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Performance of Bridge Deck Overlays in Virginia: Phase II: Service Life Performance

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16. Abstract:

Overlaying bridge decks has remained one of the best rehabilitation methods to extend their service life, and the Virginia Department of Transportation (VDOT) has been a leader in the use of bridge deck overlays. Although VDOT has extensive experience in overlays, the long-term performance of overlays has not been entirely understood. One of the biggest challenges for studying the performance of overlays is that only minimal information is available in bridge inventory and inspection records. This limits any scientific assessment of this system. Therefore, the purpose of this study was to provide a strong framework for the understanding of the long-term performance of overlays and the factors affecting them.

This Phase II report reports on an extensive data collection process that led to the development of a robust database of 133 overlaid bridge decks after verification of historical inspection reports, verification of as-built plans and communication with VDOT district bridge engineers. This helped in developing a model for understanding the amount of time it takes for bridge decks to require the first major rehabilitation and the major factors influencing the durability. A database of information about overlays that were replaced at the end of their functional service life was compiled. This helped develop a multiple regression model for understanding the factors that affected the durability of overlays.

Survival analyses were conducted to estimate the service life of overlays and corresponding risk. As a preventive method, epoxy concrete (EC) overlays were predicted to serve an average of 20.9 years, with 18 to 22 years at a 95 percent confidence level. As a rehabilitative method, rigid concrete overlays were predicted to serve an average of 25.9 years, with 21 to 32 years at a 95 percent confidence level.

The recent trend of preferred overlay types has been identified as EC and very-early- strength latex-modified concrete (VELMC) overlays. EC overlays have proven to be one of the better performing overlays through extensive VDOT experience. VELMC overlays are an improvement upon latex-modified concrete overlays by vastly reducing the time of construction and thus become more suitable for decreased construction time, reduced traffic disruption, and lessened worker exposure to the field environment.

An important discovery was the identification of the influence of the degree of deck damage prior to overlaying on the service life of overlays. Preventive EC overlays should be used in a preventive sense, as the name suggests. If preventive EC overlays are installed on bridge decks with spalls, patches, or delaminations, irrespective of the amount of damage, an increased rate of deterioration in the overlays is likely to follow.

The future performance of rehabilitative overlays such as latex-modified concrete, silica fume, and VELMC overlays will not be influenced by the presence of bridge deck damage prior to overlaying. This might be because of the removal of deteriorated concrete before these rigid overlays are constructed. This emphasizes the importance of proper removal of poor quality concrete from bridge decks before overlaying during rehabilitation.

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FINAL REPORT

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ABSTRACT

Overlaying bridge decks has remained one of the best rehabilitation methods to extend their service life, and the Virginia Department of Transportation (VDOT) has been a leader in the use of bridge deck overlays. Although VDOT has extensive experience in overlays, the long-term performance of overlays has not been entirely understood. One of the biggest challenges for studying the performance of overlays is that only minimal information is available in bridge inventory and inspection records. This limits any scientific assessment of this system. Therefore, the purpose of this study was to provide a strong framework for the understanding of the long-term performance of overlays and the factors affecting them.

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The future performance of rehabilitative overlays such as latex-modified concrete, silica fume, and VELMC overlays will not be influenced by the presence of bridge deck damage prior to overlaying. This might be because of the removal of deteriorated concrete before these rigid overlays are constructed. This emphasizes the importance of proper removal of poor quality concrete from bridge decks before overlaying during rehabilitation.

FINAL REPORT

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INTRODUCTION

Bridges age through the application of environmental and traffic exposure stresses, resulting in a decline in service performance characteristics. The deck is the most exposed element of a bridge to traffic and the environment, so it degrades faster than the other bridge elements. Restoring performance includes increasing the resistance to deicing salt chloride penetration and improving skid resistance, decreased by traffic abrasion and cycles of freezing and thawing. This restoration is first addressed through application of a deck overlay system and later by application of a second-generation overlay or replacement of the deck.

Bridge decks are exposed to the synergy of the degrading mechanical and environmental traction forces. Mechanical forces include abrasion, thermal stresses, and deflection-induced stresses. Environmental forces include freezing and thawing and the ingress of aggressive chemical species. The severity of these degrading forces directly influences the service life of concrete bridge decks. For newly built concrete decks in the northern climatic regions of the United States, it is well known that winter maintenance activities through the application of chloride-bearing deicing salts significantly influences the service life of concrete bridge decks through corrosion of the reinforcing steel and the subsequent cracking and spalling of the cover concrete.[1]

It has been shown that the best predictors of the performance of new concrete bridge decks exposed to chloride-bearing deicing salts are the depth of the concrete cover over the reinforcing steel, the type of reinforcing steel, the amount of deicing salts applied during the winter months, and the degree of resistance of the concrete to chloride ingress.[2] New decks upon reaching an unacceptable degradation in riding quality or reduction in skid resistance are overlaid to extend their service life.

The service life of overlaid bridge decks can be significantly different from that of new decks, as at the time of overlay they have been exposed to years of mechanical and environmental forces. Weyers et al., under the Strategic Highway Research Program, conducted a comprehensive study of the performance of overlays in the early 1990s.[3, 4] As identified in the Phase I report,[5] overlay usage accelerated only in the 1970s and 1980s, thus restricting the scope of that study. Thus, Weyers et al. made predictions about the future performance of overlays based on the relatively short-term data available.

Previous studies[6-12] identified the factors that may influence the service life of overlaid bridge decks, including the following:

- the degraded state of the deck concrete surface at overlay
- the degraded state of the bottom surface of the deck and/or the degraded state of the deck soffit at overlay
- average daily traffic (ADT) and/or average daily truck traffic (ADTT)
- the flexibility of the deck under load
- temperature exposure extremes
- the quality of overlay construction as indicated by the condition 3 years after construction
- the chloride concentration in-place at the reinforcing bar depth
- the application rate of deicing salts on decks in chloride per lane-mile per year.

Even though overlaying bridge decks has remained one of the best rehabilitation methods to extend service life, the long-term performance of overlays has not been entirely understood. One of the biggest challenges in studying the performance of overlays is that only minimal information is available in bridge inventory and inspection records. This limits any scientific assessment of this maintenance system. Therefore, an aim of this study was to provide a strong framework for understanding the long-term performance of overlays and the factors affecting them.

Background

Assessing the long-term performance of bridge deck overlays and their effectiveness in extending the service life of decks was the primary purpose of this study. Three phases were initially planned on an as-needed basis. Phase I included interviews with Virginia Department of Transportation (VDOT) district bridge engineers and an extensive database exploration to understand the overlay usage in Virginia.[5] Phase II, the current study, includes in-depth analysis of bridge inspection reports and subsequent communications with VDOT district bridge engineers to assess the performance characteristics of overlays. Phase III will be a field study to observe overlaid field structures and confirm the findings of Phase II. The specific purpose and scope of each of the three phases are presented here.

Phase I: State of Overlays

The Phase I study was undertaken to determine the extent of overlay use in Virginia.[5] VDOT district bridge engineers were interviewed to gather information about the factors related to overlay selection and application in each district and their subjective experience with each of the overlay types. The information aided in narrowing down the most used overlay types and in comprehending the reasons behind their use in general. Further, to understand the effectiveness of overlays in extending the service life of bridge decks, VDOT bridge inventory and element condition-state databases were explored. An extensive literature search was also conducted on the performance of overlays. However, the information available in the databases was found to be inadequate to understand the overlay performance.

Two critical pieces of information were not available in the records:

1. *Year of overlay construction.* Year of construction was not recorded in any of the searched databases. Without this information, it is impossible to determine the age of the overlays and thus the subsequent life performance characteristics.

2. *Overlay type.* Overlay type was not clearly recorded in the databases and if present was not entirely reliable.

Without these critical pieces of information, it was not possible to assess the effectiveness of overlays. These results required the initiation of the current Phase II study to collect comprehensive information concerning overlay performance characteristics.

Phase II: Performance of Overlays

This Phase II study was initiated to collect in-depth information relative to a significant set of overlaid bridge decks. To understand the performance of a larger system, a set of random samples from the total population is crucial. Once the performance of the samples is clearly understood, generalizations can be made for the total population. This method is commonly used in pharmaceutical studies, pre-election polls, engineering material tests, and other such fields.

Therefore, the Phase II study focused on collecting extensive and meticulous details on a randomly selected sample of overlaid bridge decks. Information from the sample sets was analyzed to understand the factors affecting the service life of bridge decks and overlays. Service life estimations were made for the bridge deck overlays using statistical methods.

Phase III: Field Verification

The Phase III study will evaluate a smaller set of overlays in the field. Models were developed in Phase II to characterize the performance of overlays. However, without validation, the models cannot be applied with conviction. Therefore, the Phase III study will aid in confirming and validating the findings from the first two phases.

Problem Statement

The Phase I study identified the five most commonly used types of overlays in Virginia.[5]

- A hot-mix asphalt overlay with a membrane is used primarily on low volume roadways.

- Thin epoxy concrete (EC) overlays are used to restore skid resistance and to offer resistance to chloride penetration, particularly by infiltration of epoxy through the cracks in the deck surface.

- Latex-modified concrete (LMC), SF, and very-early-strength latex-modified concrete (VELMC) overlays are used to restore the riding quality of the surface of the damaged concrete deck.

As previously stated, overlay service life performance is influenced by a number of factors including material type. Of interest is how these characteristics influence service life and thus overlay selection type to maximum performance.

PURPOSE AND SCOPE

The purpose of this study was to identify how bridge deck performance characteristics interact to influence the service life of different types of bridge deck overlays and to target further specific study parameters for Phase III.

The scope of this study was limited to bridges for which EC, LMC, SF, and VELMC overlays were used. Overlay conditions and bridge deck structural characteristics reported in inspection reports from the nine VDOT districts were compiled. In addition, deicing salt application rates for Virginia roadways from all VDOT area headquarters (AHQs) were studied.

METHODS

Phase II consisted of the following tasks.

1. *Finalize the list of bridge decks for the Phase II study based on the depth and reliability of information available.* Perform a review of the bridge inspection reports to confirm the years the decks were built, the years the decks were overlaid, the deck condition prior to overlay, and the condition at the latest available bridge inspection reports. In addition, compile as-built dimensions of the bridges and wearing surface, number of spans, superstructure material, design type, annual average daily traffic (AADT), annual average daily truck traffic (AADTT), and other related factors.

2. Determine the deicing salt chloride application rate for each AHQ within VDOT's nine districts and correlate the application rate to the county in which the bridge is located.

3. Identify the type of overlays and their service life performance, along with second-generation overlays. In addition, determine the performance of the decks prior to overlay.

Task 1: Selection of Phase II Study Candidates

The study matrix for this task was determined from the results of the Phase I study, as noted in Table 1.

VDOT's nine district bridge divisions were asked to provide information on bridges as per the study matrix in Table 1. Five of the nine districts submitted bridges for the study. Table 2 presents the final Phase II study matrix. The districts were asked to provide information on bridge deck overlays based on when they were constructed: i.e., constructed less than 3 years ago, between 5 and 10 years ago, and more than 15 years ago.

As shown in Table 2, the initial number of bridge decks was 139, an increase of about 30 percent over the proposed 108 bridge decks presented in Table 1. The greatest number of bridge decks for an overlay material was for the EC and LMC materials. This is likely due to the longer period of use of these two overlay materials compared to VELMC and SF materials. The lower number of EC overlays at greater than 15 years is related to the limited service life of EC overlays as compared to the other cement-based overlay materials. Likewise, the small number of VELMC overlays older than 15 years is likely related to the relatively new use of this overlay material. With regard to the SF overlay material, the smaller number of bridge decks in this category compared to the EC and LMC materials is due to the limited application of this material in the five district submittals.

Table 1. Number of Bridge Decks With Overlays per VDOT District for Screening

District	Type of Overlay				Total
	EC	LMC	VELMC	SF	
Bristol	0	4	4	4	12
Salem	3	3	3	3	12
Lynchburg	3	0	0	9	12
Richmond	0	6	6	0	12
Hampton	6	3	3	0	12
Fredericksburg	0	6	3	3	12
Culpeper	9	3	0	0	12
Staunton	6	3	3	0	12
NOVA	3	3	6	0	12
Statewide	30	31	28	19	108

EC = epoxy concrete; LMC = latex-modified concrete; VELMC = very-early-strength latex-modified concrete; SF = silica fume; NOVA = Northern Virginia.

