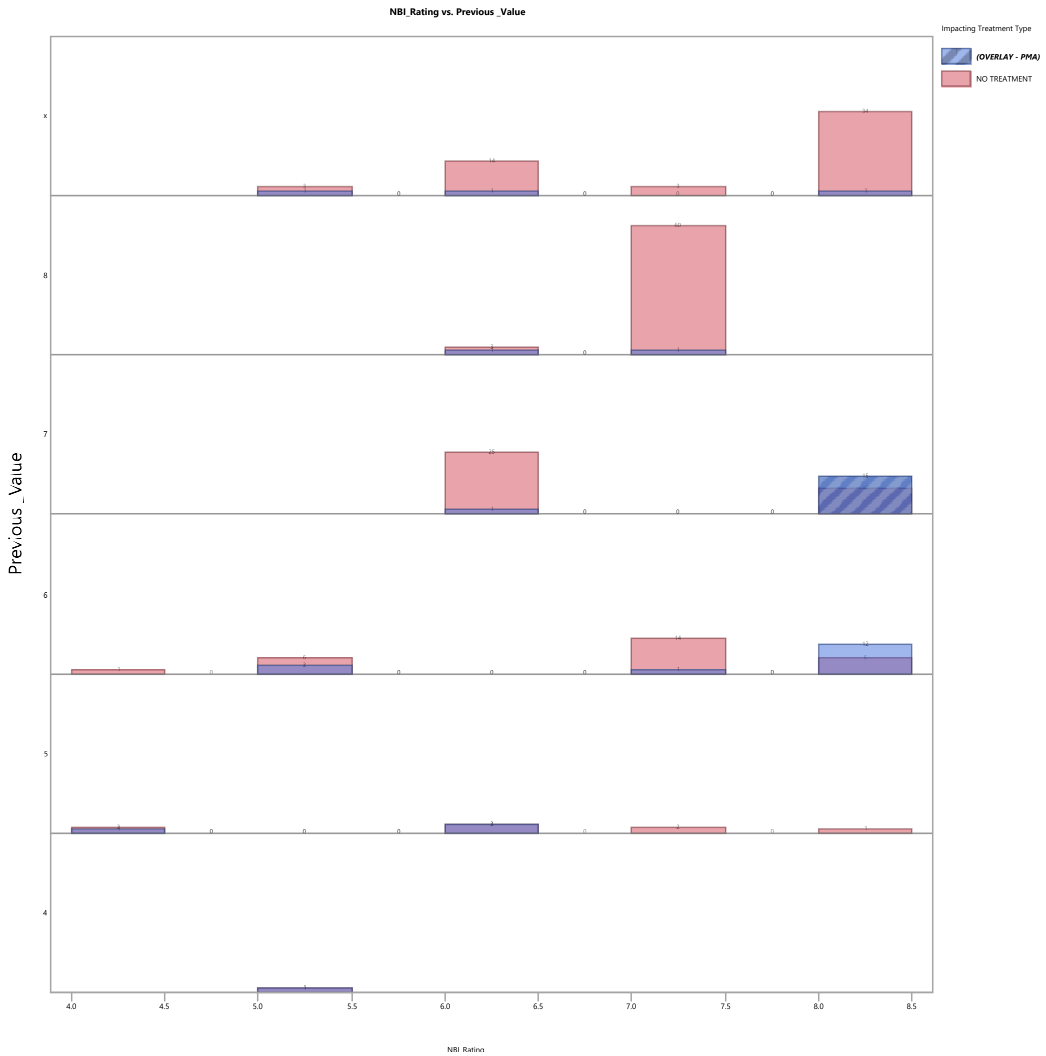
Distributions NBI_Rating=8

TIS

Quantiles		
100.0%	maximum	18
99.5%		18
97.5%		18
90.0%		12
75.0%	quartile	8
50.0%	median	4
25.0%	quartile	4
10.0%		2
2.5%		2
0.5%		2
0.0%	minimum	2

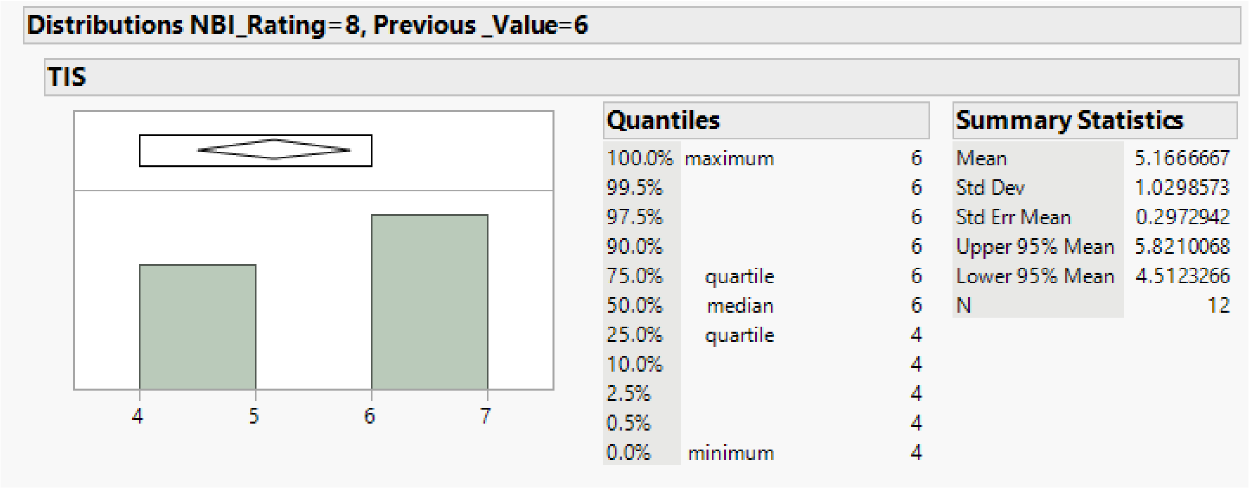
Summary Statistics	
Mean	6.2105263
Std Dev	4.0903538
Std Err Mean	0.9383915
Upper 95% Mean	8.1820137
Lower 95% Mean	4.2390389
N	19

The figure below indicates that most polymer-modified asphalt (PMA) overlays increased deck GCR from 6 or 7 to 8 (as observed in 27 cases). However, six observations where a GCR of 7 resulted had a significantly different average than that of untreated decks. Therefore, at the treatment level, we could not find significantly different performance for PMA overlays that led to a GCR of 8. More than half of PMA overlays that led to a GCR of 8 were placed in 2013 or later. Future data on these overlays would show their impact and should be revisited.



-

The three distributions below were used for the life-cycle profiles.