Table 2. Phase II Study Matrix

Age Category	EC	LMC	VELMC	SF	Total
Less than 3 years	19	4	12	7	42
5 to 10 years	18	11	13	8	50
Greater than 15 years	6	31	2	8	47
Total	43	46	27	23	139

EC = epoxy concrete; LMC = latex-modified concrete; VELMC = very-early-strength latex-modified concrete; SF = silica fume.

As identified in Phase I of this study, four overlay types, EC, LMC, VELMC, and SF, were studied. Asphalt overlays with or without membranes were not included, since the recent notion is to move away from asphalt overlays for bridge decks. This is because asphalt overlays do not provide adequate protection from moisture and chloride penetration into underlying concrete.

For the bridge decks evaluated in Table 2, the bridge dimensions and study characteristics were compiled from the VDOT bridge inventory. Years at which overlays were installed were confirmed by reviewing the historical inspection reports.

Task 2: Determination of Deicing Salt Usage

To determine the annual deicing salt usage in terms of tons of chloride per lane-mile (tCl^-/l-m) in Virginia, two databases were used for each county: VDOT's Mileage Tables of the State Highway Systems dated December 31, 2016, and the Severe Weather Application System (SWAS) for winters from 2012-2017. For the secondary roadway system, the VDOT-maintained lane-mile was corrected to exclude the secondary system roadway surfaces, which were not hard-surfaced. "Tons of chloride" was determined from solids and solids in solutions of sodium, calcium, and magnesium chloride quantities per Virginia county.

Task 3: Determination of Performance of Overlays and Decks Prior to Overlay

To determine the performance of overlays, the first step was to confirm the original type of overlay in the decks, since incorrect classifications in the VDOT bridge inventory had been noted previously. Using deck condition data from the inspection reports, the performance of the decks and overlays was analyzed using appropriate statistical methods.

RESULTS AND DISCUSSION

Task 1: Data Collection Process

The data collection process was the most challenging and time-consuming task in the study. Information about the construction or replacement of bridge deck overlays is not stored in the VDOT bridge inventory or in any other database. Without this information, it is not possible to study the actual field performance of overlays. However, there were indirect ways to access this information. The following sources of information were found to be fruitful in obtaining details about overlaid bridge decks.

District Bridge Engineers

The expertise of the district bridge engineers proved to be paramount for collecting preliminary data about overlaid bridge decks. Each district was sent a questionnaire requesting information on bridge decks with known overlay types and construction years. The researchers received data on a varying number of bridges from five districts. The Culpeper District had sent additional information on previous overlays that were replaced by second-generation overlays on some of their bridge decks. This encouraged setting up an effort to assemble information on second-generation overlays. This was particularly challenging, since older records are not in digital format and very few records contained information about older overlay constructions.

Inspection Reports

All VDOT bridges undergo routine inspections at least once every 24 months. These inspection reports offer valuable information on the condition of the bridge elements. However, the format of the inspection reports has been changing every few years. In addition, only inspection reports going back to 2005 are available in an editable word processor file format. The prior inspection reports are available in scanned images or PDF format. Therefore, text-mining techniques could be used only on the recent inspection reports (2005 to present). However, historical performance information prior to 2005 was needed to understand the behavior of the bridge decks and overlays, thus making text-mining techniques impractical and inadequate for this purpose. Thus, as a consequence, the researchers had to examine more than 800 inspection reports manually to understand the historical performance of the decks.

There was much variation between successive and consecutive inspection reports and between VDOT districts, particularly between consulting firms, and sometimes within consulting firm reports. Sometimes the reported overlay type does not match the field conditions and this was not corrected for several successive reports. Most often, the rigid concrete overlay type was not known or reported in the inspection report. Occasionally, the wearing surface deterioration was less for the current report than for the previous report(s) without any explanation. Sometimes, the wearing surface condition was too consistent or the same between multiple succeeding inspection reports without explanation. Several inspection reports included the same photographs from previous inspection reports.

Much of the descriptive terminology was inconsistent, vague, and qualitative. Examples include the following:

- random cracking throughout deck
- severe spalling
- medium random cracking
- hairline cracking transverse, diagonal
- light spalling
- at random location, map cracking

- medium transverse cracking
- pop outs
- light patching
- entire deck, light scaling, aggregate polishing, map cracking
- aggregate exposure
- heavy scaling
- D-spalling
- scaling throughout
- map cracking
- small pop outs
- moderate spalling.

Rehabilitation Plans

Years at which major bridge rehabilitations, which may or may not include overlay constructions, have taken place are found in the VDOT bridge inventory. For most cases, these typically have as-built plans in the records, and these plan documents are in the form of scanned digital images. There is a field in the inventory that shows the reconstruction years of decks, but it could mean a number of activities including complete replacement of the superstructure and deck, major rehabilitation of the deck with overlays, and joint replacements. Thus, the exact year of bridge deck construction was not clear from the inventory. Therefore, for these bridges, the as-built reconstruction plans had to be reviewed to confirm the years of deck construction and overlay construction.

Summary of Data

A final list of 133 bridges was narrowed down from 139 decks based on the depth and reliability of information available on them. The locations of the 133 bridges are shown in Figure 1. Figure 2 shows the histograms of bridge decks by district and highway type (inventory keyword: KIND_HWY). Figure 3 shows the latest construction years for the bridge decks, verified by examination of the as-built reconstruction plans, if present. These years had to be verified, since this is a critical parameter for understanding the age of decks at first overlay and thus the service life of the overlays. As shown, most of the study bridges were built in the major interstate construction era of 1960 to 1980.

Figure 4 shows the distributions of bridge deck dimensions, such as length and road width. Figure 5 shows the number of bridges with various superstructure material types and design types. Some of the categories did not have much representation in the study database, so they were appropriately used or eliminated in related analyses. Figure 6 shows the histograms of AADT and AADTT, which had a good spread of data points. Figure 7 shows the number of decks with and without stay-in-place (SIP) forms. The influence of SIP forms on the performance of bridge decks is debated, so this parameter was included in the study. Figure 8 shows the frequency of bridge decks with each of the four overlay types studied.

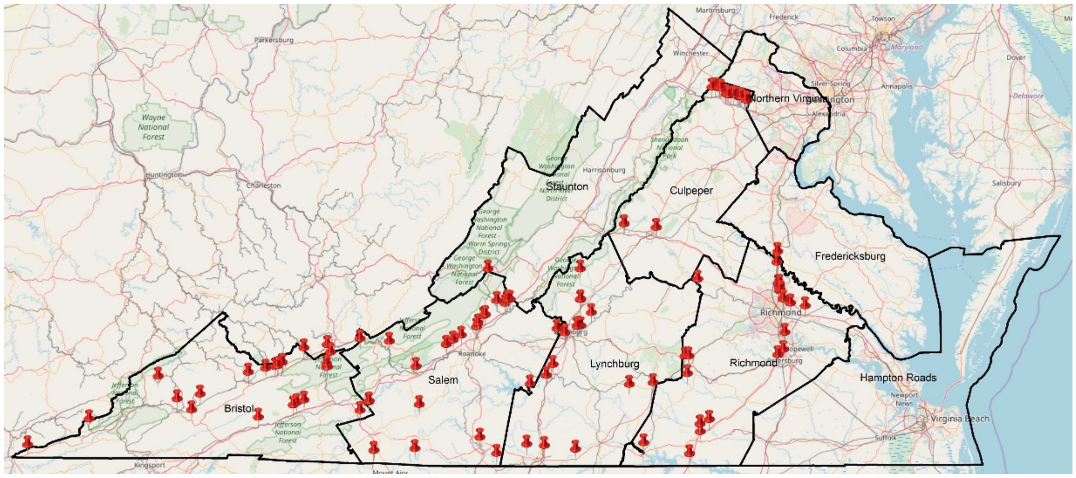


Figure 1. Locations of Phase II Bridge Decks

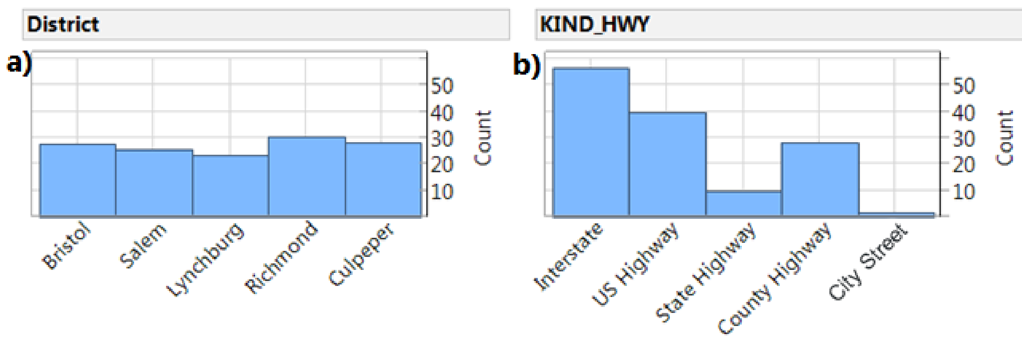


Figure 2. Selected Bridges: (a) VDOT district; (b) highway type

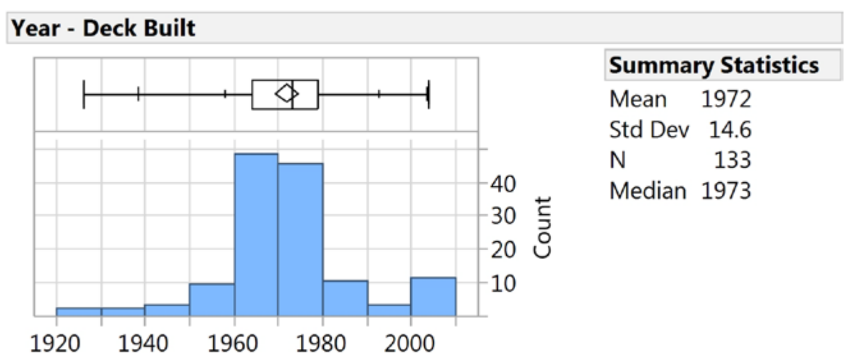


Figure 3. Histogram of Year of Bridge Deck Construction

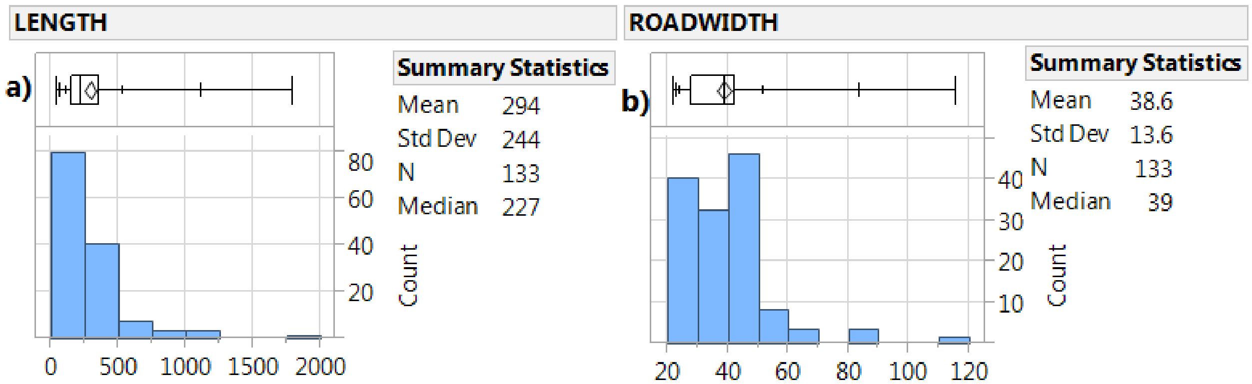


Figure 4. Histograms of (a) Length and (b) Road Width of Bridges

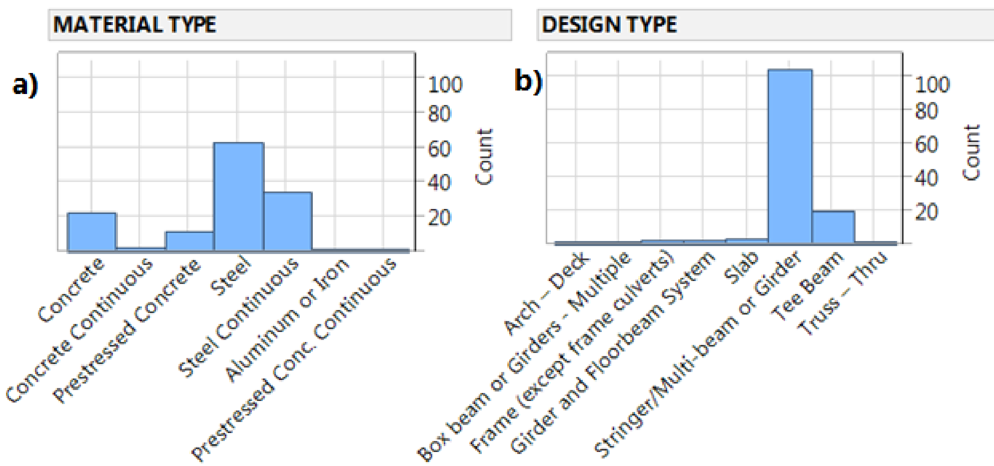


Figure 5. Histograms of (a) Material Type and (b) Design Type of Bridges

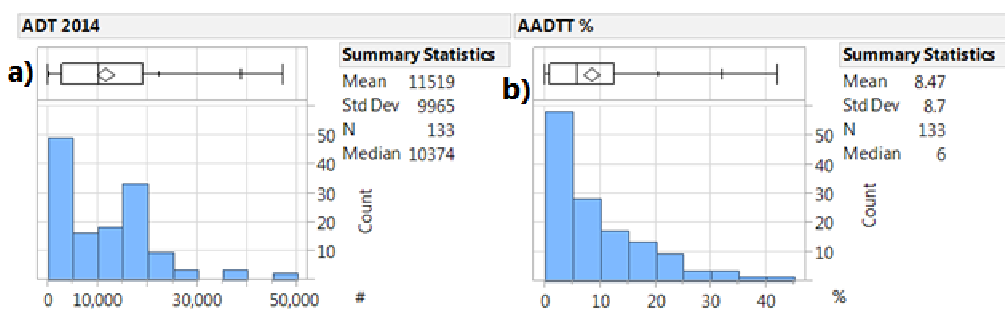


Figure 6. Histograms of (a) Annual Average Daily Traffic and (b) Annual Average Daily Truck Traffic

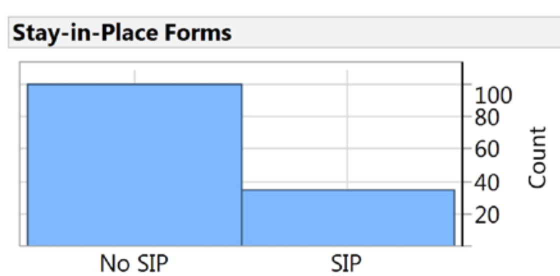


Figure 7. Histogram of Bridge Decks by Presence of Stay-in-Place (SIP) Forms

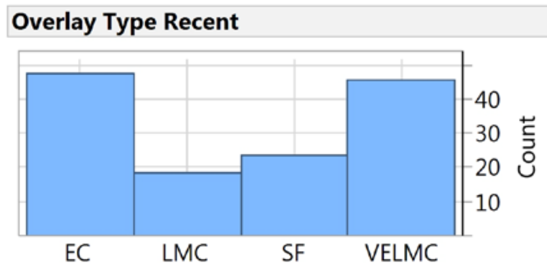


Figure 8. Selected Bridge Decks by Current Overlay Type

Task 2: Deicing Salt Application Rates

Deicing salt usage during winter maintenance activities has a significant influence on the corrosion of steel reinforcement in concrete decks. This parameter deserves abundant attention when evaluating the performance of bridge decks and overlays.

Weyers had conducted an unpublished analysis of the chloride application rates for Virginia roadways, which was summarized later by Williamson.[2] The objective of the analysis was to identify the severity of the Virginia climate zones with regard to concrete bridges in tons of chloride per lane-mile (tons Cl^-/lane-mile). Six climate zones were used: Tidewater (TW), Eastern Piedmont (EP), Western Piedmont (WP), Northern (N), Central Mountains (CM), and Southwestern Mountains (SM) referred from the National Climatic Data Center. Salt qualities used for the winter years of 2000-01, 2001-02, and 2002-03 were used. Deicing salt quantities were compiled from VDOT AHQs by the amount of salt in stock at the beginning and end of the year, taking into account of the transactions among different AHQs. The quantities of the deicing salts were converted to tons of chloride, placed in the corresponding climate zone, and divided by the roadway lane-miles in each of the climate zones studied. Road lane-miles were the sum of the VDOT-maintained lane-miles of interstate, primary, secondary, and frontage systems. No correction was made for the secondary roadway surface types: hard, untreated, or unsurfaced. The objective of the analysis was to select representative exposure conditions for studies and to develop of a simplified parameter for bridge design and maintenance. Table 3 presents the results of that analysis.

Table 3. Virginia Climate Zone Deicing Salt Chloride Application Rates: Winter Years of 2000-01 to 2002-03

Climate Zone	Lane-mile	2000-01 Tons of Chloride/Lane-mile	2001-02 Tons of Chloride/Lane-mile	2002-03 Tons of Chloride/Lane-mile	Average Tons of Chloride/Lane-mile
TW	21,164	0.20	0.34	0.68	0.41
EP	23,639	0.53	0.50	1.79	0.94
WP	21,909	0.20	0.10	0.87	0.39
N	22,317	3.56	5.29	14.4	7.75
CM	12,072	0.68	0.67	2.21	1.19
SM	22,156	1.25	0.56	1.84	1.22

TW = Tidewater; EP = Eastern Piedmont; WP = Western Piedmont; N = Northern; CM = Central Mountains; SM = Southwestern Mountains.

As shown in Table 3, the winter salt application rates were highly variable from year to year and between climate zones. The averages, which tended to smooth out the year over year variability, were influenced by the annual weather conditions. In general, the colder the winter climate, the greater the rate of chloride application, as shown by the differences between the TW and SM climate zones, 0.41 and 1.22, respectively. However, the rates also appear to be influenced by population density; the greater the population within a climate zone, the greater the application rate, as shown by the differences between the EP and the WP climate zones, 0.94 and 0.39, respectively.

Thus, to determine the influence of deicing salt application rates on the service life performance of individual new and overlaid bridge decks, a more exacting rate per deck is needed rather than a determination of in which climate zone the bridge is located. A better choice would be the deicing salt routes of VDOT's AHQs. However, the AHQ roadway lane-miles are not centrally available and finding them was very difficult. Bridge inspection reports identify in which Virginia county a bridge is located. Each county has multiple AHQs that can be related to the appropriate county. In addition, VDOT-maintained roadway lanes are readily available for each county. Thus, the county-level deicing salt usage was chosen to be associated with each bridge deck under study.

The SWAS data were separated for each district for the assessment years of material application and deicing salt material type. In addition, the transactions between AHQs, residencies, and districts were taken into account. The AHQ quantities were assigned to a county within a district, and the tCl^-/l-m was calculated for each county. Tables 4 through 8 present the results of the data collection process.

As shown in Table 4, there is a relatively large variation in the deicing salt application rates among counties in the Bristol District from 2000-2003, as shown by the range and coefficients of variation for tCl^-/l-m. To determine a better representation of tCl^-/l-m, the analysis period was increased from the previous study of a 3-year period (2000-2003) to a 6-year period (2012-2017), and the chloride values were averaged. Tables 5 through 7 present the chloride application rates for the Bristol, Salem, and Lynchburg districts; the Richmond, Hampton Roads, and Fredericksburg districts; and the Culpeper, Staunton, and Northern Virginia (NOVA) districts, respectively.

Table 4. Bristol District Chloride Application Rate (tCl^-/l-m) by County: 2000-2003

County	Range	Average	Standard Deviation	Coefficient of Variation, %
Bland	0.99-2.28	1.33	0.52	39
Buchanan	0.56-2.50	1.55	0.70	45
Dickenson	0.43-1.68	1.15	0.46	40
Grayson	0.49-1.01	0.83	0.34	41
Lee	0.45-1.74	0.84	0.47	56
Russell	0.27-1.79	0.88	0.55	62
Scott	0.58-2.36	1.66	0.81	49
Smyth	0.55-2.36	1.52	0.65	43
Tazewell	1.38-3.44	2.07	0.78	38
Washington	0.96-2.05	1.46	0.70	48
Wise	2.08-3.89	2.96	1.69	57
Wythe	1.44-4.88	2.09	1.37	65

Table 5. Chloride Application Rates ($tCl^-/l\text{-}m$) for Bristol, Salem, and Lynchburg Districts by County: Winters 2012-2017

Bristol District County	Rate	Salem District County	Rate	Lynchburg District County	Rate
Bland	1.75	Bedford	0.37	Amherst	1.03
Buchanan	1.63	Botetourt	1.25	Appomattox	0.58
Dickenson	1.18	Carroll	1.76	Buckingham	0.50
Grayson	1.31	Craig	1.48	Campbell	0.58
Lee	1.19	Floyd	1.95	Charlotte	0.59
Russell	1.44	Franklin	0.52	Cumberland	0.94
Scott	2.45	Giles	1.52	Halifax	0.59
Smyth	1.95	Henry	0.31	Nelson	0.81
Tazewell	2.37	Montgomery	2.53	Pittsylvania	0.49
Washington	1.49	Patrick	0.61	Prince Edward	0.98
Wise	3.78	Pulaski	1.68		
Wythe	3.17	Roanoke	1.55		
I-77	1.93				
I-81	4.20				

Table 6. Chloride Application Rates ($tCl^-/l\text{-}m$) for Richmond, Hampton Roads, and Fredericksburg Districts by County: Winters 2012-2017

Richmond District County	Rate	Hampton Roads District County	Rate	Fredericksburg District County	Rate
Amelia	1.66	Accomack	1.58	Caroline	3.58
Brunswick	2.32	Greenville	2.15	Essex	1.61
Charles City	0.63	Isle of Wright	1.47	Gloucester	1.51
Chesterfield	1.97	James City	3.79	King & Queen	2.24
Dinwiddie	1.21	Northampton	1.12	King George	1.55
Goochland	2.78	Southampton	1.14	King William	1.60
Hanover	0.83	Surry	0.51	Lancaster	1.52
Henrico	1.68	Sussex	1.04	Mathews	1.80
Lunenburg	0.54	York	0.62	Middlesex	1.61
Mecklenburg	1.24	Interstate	4.00	Northumberland	0.88
New Kent	1.87			Richmond	1.06
Nottoway	1.97			Spotsylvania	3.05
Powhatan	3.27			Stafford	6.36
Prince George	2.10			Westmoreland	1.60

Table 7. Chloride Application Rates ($tCl^-/l\text{-}m$) for the Culpeper, Staunton, and Northern Virginia Districts by County: Winters 2012-2017

Culpeper District County	Rate	Staunton District County	Rate	Northern Virginia District County	Rate
Albemarle	2.05	Allegheny	1.94	Arlington	8.15
Culpepper	1.38	Augusta	2.32	Fairfax	9.50
Fauquier	2.62	Bath	2.00	Loudoun	4.48
Fluvanna	0.38	Clarke	3.94	Prince William	7.52
Green	1.34	Frederick	2.35		
Madison	2.63	Highland	4.00		
Louisa	1.70	Page	1.20		
Orange	1.79	Rockbridge	1.93		
Rappahannock	3.33	Rockingham	2.30		
		Shenandoah	2.55		
		Warren	2.88		

Table 8. Mean Chloride Application Rate ($tCl^-/l\text{-}m$) by VDOT District: Winters 2012-2017

Bristol	Salem	Lynchburg	Richmond	Hampton Roads	Fredericksburg	Culpeper	Staunton	Northern Virginia
2.13	1.29	0.71	1.72	1.74	2.14	1.91	2.49	7.41

As shown in Tables 5 through 7, there was significant variability in the chloride application rate for county roadways in all nine districts. Table 8 presents the mean chloride applicate rate for the nine VDOT districts.