Distributions NBI_Rating=8, Previous _Value=6

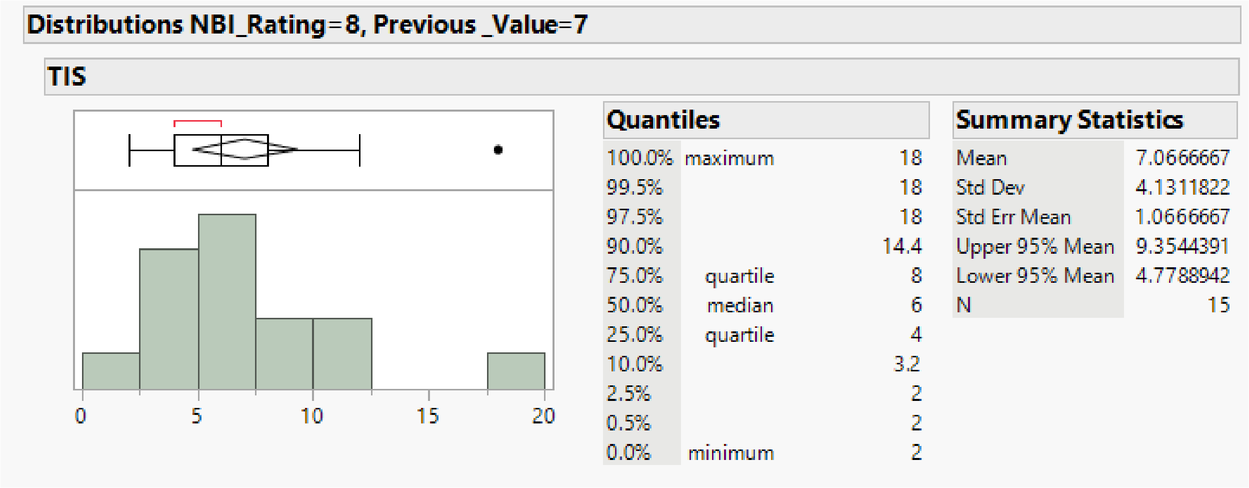
TIS

Quantiles

100.0%	maximum	6
99.5%		6
97.5%		6
90.0%		6
75.0%	quartile	6
50.0%	median	6
25.0%	quartile	4
10.0%		4
2.5%		4
0.5%		4
0.0%	minimum	4

Summary Statistics

Mean	5.1666667
Std Dev	1.0298573
Std Err Mean	0.2972942
Upper 95% Mean	5.8210068
Lower 95% Mean	4.5123266
N	12



Distributions NBI_Rating=8, Previous _Value=7

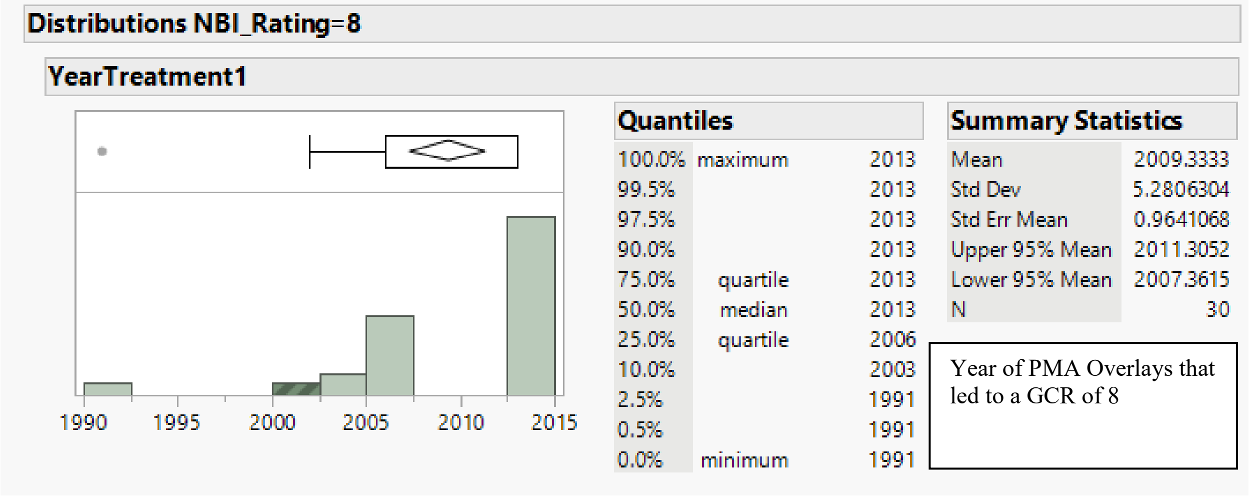
TIS

Quantiles

100.0%	maximum	18
99.5%		18
97.5%		18
90.0%		14.4
75.0%	quartile	8
50.0%	median	6
25.0%	quartile	4
10.0%		3.2
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	7.0666667
Std Dev	4.1311822
Std Err Mean	1.0666667
Upper 95% Mean	9.3544391
Lower 95% Mean	4.7788942
N	15



Distributions NBI_Rating=8

YearTreatment1

Quantiles

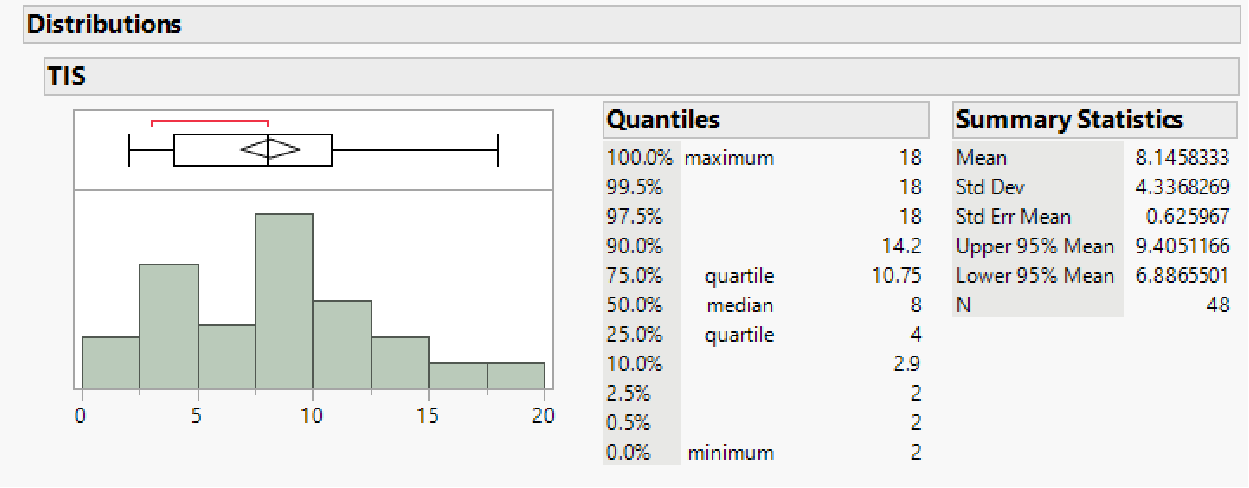
100.0%	maximum	2013
99.5%		2013
97.5%		2013
90.0%		2013
75.0%	quartile	2013
50.0%	median	2013
25.0%	quartile	2006
10.0%		2003
2.5%		1991
0.5%		1991
0.0%	minimum	1991

Summary Statistics

Mean	2009.3333
Std Dev	5.2806304
Std Err Mean	0.9641068
Upper 95% Mean	2011.3052
Lower 95% Mean	2007.3615
N	30

Year of PMA Overlays that led to a GCR of 8

Concrete Overlay – 5 > 7



Distributions

TIS

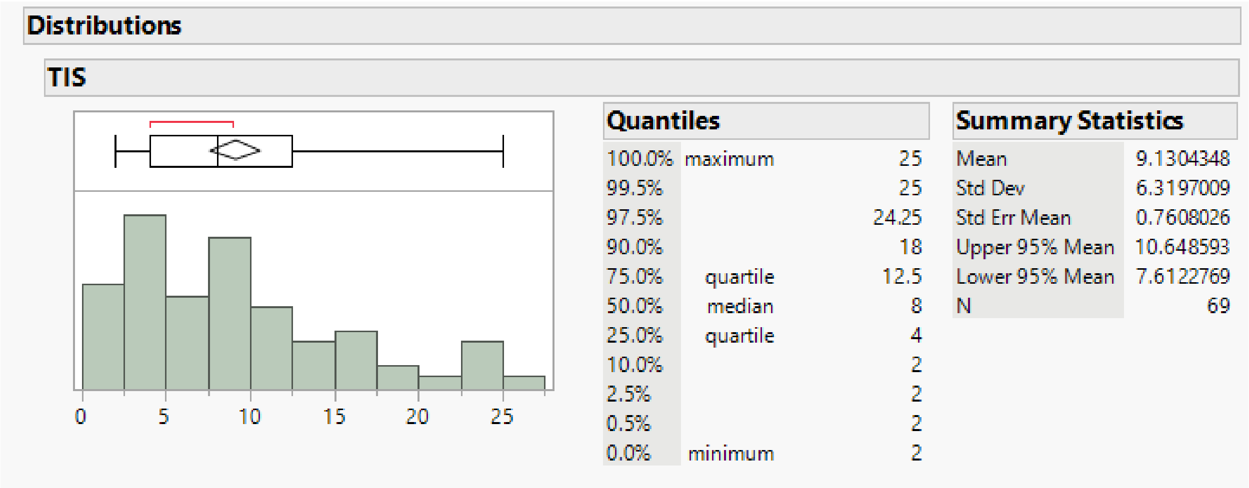
Quantiles

100.0%	maximum	18
99.5%		18
97.5%		18
90.0%		14.2
75.0%	quartile	10.75
50.0%	median	8
25.0%	quartile	4
10.0%		2.9
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	8.1458333
Std Dev	4.3368269
Std Err Mean	0.625967
Upper 95% Mean	9.4051166
Lower 95% Mean	6.8865501
N	48

Concrete Overlay – 6 > 7



Distributions

TIS

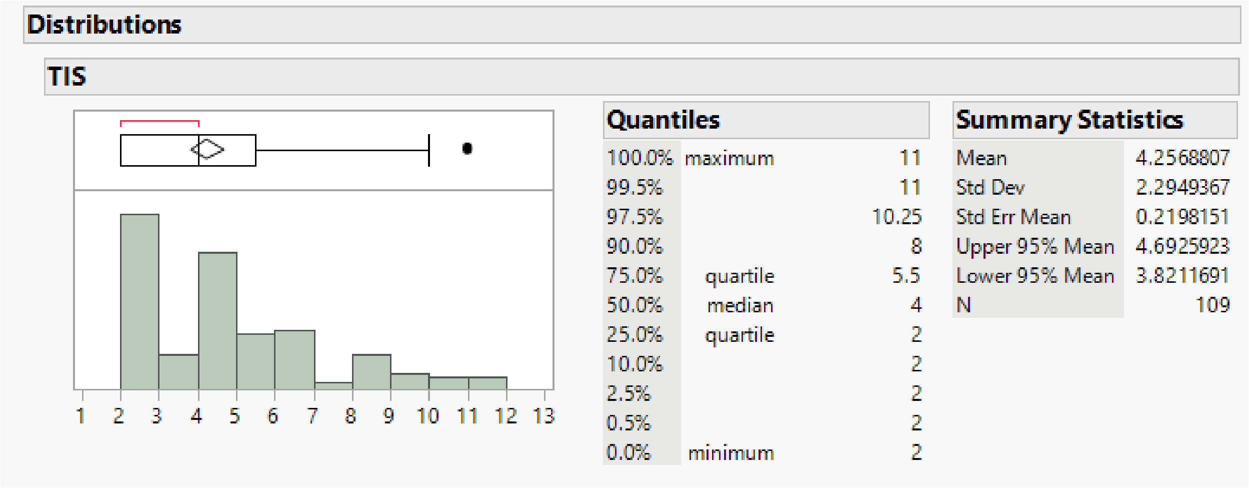
Quantiles

100.0%	maximum	25
99.5%		25
97.5%		24.25
90.0%		18
75.0%	quartile	12.5
50.0%	median	8
25.0%	quartile	4
10.0%		2
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	9.1304348
Std Dev	6.3197009
Std Err Mean	0.7608026
Upper 95% Mean	10.648593
Lower 95% Mean	7.6122769
N	69

Concrete Overlay – 6 > 8



Distributions

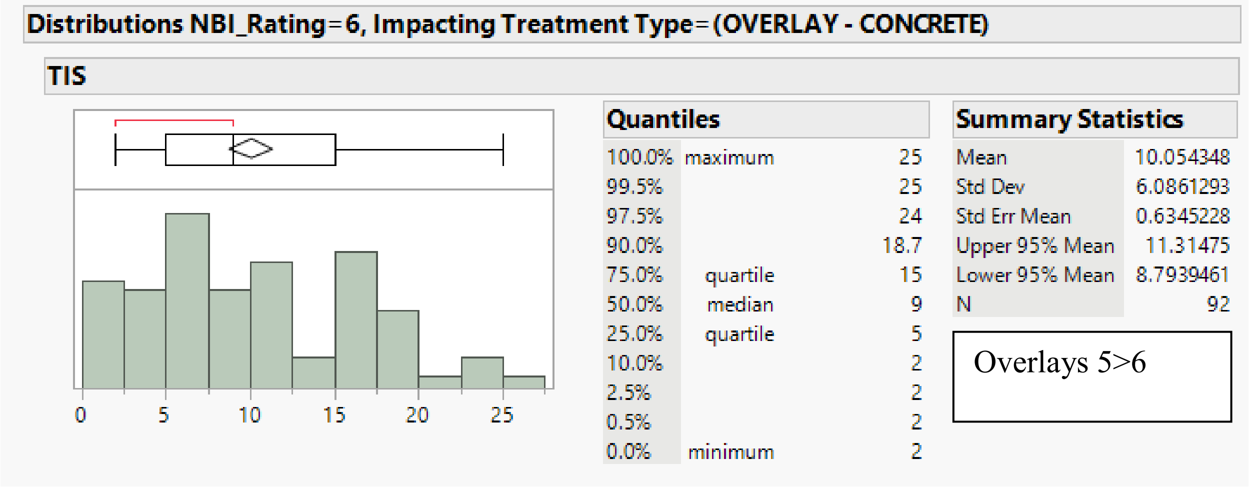
TIS

Quantiles

100.0%	maximum	11
99.5%		11
97.5%		10.25
90.0%		8
75.0%	quartile	5.5
50.0%	median	4
25.0%	quartile	2
10.0%		2
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	4.2568807
Std Dev	2.2949367
Std Err Mean	0.2198151
Upper 95% Mean	4.6925923
Lower 95% Mean	3.8211691
N	109



Distributions NBI_Rating=6, Impacting Treatment Type=(OVERLAY - CONCRETE)