As shown in Table 8, the chloride application rate for district roadways appears to be related to climate zones and is influenced by population density in the district. For example, the NOVA District is in the Northern climate zone and the Bristol District is in the Southwestern Mountains climate zone, but the NOVA District is a heavily populated area with a salt application that is 3.48 times greater than in the Bristol District.

For all Phase II bridge decks, the chloride application rates were related to counties using the data previously described. The histogram of the chloride application rates is shown in Figure 9 and appears normally distributed. Figure 10 shows the average chloride application rates by counties in Virginia from 2012-2017.

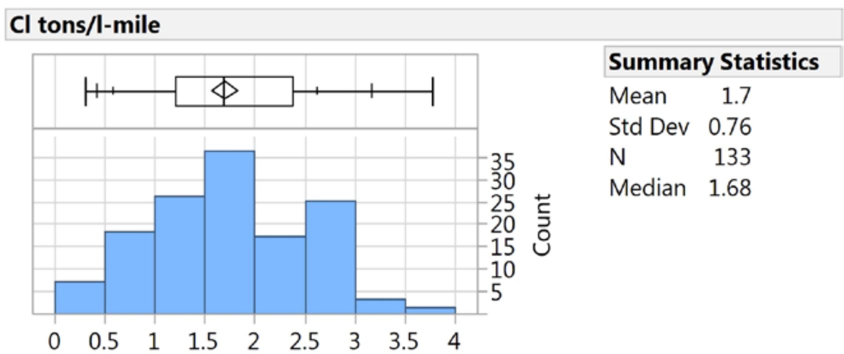


Figure 9. Histogram of Chloride Application Rates on Phase II Bridge Decks

Task 3: Bridge Deck Characteristics and Overlay Performance

Along with the submitted bridge deck overlays within the requested categories, the districts were requested to provide the year of overlay construction, if known. Districts provided this information for some of the bridge decks, but for the rest of them, the researchers found the year of overlay through historical inspection reports and as-built rehabilitation plans. Bridge inspection reports 2 years before and 2 years after the year of overlay and the latest reports were gathered to verify the year of overlay and to determine the deck conditions immediately before the overlay and at the latest inspection year. When the year of overlay was not known, longer periods of inspection reports were reviewed to determine it. In some instances, the year of overlay was included in the inspection reports. For some cases, this could not be verified by any means. VDOT databases were also searched to determine bridge deck characteristics.

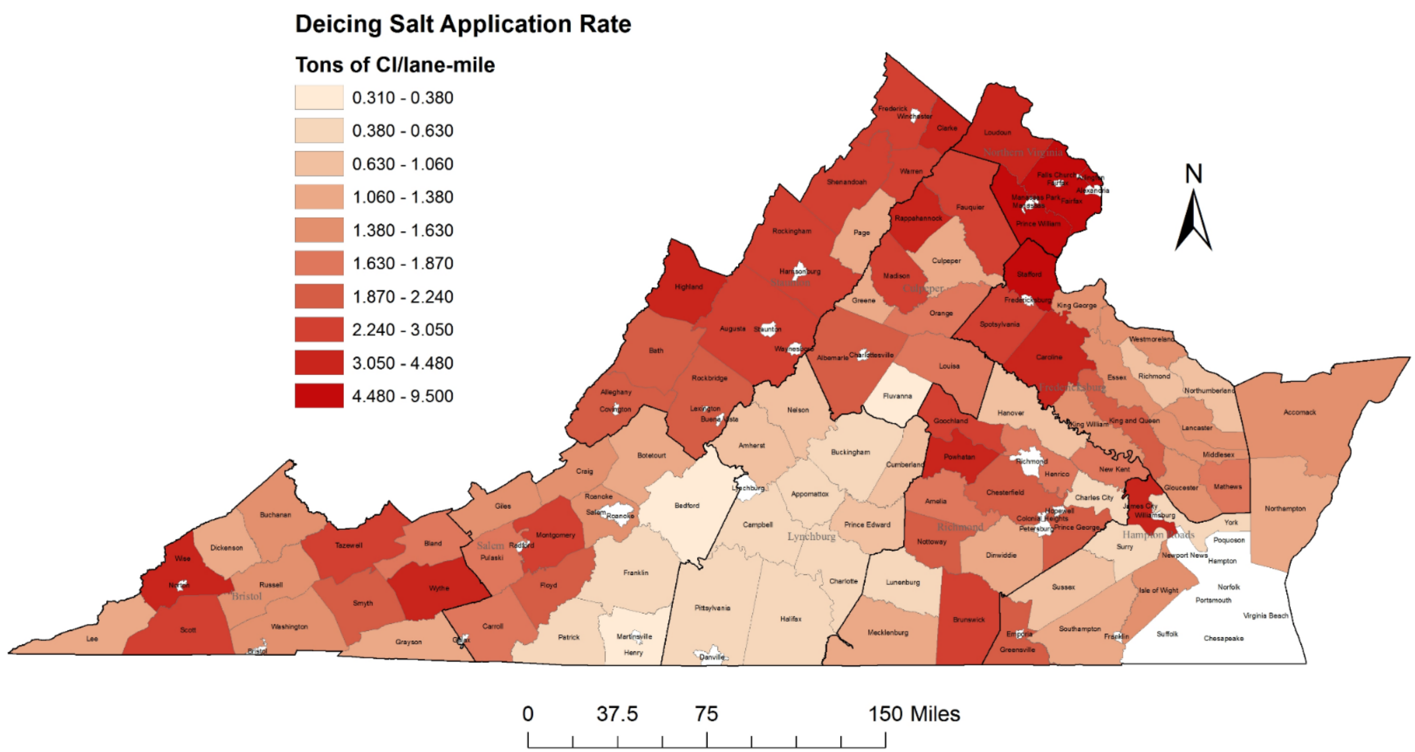


Figure 10. Deicing Salt Application Rates by County (tCl^-/l-m)

For this study, the assessed deck deterioration was separated into three categories: cracks, surface wear, and damages. *Cracks* is the sum of the linear cracking and map cracking. *Surface wear* is scaling, aggregate exposure, and pop-outs. *Damages* is patches, spalls, and delaminations. The three categories are expressed in quantitative terms as the percent of deck wearing surface as cracks (%C), surface wear (%S), and damages (%D).

Linear cracks were converted to square feet by multiplying the length of the crack by 0.333 ft, the estimated crack-influenced zone along the linear crack.[1] In calculating the deteriorated areas, only the quantitative values presented in the inspection reports were used. No attempt was made to quantify qualitative statements in the inspection reports, for example, inspector comments such as "linear or map cracking throughout deck," "wear generally in wheel paths," or "perpendicular cracks at joints." It was generally difficult to determine the condition of the decks from inspection reports because of the lack of consistent terminology among reports.

For robust statistical analysis, it is essential to have reasonable variation in the data points. This avoids the issue of unintended bias in the results. Figure 11 shows the frequency of overlays by construction year ranges and overlay types.

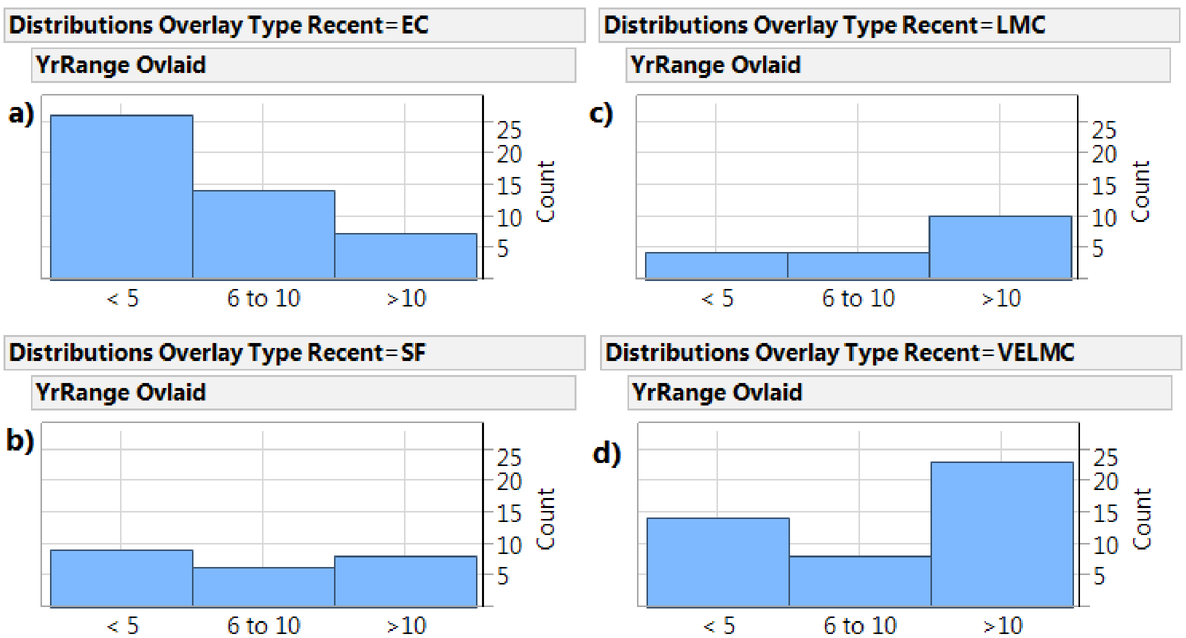


Figure 11. Ranges of Overlay Construction Years for Phase II Bridges: (a) EC overlays; (b) SF overlays; (c) LMC overlays; (d) VELMC overlays. EC = epoxy concrete; SF = silica fume; LMC = latex-modified concrete; VELMC = very-early-strength latex-modified concrete.

EC Overlays

Figure 12 shows the histograms of the three categories of deck deterioration immediately before the time of EC overlay construction and in the most recent inspection. The summary statistics to the right side of the histograms display the basic statistics of the distributions.

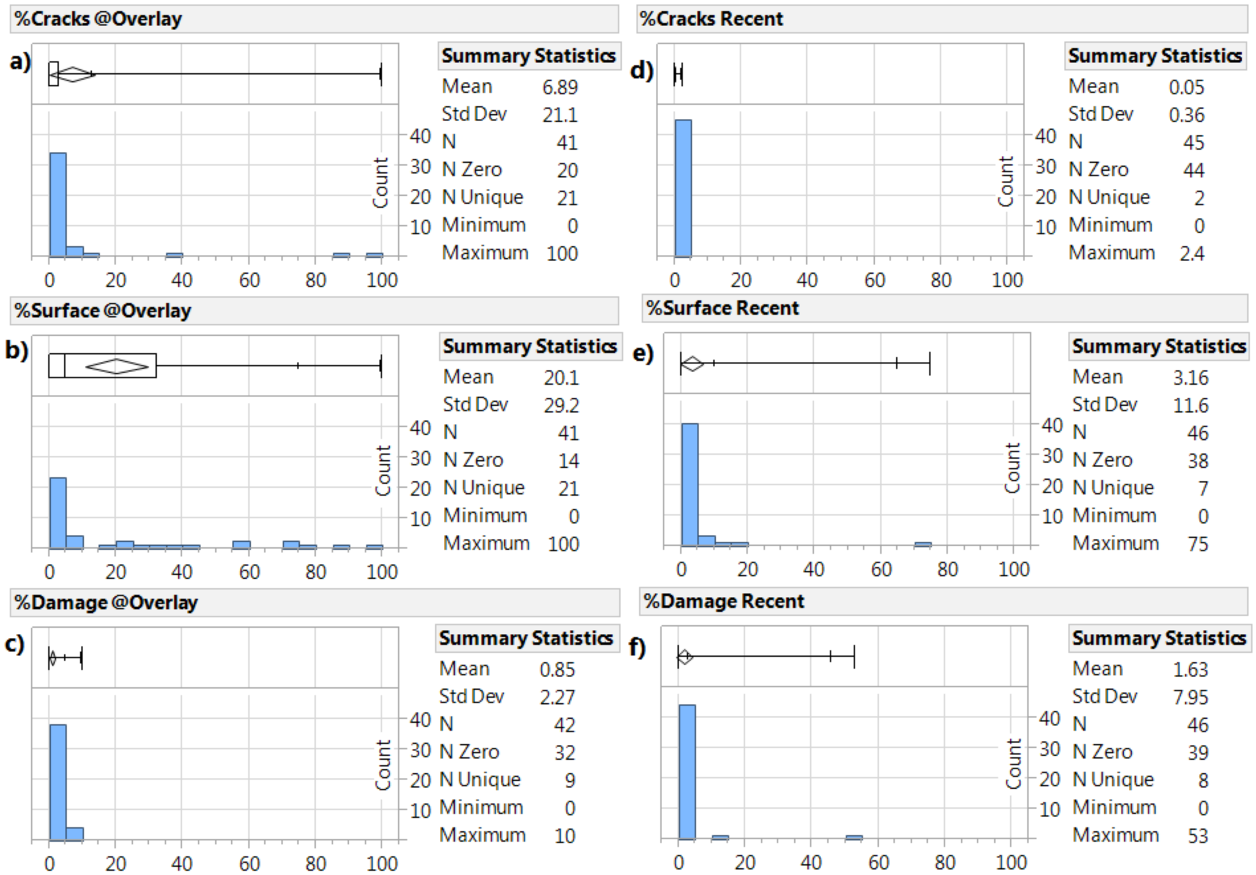


Figure 12. Histograms for Epoxy Concrete Overlays: (a) %Cracks at Overlay; (b) %Surface at Overlay; (c) %Damage at Overlay; (d) %Cracks Recent; (e) %Surface Recent; (f) %Damage Recent

The N zero statistic shows the count of decks with zero or no degradation; N shows the total number of decks; and N Unique is the count of unique deterioration rates. The ratio of these two values is useful in getting a sense of the importance of the variable. This factor is used because the reported quantities of deterioration were quite small and were inherently variable because of the subjective nature of the routine inspections.