TIS

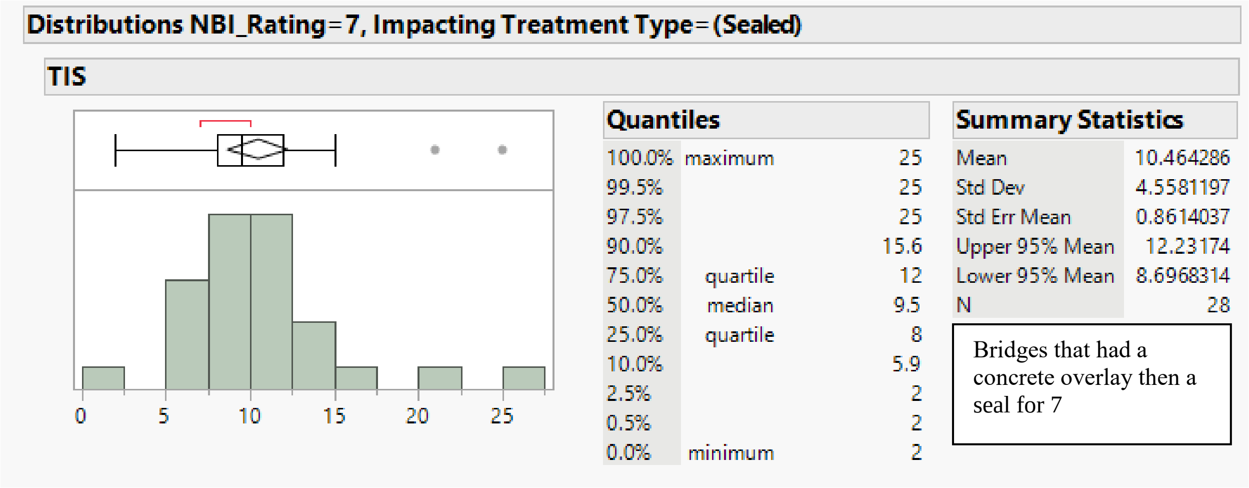
Quantiles

100.0%	maximum	25
99.5%		25
97.5%		24
90.0%		18.7
75.0%	quartile	15
50.0%	median	9
25.0%	quartile	5
10.0%		2
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	10.054348
Std Dev	6.0861293
Std Err Mean	0.6345228
Upper 95% Mean	11.31475
Lower 95% Mean	8.7939461
N	92

Overlays 5>6



Distributions NBI_Rating=7, Impacting Treatment Type=(Sealed)

TIS

Quantiles

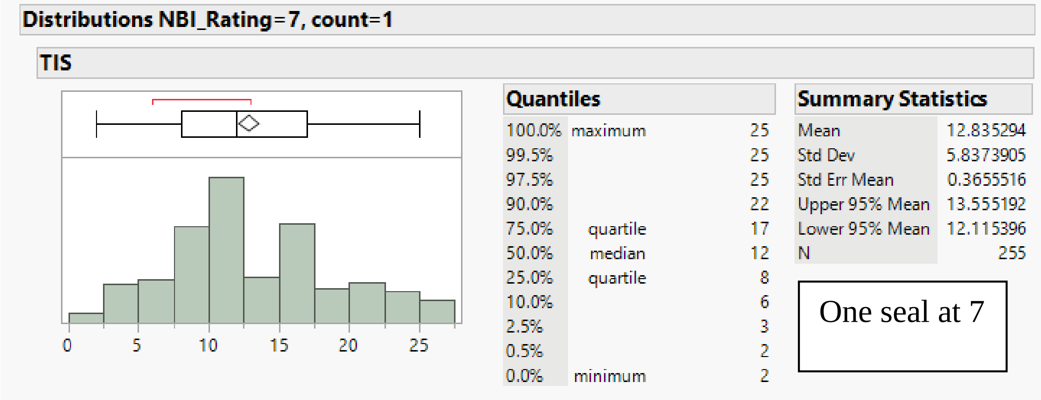
100.0%	maximum	25
99.5%		25
97.5%		25
90.0%		15.6
75.0%	quartile	12
50.0%	median	9.5
25.0%	quartile	8
10.0%		5.9
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	10.464286
Std Dev	4.5581197
Std Err Mean	0.8614037
Upper 95% Mean	12.23174
Lower 95% Mean	8.6968314
N	28

Bridges that had a concrete overlay then a seal for 7

Double-Sealed Structures



Distributions NBI_Rating=7, count=1

TIS

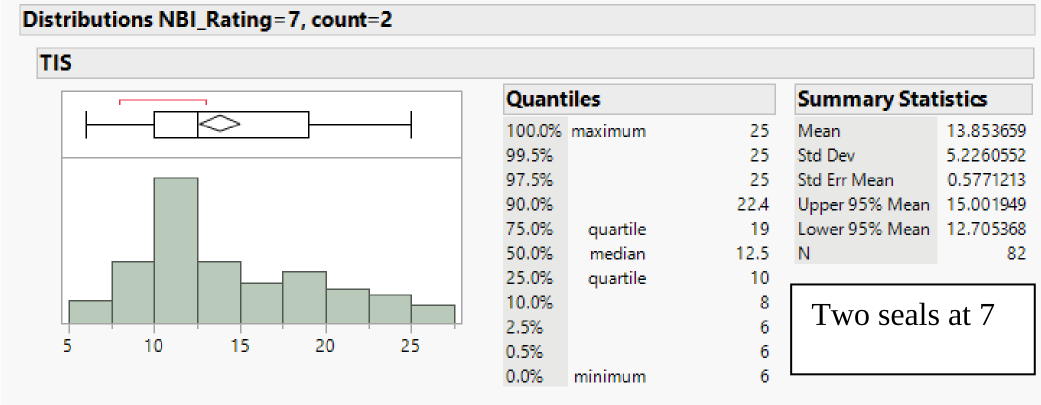
Quantiles

100.0%	maximum	25
99.5%		25
97.5%		25
90.0%		22
75.0%	quartile	17
50.0%	median	12
25.0%	quartile	8
10.0%		6
2.5%		3
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	12.835294
Std Dev	5.8373905
Std Err Mean	0.3655516
Upper 95% Mean	13.555192
Lower 95% Mean	12.115396
N	255

One seal at 7



Distributions NBI_Rating=7, count=2

TIS

Quantiles

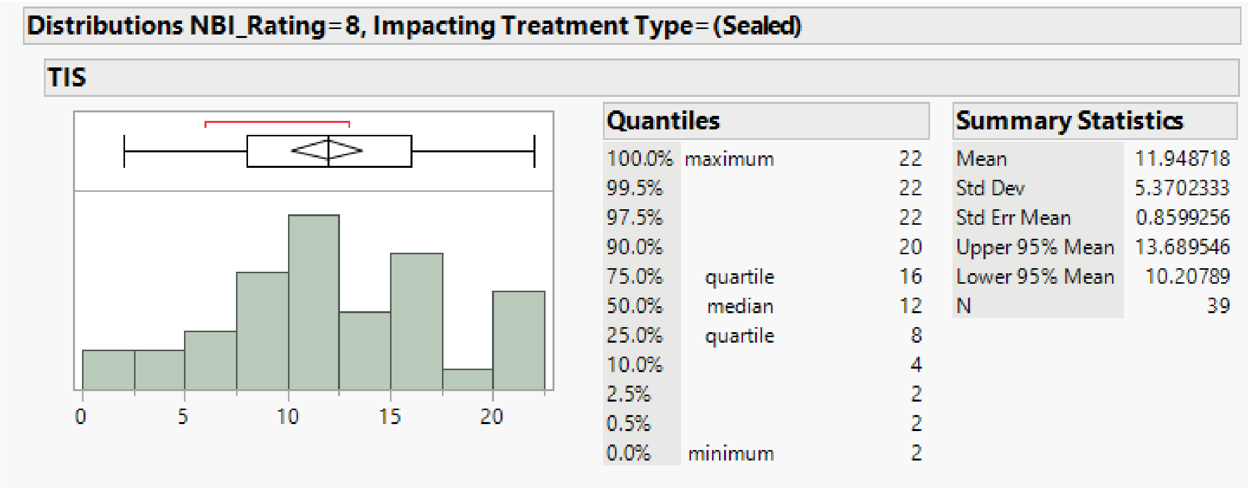
100.0%	maximum	25
99.5%		25
97.5%		25
90.0%		22.4
75.0%	quartile	19
50.0%	median	12.5
25.0%	quartile	10
10.0%		8
2.5%		6
0.5%		6
0.0%	minimum	6