For example, if all 41 decks in this analysis had damages prior to overlay, then N Zero = 0; therefore, the (N Zero / N) ratio is (0/41) = 0. If none of the decks had damages, then N Zero = 41; therefore, the (N Zero / N) ratio is (41/41) = 1. So, the higher the ratio, the lower the occurrence of damages prior to overlay.

Regarding deterioration prior to EC overlay, the ratios of N Zero to N were 0.49, 0.34, and 0.76 for cracks, surface wear, and damages, respectively. The lower the ratio, the higher the occurrence of that type of deterioration prior to overlay. This is important because this identifies the factors that influenced the bridge engineers to choose this type of overlay to address that type of deterioration or combination of deterioration types. This shows that the occurrence of cracks and surface wear such as aggregate polishing and loss of skid resistance were influential for districts in deciding to choose EC overlays. Ten of 42 decks had visible damages; however, the damages comprised an average of 0.85 percent by surface area. The ideal time to apply an EC overlay is before spalling damages start appearing on the surface. This analysis shows that VDOT districts have used EC overlays appropriately as a preventive measure in most cases.

Regarding the deterioration reported in the most recent inspection, the proportions of zero values were 0.98, 0.83, and 0.85, respectively, for cracks, surface wear, and damages. Considering the spread of the service life of the EC overlays under study, this shows that EC overlays are more likely to have surface wear and damages than to have cracks.

LMC Overlays

Figure 13 shows the histograms of the three categories of deck deterioration immediately before the time of LMC overlay construction and in the most recent inspection.

Regarding deterioration prior to LMC overlay, the proportions between N Zero and N were 0.36, 0.57, and 0.07 for cracks, surface wear, and damages, respectively. Only 1 deck had no visible damages prior to LMC overlay. This shows that for most cases, the high occurrence of spalling damages and patches dictated the selection of an LMC overlay. In addition, the presence of cracks and surface wear may be irrelevant for this overlay.

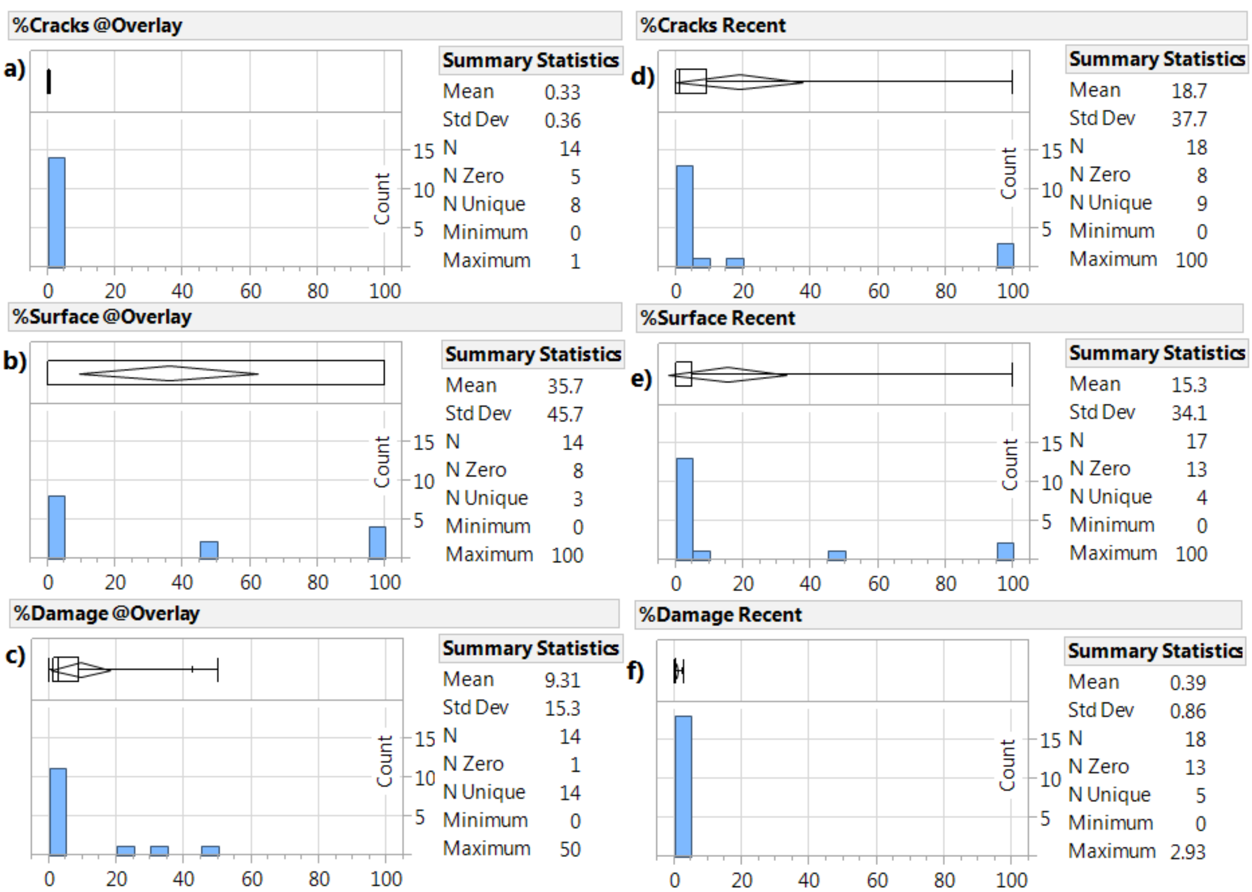


Figure 13. Histograms for Latex-Modified Concrete Overlays: (a) %Cracks at Overlay; (b) %Surface at Overlay; (c) %Damage at Overlay; (d) %Cracks Recent; (e) %Surface Recent; (f) %Damage Recent

Regarding the deterioration reported in the most recent inspection, the proportions of zero values were 0.44, 0.76, and 0.72, respectively, for cracks, surface wear, and damages. Considering the spread of the age of LMC overlays under study, the overlays are slightly biased to crack more than to have surface wear or damages.

SF Overlays

Figure 14 shows the histograms of the three categories of deck deterioration immediately before the time of SF overlay construction and in the most recent inspection.

Regarding deterioration prior to overlay, the proportions between N Zero and N were 0.24, 0.29, and 0.29 for cracks, surface wear, and damages, respectively. This shows that for most cases, the high occurrence of all three categories of deterioration led to the selection of SF overlays.

Regarding the deterioration reported in the most recent inspection, the proportions of zero values were 0.26, 0.83, and 0.39, respectively, for cracks, surface wear, and damages. Considering the spread of the age of the SF overlays under study, the overlays are heavily biased to crack and spall more than to have surface wear.

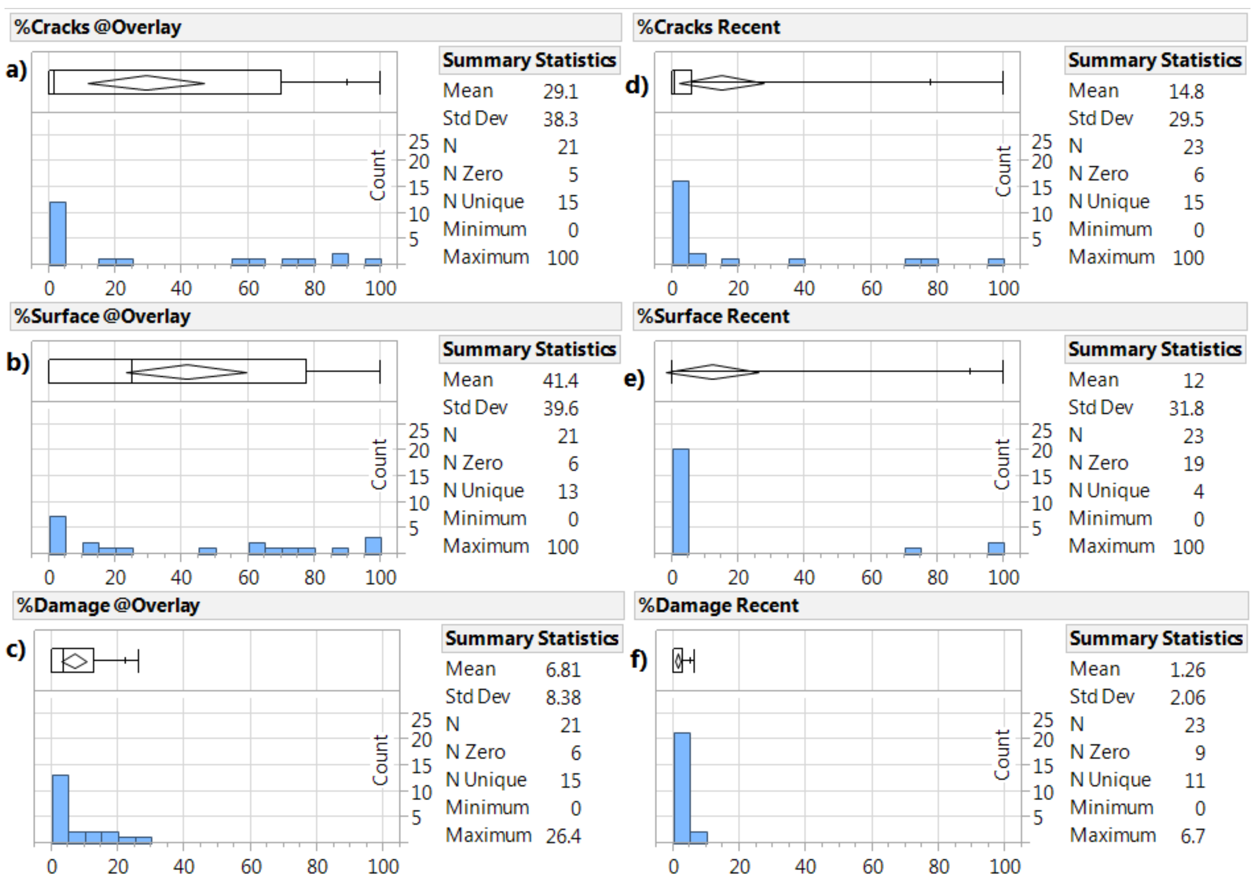


Figure 14. Histograms for Silica Fume Overlays: (a) %Cracks at Overlay; (b) %Surface Wear at Overlay; (c) %Damage at Overlay; (d) %Cracks Recent; (e) %Surface Wear Recent; (f) %Damage Recent

VELMC Overlays

Figure 15 shows the histograms of the three categories of deck deterioration immediately before the time of VELMC overlay construction and in the most recent inspection.

Regarding deterioration prior to the overlay, the proportions between N Zero and N were 0.58, 0.71, and 0.13 for cracks, surface wear, and damages, respectively. This shows that for most cases, the high occurrence of damages led to the selection of VELMC overlays, whereas cracking and surface wear conditions may have remained irrelevant for decision-making purposes.

Regarding the deterioration reported in the most recent inspection, the proportions of zero values were 0.39, 0.85, and 0.49, respectively, for cracks, surface wear, and damages. Considering the spread of the age of VELMC overlays under study, the overlays are biased to crack and spall more than to have surface wear.

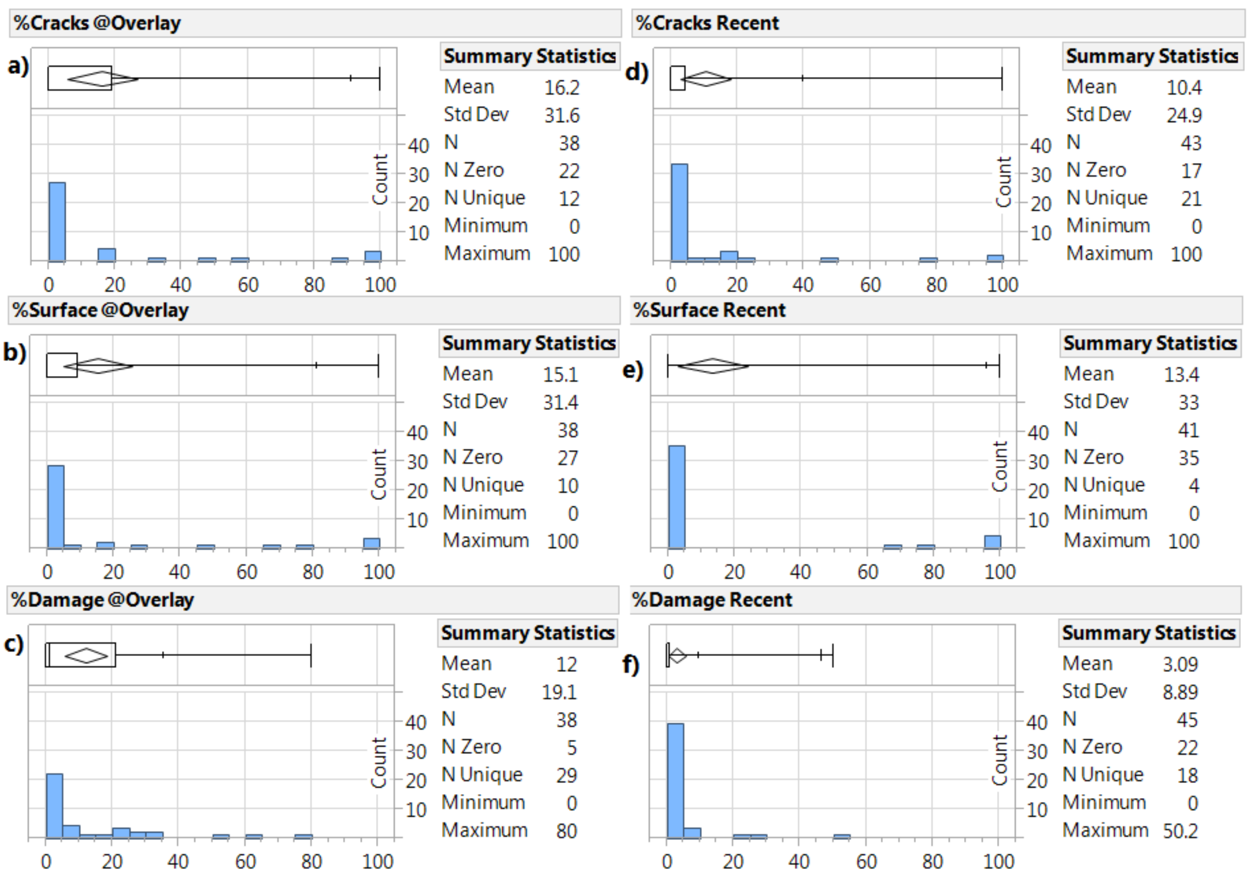


Figure 15. Histograms for Very-Early-Strength Latex-Modified Concrete Overlays: (a) %Cracks at Overlay; (b) %Surface Wear at Overlay; (c) %Damage at Overlay; (d) %Cracks Recent; (e) %Surface Wear Recent; (f) %Damage Recent

Performance of Bare Bridge Decks Prior to Overlay

The time taken for a newly constructed bridge deck to need the first major maintenance activity involving overlay construction is of interest to both engineers and researchers. This is an indication of the quality of construction, environmental exposure level, quality of structural materials, and effectiveness of routine maintenance. The timing of the first overlay depends on a number of factors; however, the following two are considered the major influencers:

1. *Availability of maintenance funds.* VDOT district bridge engineers manage hundreds of bridges at any given time and must prioritize bridges for rehabilitation based on the degree of deterioration, traffic volume, and importance and take the best course of action allowed by the available funds.

2. *Appraisal of deck condition.* Decisions about repair and rehabilitation of decks are often made according to information presented in inspection reports. Routine inspections are mainly visual in nature and often cannot identify hidden or inaccessible damages until they propagate and are visually evident. So, the time to first overlay may be influenced by only the visible condition.

Figure 16 shows a distribution of age of bridge decks when they were first overlaid for the selected bridge decks under study. Figure 17 shows a histogram of the years in which the bridges were overlaid to provide a sense of the overlay construction era.

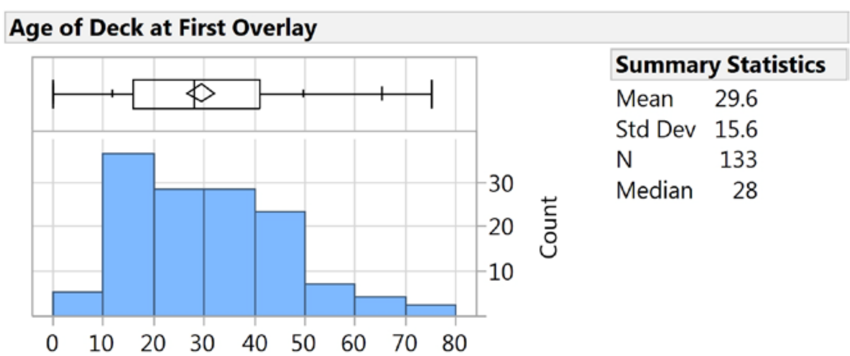


Figure 16. Histogram of Age of Bridge Deck at Time of First Overlay

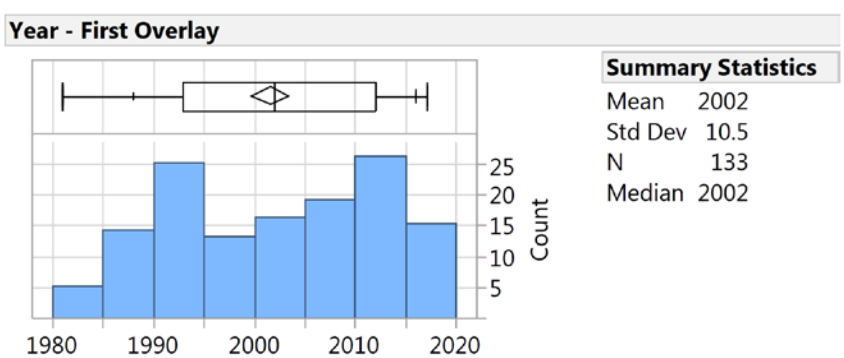


Figure 17. Histogram of Years in Which Bridge Decks Received Their First Overlay

Phase I of this study showed that EC overlays were used as a preventive method and rigid overlays (LMC, SF, and VELMC) were typically used as a rehabilitative method. Thus, age of decks at first overlay was plotted separately by overlay type. As shown in Figure 18, it is clear that the EC overlays were constructed earlier than the rigid overlays.

With the acceptance and widespread demand for an accelerated bridge construction system, the researchers thought that a separate evaluation of these four bridges, built with rigid overlays at construction, would offer valuable insight about the influence of accelerated bridge construction on the durability of decks.

To quantify the differences between the overlay types and construction ages, Figure 19 shows a one-way analysis of age of decks at first overlay and overlay type. The connecting letters report on the right shows that EC overlays were indeed applied significantly earlier than the rigid overlays. This is the intended way of using the EC overlay to improve the durability of concrete bridge decks. The ages at first overlay were not significantly different for the other three overlay types, i.e., SF, LMC, and VELMC.

Surprisingly, four VELMC overlays were installed immediately after the construction of the bridge decks. These VELMC decks were on interstate bridges passing over interstate roads. These rigid overlays at construction were anomalies in their time; they were used to save construction time and to ensure durable decks, since it is difficult to perform repairs or rehabilitations on high-traffic interstate highways.

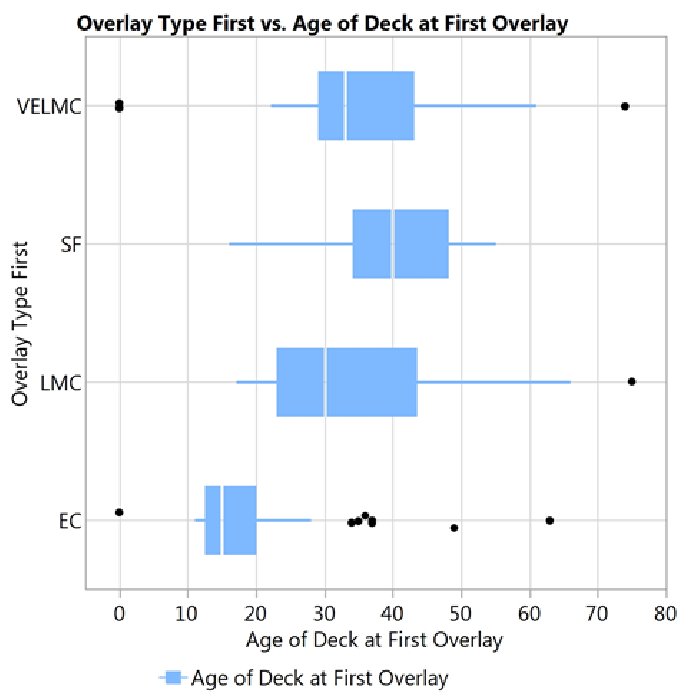
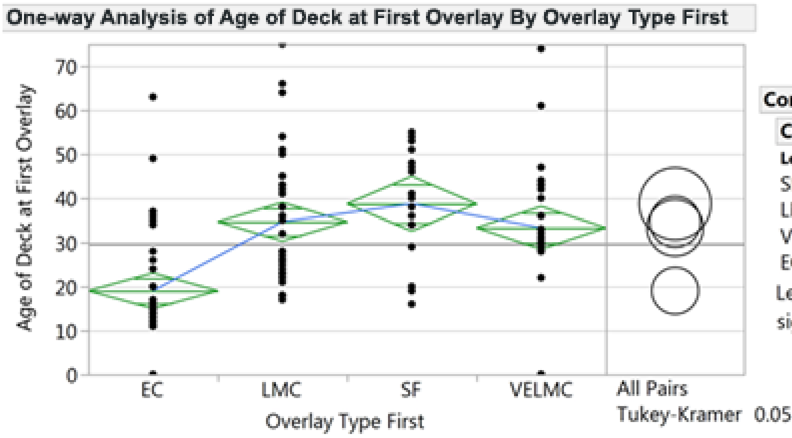


Figure 18. Age of Bridge Decks at First Overlay and Corresponding Overlay Type. VELMC = very-early-strength latex-modified concrete; SF = silica fume; LMC = latex-modified concrete; EC = epoxy concrete.



Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

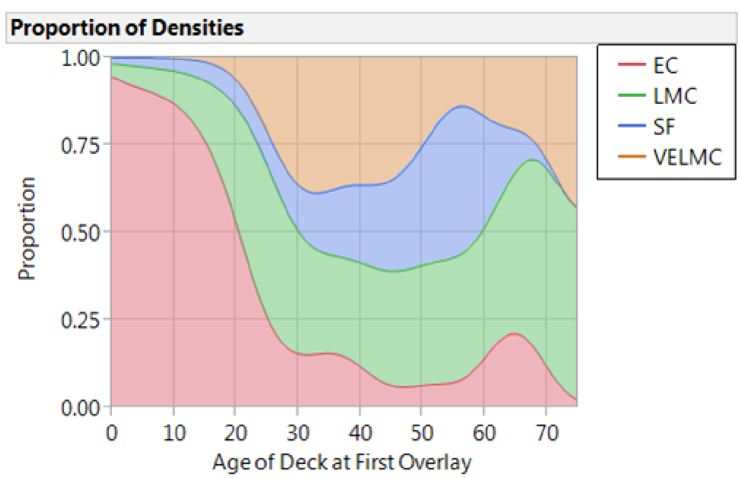
Level			Mean
SF	A		38.7
LMC	A		34.7
VELMC	A		33.3
EC		B	19.0

Levels not connected by same letter are significantly different.

Figure 19. One-way Analysis of Age of Bridge Decks at First Overlay and Overlay Type. EC = epoxy concrete; SF = silica fume; LMC = latex-modified concrete; VELMC = very-early-strength latex-modified concrete.

Figure 20 shows the relationship between age of decks at first overlay and overlay type; the special case of accelerated bridge construction was excluded by eliminating the four decks overlaid with VELMC at construction. The proportion of densities shows that the degree of usage of rigid overlays as opposed to EC overlays was about 25 percent at 15 years of deck age, 50 percent at 20 years of deck age, and 75 percent at 25 years of deck age. This gives an indication of the general maintenance approach in Virginia.

The connecting letters report in Figure 20 is similar to the one in Figure 19, with an increase in the mean value for VELMC decks from Figure 19, since four anomalous decks were removed from this analysis.



Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

Level			Mean
SF	A		38.7
VELMC	A		38.2
LMC	A		34.7
EC		B	19.0

Levels not connected by same letter are significantly different.

Figure 20. Age of Bridge Decks at First Overlay Excluding Anomalies. EC = epoxy concrete; SF = silica fume; LMC = latex-modified concrete; VELMC = very-early-strength latex-modified concrete.

A simple, but surprising, inverse correlation exists between age of deck at first overlay and year of deck construction (Figure 21). This might reveal the naturally growing reliance on overlays for deck rehabilitation in recent decades; however, it may also hint at the increased deterioration rates of recently built bridge decks. The quality of construction materials and methods has improved significantly in the more recent decades, which were not included in this study, including the use of low-permeability high performance concrete, corrosion-resistant reinforcement, and a deeper concrete cover over reinforcing steel. However, proportionally, the need to keep the roadways bare of snow and ice has called for increased use of increasingly corrosive pre-treatment methods.

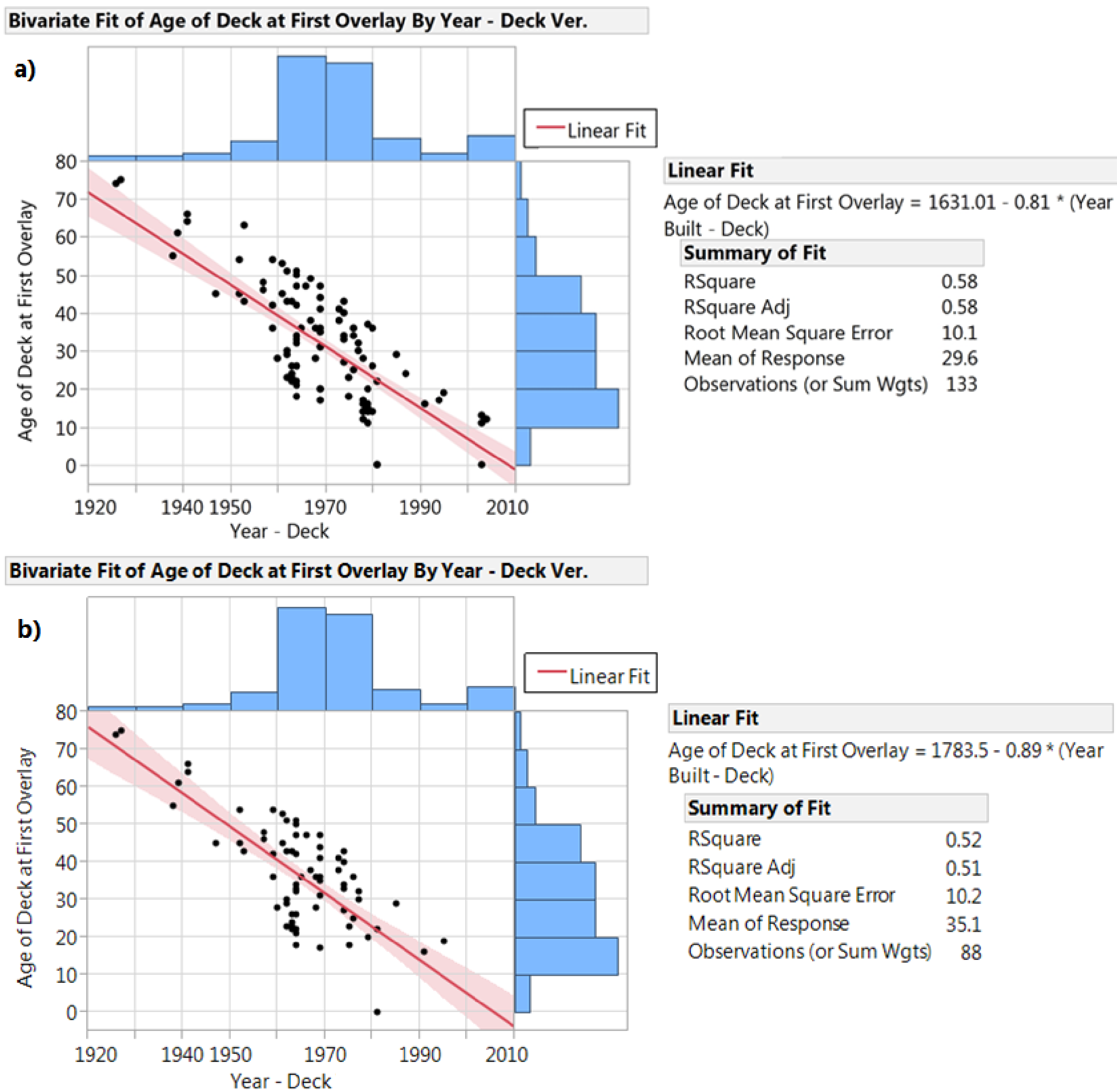


Figure 21. Relationship Between Age of Bridge Deck at First Overlay and Year of Deck Construction: (a) all decks under study; (b) excluding epoxy concrete overlays

Since EC overlays are preventive in nature in contrast to rigid overlays, it is important to assess their influence in this correlation. Figure 21b shows the scatterplot and the inverse relationship between age of deck at first overlay and year deck was built, excluding decks with EC overlays. The relationship did not change by much. It is important to note that a large portion of the decks were built during a primary interstate construction era in the 1960s to 1980s. Thus, they represent construction materials and methods of this time period.

To comprehend the existence of this correlation, evaluation of the influence of winter pre-treatment methods on performance of newer bridge decks is recommended.

Effect of SIP Forms

SIP forms are galvanized steel forms that are left in place after construction of decks. They contribute to faster construction by eliminating the need to remove the formwork after the concrete cures and lead to worker safety by reducing field exposure times. However, SIP forms can modify the moisture profile in the cross section of the concrete deck, since the concrete pore water is prevented from evaporating from the bottom of the deck. In addition, they prevent visual inspection of the deck soffits. A previous study[13] on concrete specimens made with mixture proportions and ingredients used in Virginia with and without SIP forms showed that SIP forms did not significantly influence the rate of corrosion. However, the field performance of decks constructed with SIP forms is not clearly known.

Figure 22 shows the one-way analysis of age of bridge deck at first overlay by presence of SIP forms. Of interest, the Tukey-Kramer test showed through the connected letters report on the right that the decks built with SIP forms were overlaid significantly earlier than decks built without SIP forms. It should be noted that this finding is about the correlation between the two parameters only, i.e., age of deck at first overlay and use of SIP forms. There are other factors that could have influenced bridge deterioration.

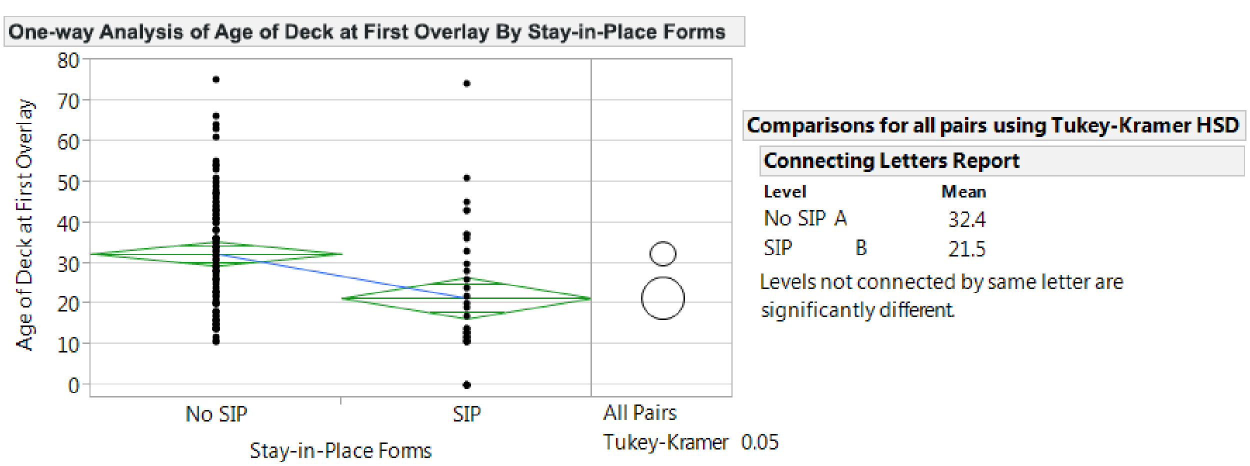


Figure 22. One-way Analysis of Age of Bridge Deck at First Overlay by Presence of Stay-in-Place Forms. SIP = decks with stay-in-place forms; No SIP = decks without stay-in-place forms.

As a further evaluation of this reason behind this trend, it is to be noted that the SIP forms have been commonly used on more recently built decks. In Figure 23, the connecting letters report shows that decks with SIP forms are significantly younger. As it was found from Figure 21, this might simply echo the finding that newer decks are overlaid sooner for other reasons. To compare the influence of this factor, a third factor considered influential with regard to bridge deck deterioration (i.e., salt application rates in tons of chloride per lane-mile) was compared.

Figure 24 shows the one-way analysis of salt usage by the presence of SIP forms. The results show that decks with SIP forms received significantly less chloride exposure. This might further indicate that the use of SIP forms does influence the rate of deterioration of bridge decks, as decks with SIP forms were overlaid sooner and received less salt application. However, the chloride exposure parameter is an average for the entire county and is not specific to a bridge deck. In addition, this parameter is a snapshot of the total exposure period from 2012-2017, which includes pretreatment methods, rather than the entire period, which would include varying deicing treatment methods. Thus, the influence of SIP forms on the service life of new decks remains debatable to date.