Summary Statistics

Mean	13.853659
Std Dev	5.2260552
Std Err Mean	0.5771213
Upper 95% Mean	15.001949
Lower 95% Mean	12.705368
N	82

Two seals at 7

Seal at 8 Followed by Another Seal at 7



Distributions NBI_Rating=8, Impacting Treatment Type=(Sealed)

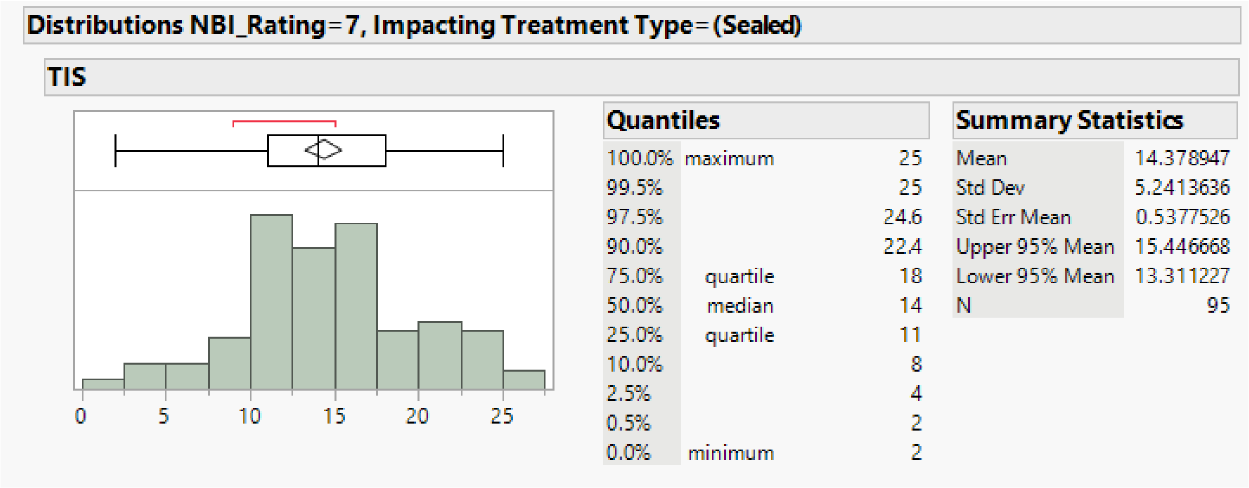
TIS

Quantiles

100.0%	maximum	22
99.5%		22
97.5%		22
90.0%		20
75.0%	quartile	16
50.0%	median	12
25.0%	quartile	8
10.0%		4
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	11.948718
Std Dev	5.3702333
Std Err Mean	0.8599256
Upper 95% Mean	13.689546
Lower 95% Mean	10.20789
N	39



Distributions NBI_Rating=7, Impacting Treatment Type=(Sealed)

TIS

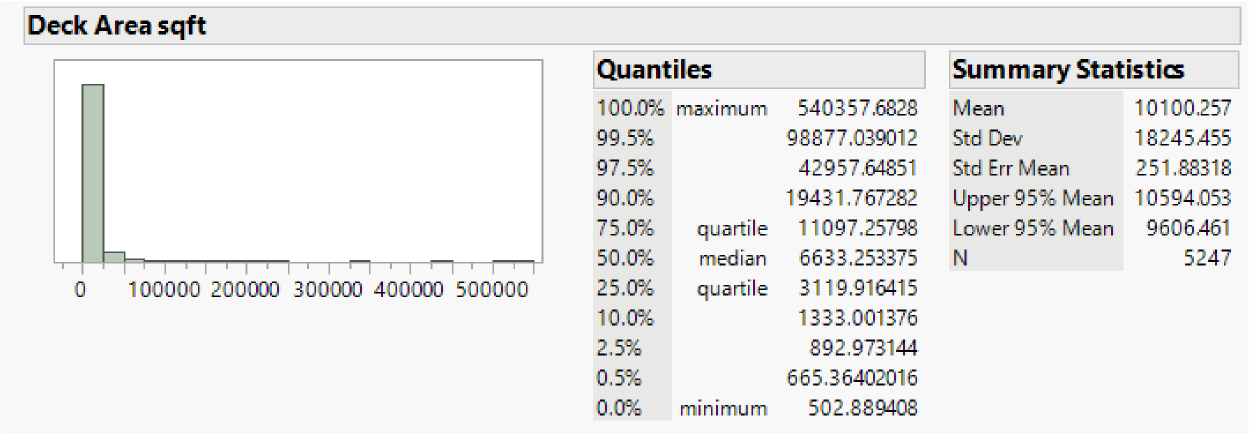
Quantiles

100.0%	maximum	25
99.5%		25
97.5%		24.6
90.0%		22.4
75.0%	quartile	18
50.0%	median	14
25.0%	quartile	11
10.0%		8
2.5%		4
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	14.378947
Std Dev	5.2413636
Std Err Mean	0.5377526
Upper 95% Mean	15.446668
Lower 95% Mean	13.311227
N	95

Deck Area



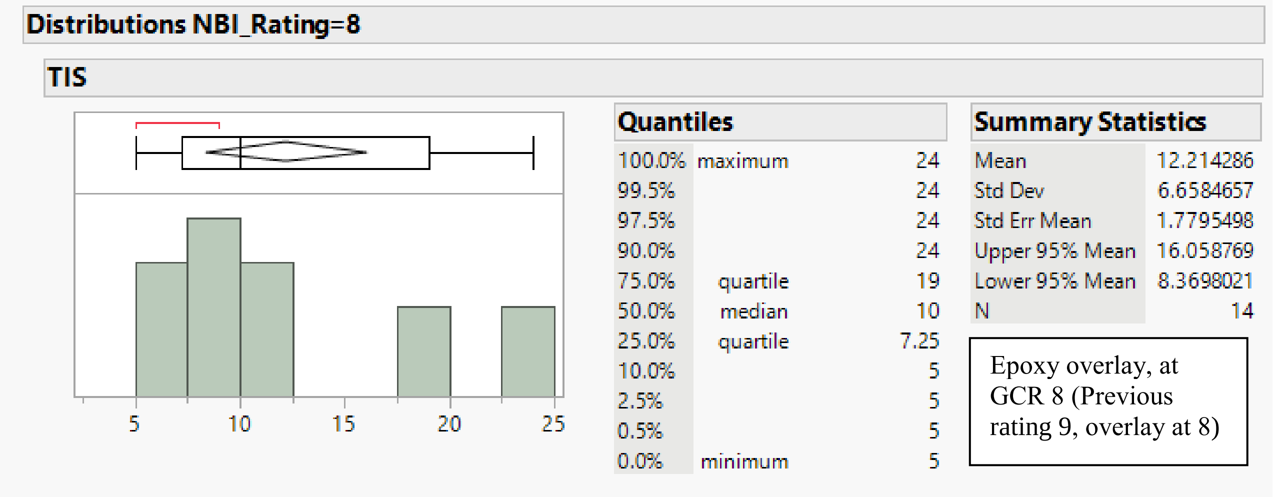
Deck Area sqft

Quantiles

100.0%	maximum	540357.6828
99.5%		98877.039012
97.5%		42957.64851
90.0%		19431.767282
75.0%	quartile	11097.25798
50.0%	median	6633.253375
25.0%	quartile	3119.916415
10.0%		1333.001376
2.5%		892.973144
0.5%		665.36402016
0.0%	minimum	502.889408

Summary Statistics

Mean	10100.257
Std Dev	18245.455
Std Err Mean	251.88318
Upper 95% Mean	10594.053
Lower 95% Mean	9606.461
N	5247



Distributions NBI_Rating=8

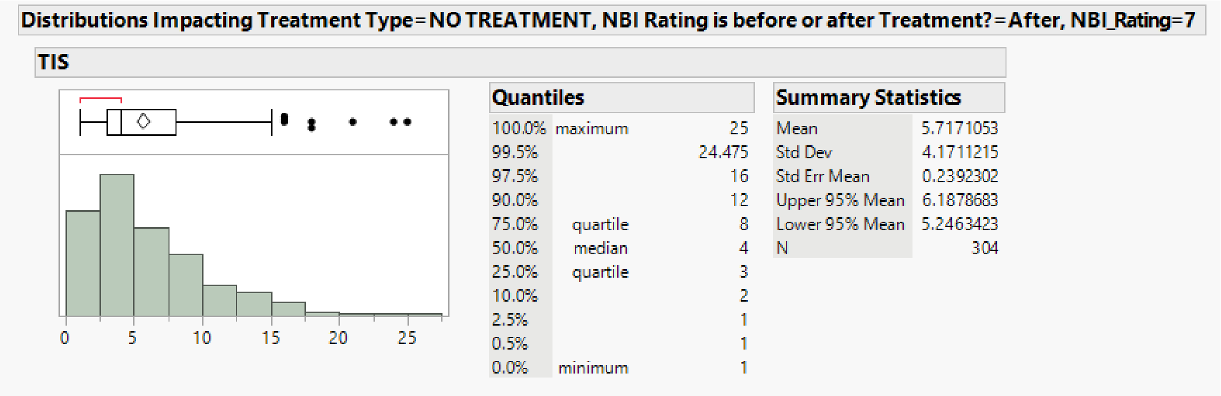
TIS

Quantiles		
100.0%	maximum	24
99.5%		24
97.5%		24
90.0%		24
75.0%	quartile	19
50.0%	median	10
25.0%	quartile	7.25
10.0%		5
2.5%		5
0.5%		5
0.0%	minimum	5

Summary Statistics	
Mean	12.214286
Std Dev	6.6584657
Std Err Mean	1.7795498
Upper 95% Mean	16.058769
Lower 95% Mean	8.3698021
N	14

Epoxy overlay, at GCR 8 (Previous rating 9, overlay at 8)

Untreated NBI TIS after a Concrete Overlay

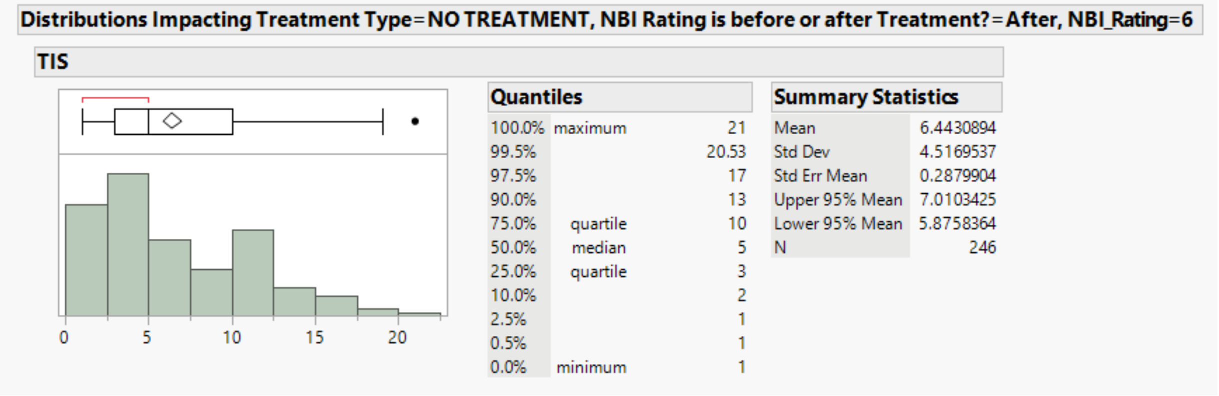


Distributions Impacting Treatment Type=NO TREATMENT, NBI Rating is before or after Treatment?=After, NBI_Rating=7

TIS

Quantiles		
100.0%	maximum	25
99.5%		24.475
97.5%		16
90.0%		12
75.0%	quartile	8
50.0%	median	4
25.0%	quartile	3
10.0%		2
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics	
Mean	5.7171053
Std Dev	4.1711215
Std Err Mean	0.2392302
Upper 95% Mean	6.1878683
Lower 95% Mean	5.2463423
N	304

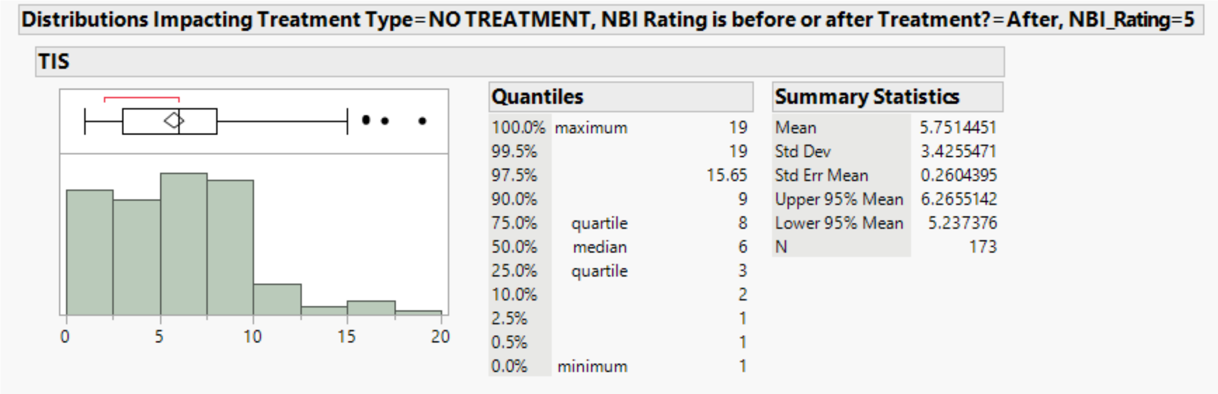


Distributions Impacting Treatment Type=NO TREATMENT, NBI Rating is before or after Treatment?=After, NBI_Rating=6

TIS

Quantiles		
100.0%	maximum	21
99.5%		20.53
97.5%		17
90.0%		13
75.0%	quartile	10
50.0%	median	5
25.0%	quartile	3
10.0%		2
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics	
Mean	6.4430894
Std Dev	4.5169537
Std Err Mean	0.2879904
Upper 95% Mean	7.0103425
Lower 95% Mean	5.8758364
N	246



Distributions Impacting Treatment Type=NO TREATMENT, NBI Rating is before or after Treatment?=After, NBI_Rating=5

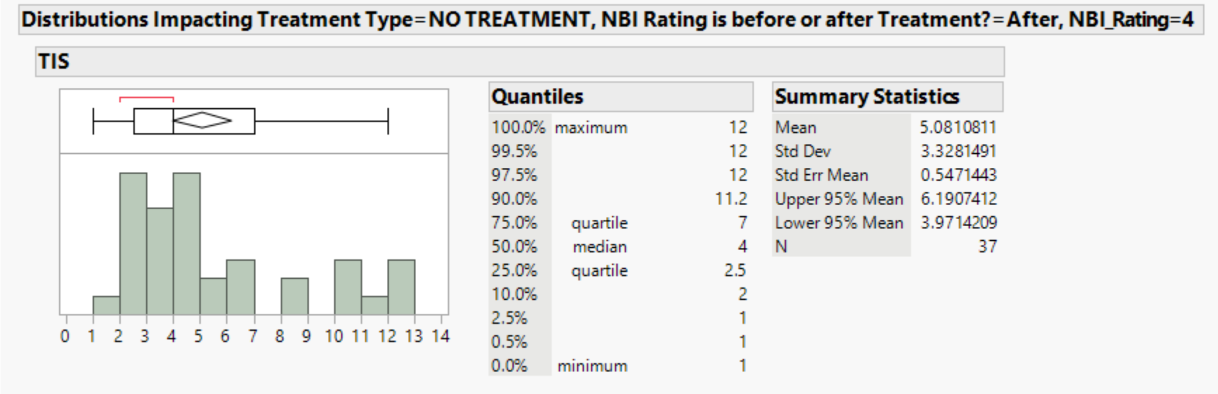
TIS

Quantiles

100.0%	maximum	19
99.5%		19
97.5%		15.65
90.0%		9
75.0%	quartile	8
50.0%	median	6
25.0%	quartile	3
10.0%		2
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	5.7514451
Std Dev	3.4255471
Std Err Mean	0.2604395
Upper 95% Mean	6.2655142
Lower 95% Mean	5.237376
N	173



Distributions Impacting Treatment Type=NO TREATMENT, NBI Rating is before or after Treatment?=After, NBI_Rating=4

TIS

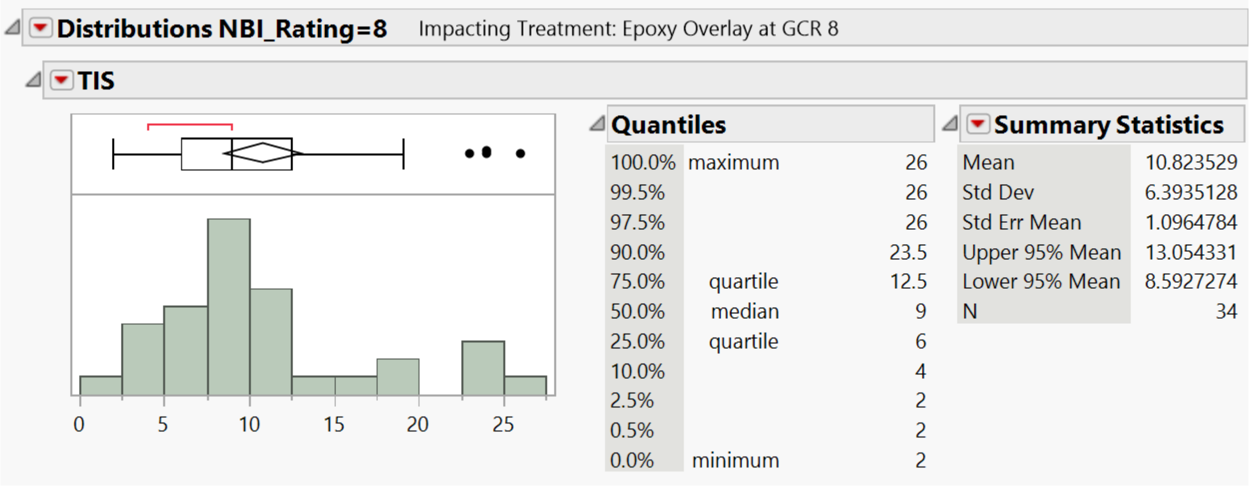
Quantiles

100.0%	maximum	12
99.5%		12
97.5%		12
90.0%		11.2
75.0%	quartile	7
50.0%	median	4
25.0%	quartile	2.5
10.0%		2
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	5.0810811
Std Dev	3.3281491
Std Err Mean	0.5471443
Upper 95% Mean	6.1907412
Lower 95% Mean	3.9714209
N	37

Epoxy Overlay at GCR 8



Distributions NBI_Rating=8 Impacting Treatment: Epoxy Overlay at GCR 8

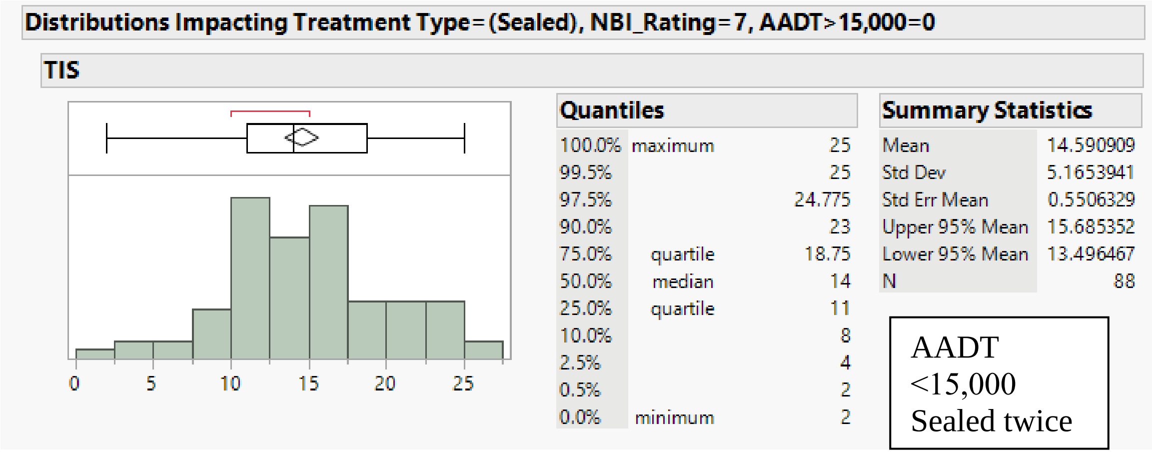
TIS

Quantiles

100.0%	maximum	26
99.5%		26
97.5%		26
90.0%		23.5
75.0%	quartile	12.5
50.0%	median	9
25.0%	quartile	6
10.0%		4
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	10.823529
Std Dev	6.3935128
Std Err Mean	1.0964784
Upper 95% Mean	13.054331
Lower 95% Mean	8.5927274
N	34



Distributions Impacting Treatment Type=(Sealed), NBI_Rating=7, AADT>15,000=0

TIS

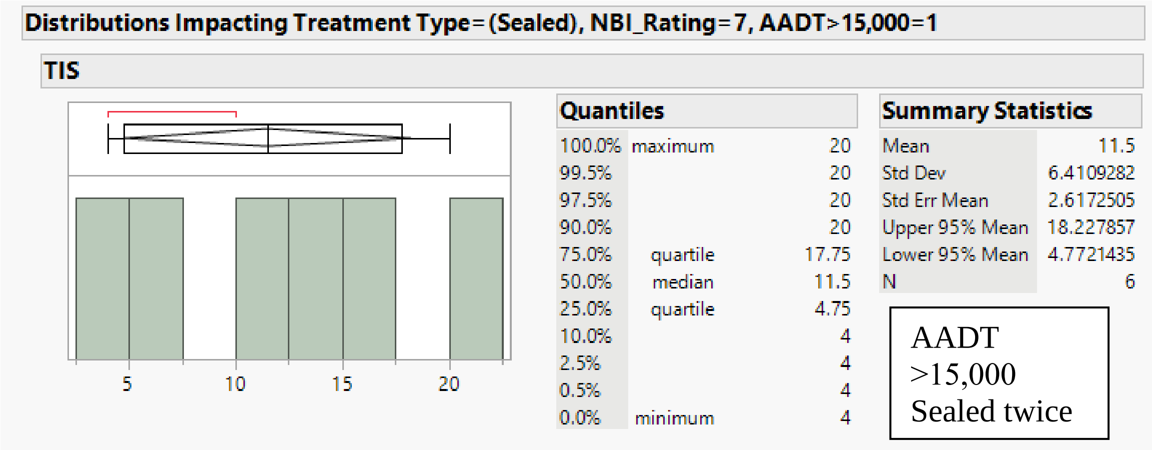
Quantiles

100.0%	maximum	25
99.5%		25
97.5%		24.775
90.0%		23
75.0%	quartile	18.75
50.0%	median	14
25.0%	quartile	11
10.0%		8
2.5%		4
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	14.590909
Std Dev	5.1653941
Std Err Mean	0.5506329
Upper 95% Mean	15.685352
Lower 95% Mean	13.496467
N	88

AADT
<15,000
Sealed twice



Distributions Impacting Treatment Type=(Sealed), NBI_Rating=7, AADT>15,000=1

TIS

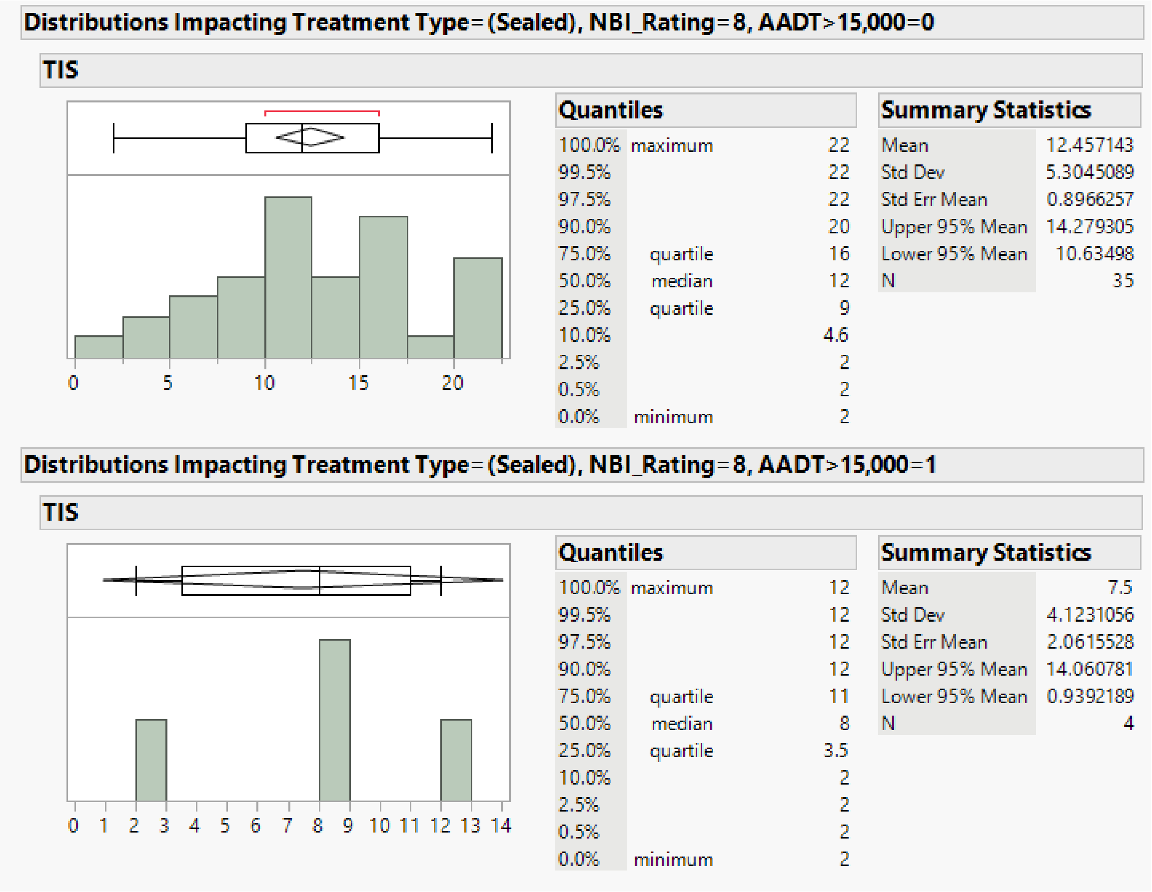
Quantiles

100.0%	maximum	20
99.5%		20
97.5%		20
90.0%		20
75.0%	quartile	17.75
50.0%	median	11.5
25.0%	quartile	4.75
10.0%		4
2.5%		4
0.5%		4
0.0%	minimum	4

Summary Statistics

Mean	11.5
Std Dev	6.4109282
Std Err Mean	2.6172505
Upper 95% Mean	18.227857
Lower 95% Mean	4.7721435
N	6

AADT
>15,000
Sealed twice



Distributions Impacting Treatment Type=(Sealed), NBI_Rating=8, AADT>15,000=0

TIS

Quantiles

100.0%	maximum	22
99.5%		22
97.5%		22
90.0%		20
75.0%	quartile	16
50.0%	median	12
25.0%	quartile	9
10.0%		4.6
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	12.457143
Std Dev	5.3045089
Std Err Mean	0.8966257
Upper 95% Mean	14.279305
Lower 95% Mean	10.63498
N	35

Distributions Impacting Treatment Type=(Sealed), NBI_Rating=8, AADT>15,000=1

TIS

Quantiles

100.0%	maximum	12
99.5%		12
97.5%		12
90.0%		12
75.0%	quartile	11
50.0%	median	8
25.0%	quartile	3.5
10.0%		2
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics

Mean	7.5
Std Dev	4.1231056
Std Err Mean	2.0615528
Upper 95% Mean	14.060781
Lower 95% Mean	0.9392189
N	4