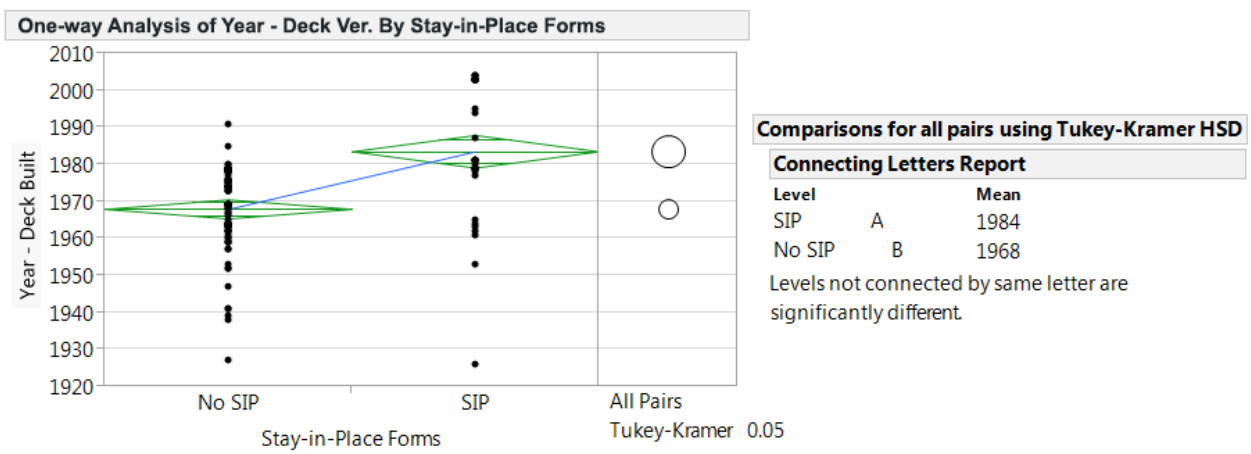


Figure 23. One-way Analysis of Year of Deck Construction and Presence of Stay-in-Place Forms. SIP = decks with stay-in-place forms; No SIP = decks without stay-in-place forms.

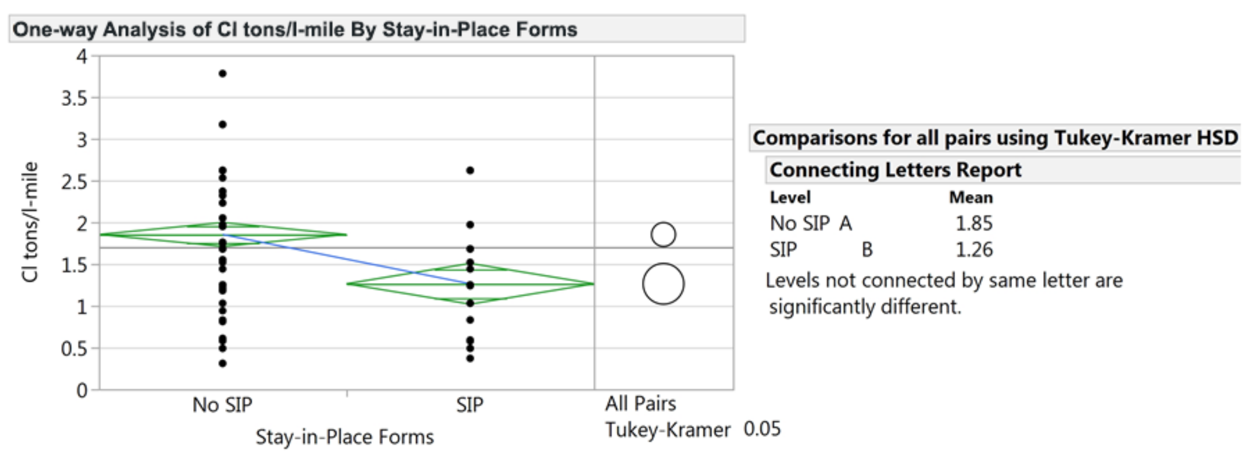


Figure 24. One-way Analysis of Rate of Chloride Application by Presence of Stay-in-Place Forms. SIP = decks with stay-in-place forms; No SIP = decks without stay-in-place forms.

As a consequence, the relationship between chloride application rate and age of deck at first overlay was analyzed in a scatterplot, as shown in Figure 25. There was a large spread; however, a weak inverse relationship can be perceived. To help with visualizing the relationship, quantile density contours are shown, which indicate a higher density of data points around the line of orthogonal fit.

The reason for a weak fit is that there were multiple factors in play leading to differences in when a deck needed a first overlay construction. The aim of this exercise of correlating two factors at a time was to determine if there were consistent relationships between factors. Since it was proven otherwise, the best course of action was to compare multiple variables at once.

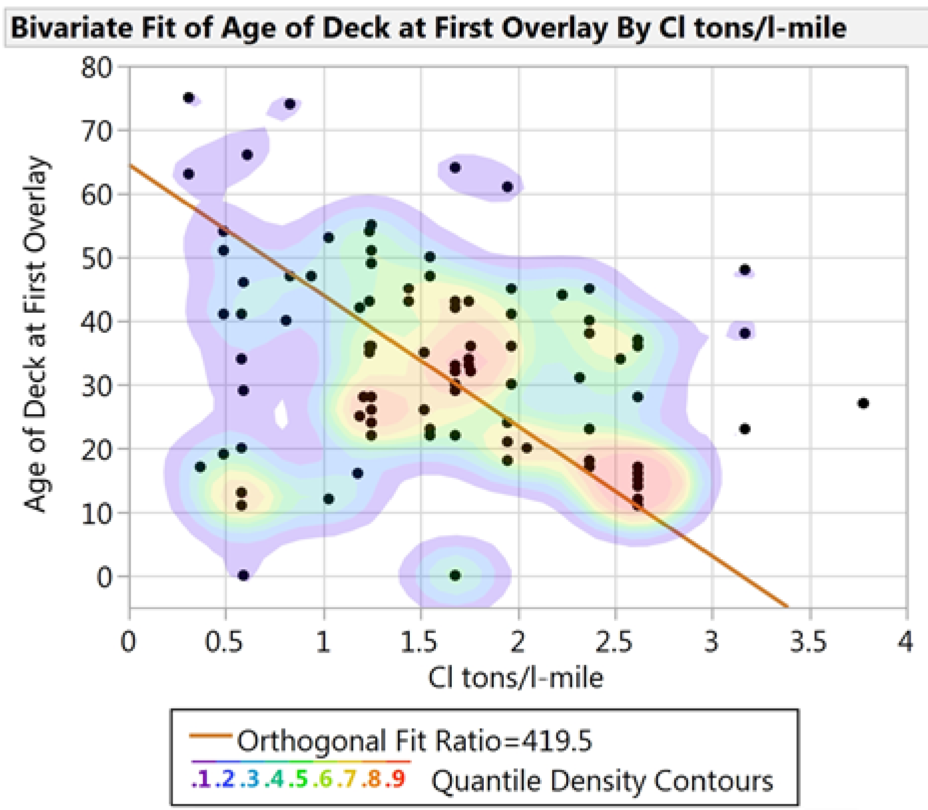


Figure 25. Relationship Between Age of Bridge Deck at First Overlay and Rate of Chloride Application

Modeling Bridge Deck Durability: Multiple Regression Analysis

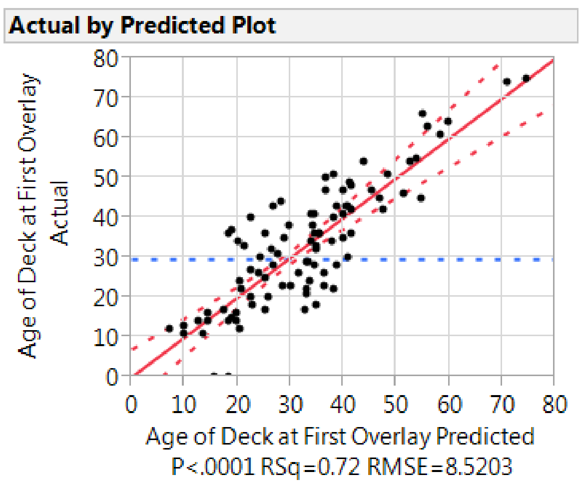
A multiple linear regression model was attempted for all decks irrespective of overlay type. Multiple regression analysis finds correlations between multiple independent variables and a single continuous dependent variable, which in this case was the age of a bridge deck at the time of first overlay.

The model for the age of a bridge deck at first overlay included the following factors:

- Annual Average Daily Traffic
- Annual Average Daily Truck Traffic Percentage

- Chloride Application Rate
- Length of Bridge
- Longest Span Length
- Deck Width
- Year – Deck Built
- Superstructure Material (MATERIAL_TYPE)
- Superstructure Design Type
- Highway Type (KIND_HWY)
- Presence of Stay-in-place Form
- Aspect Ratio (Longest Span Length ÷ Deck Width).

Stepwise regression by the forward selection technique was used to screen for only the influential factors. The resulting regression model is shown in Figure 26. Four factors were narrowed down to be statistically significant. Equation 1 shows the multiple factor correlation for understanding the role of each of these factors in affecting the age of bridge decks at first overlay, with $R^2 = 0.72$, which indicates a healthy fit, especially considering the amount of inherent variability in the data.



Summary of Fit

RSquare	0.72
RSquare Adj	0.7
Root Mean Square Error	8.52
Mean of Response	29.5
Observations (or Sum Wgts)	128

Effect Summary

Source	LogWorth	PValue
Year - Deck Built	20.697	0.00000
Cl tons/l-mile	4.064	0.00009
KIND_HWY	3.019	0.00096
MATERIAL TYPE	2.471	0.00338

Figure 26. Multiple Regression Model: Age of Bridge Deck at First Overlay

$$Age\ of\ Bridge\ Deck\ at\ First\ Overlay \qquad \text{[Eq. 1]}$$

$$= 1460 - 4.64 * Cl^{-}{}_{rate} - 0.72 * Year_{Deck} + \begin{cases} -2.46 = Interstate \\ +2.84 = US\ Highway \\ -5.1 = State\ Highway \\ +4.8 = County\ Highway \end{cases} + \begin{cases} +4.4 = Concrete \\ +2.5 = Steel \\ -2.9 = Prestressed \\ -3.97 = Steel\ Continuous \end{cases}$$

where

$Cl^{-}{}_{rate}$ = countywide chloride application rate, ton per lane-mile
$Year_{Deck}$ = year in which bridge deck was built including reconstructions.

The effect summary in Figure 26 shows the strength of the correlation between each of the factors—the higher the logworth and lower the p-value, the higher the correlation. The year the deck was built has the greatest strength and the material type the least strength, but all are significantly influencing parameters. Of interest is that for bridges carrying interstate and state highways, the age of deck at first overlay is reduced. In addition, concrete superstructures appear to delay the need for major rehabilitation involving overlays in bridge decks as opposed to other superstructure designs and materials.

Multi-Generational Overlays

VDOT has been constructing overlays long enough that some of the overlays have reached the end of their functional service life. Some of those decks have been overlaid again, noted as second-generation overlays. There are fewer second-generation overlays, and many of them have been constructed recently, so they are most likely still in service. The pool of 133 bridges in this study included 48 bridge decks with second-generation overlays. The ages of first-generation overlays were determined for 44 of the 48 bridge decks using deep exploration of the older inspection reports and rehabilitation plan drawings (Figure 27). These data are valuable since they show the entire service life of bridge deck overlays, irrespective of overlay type. The first-generation overlays have lasted for an average of 20.3 years.

Figure 28 shows the frequency of first-generation (Figure 28a) and second-generation (Figure 28b) overlays. This shows that most of the overlays replaced were EC and LMC overlays, since they have been used for a long time in Virginia. In addition, Figure 28b shows that the first-generation overlays were increasingly replaced by EC and VELMC overlays. This is an indication of the maintenance and rehabilitation trend of the future.

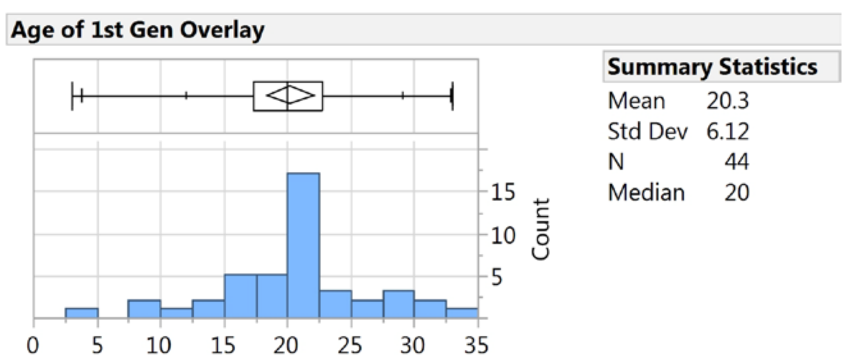


Figure 27. Histogram of Age of First-Generation Overlays

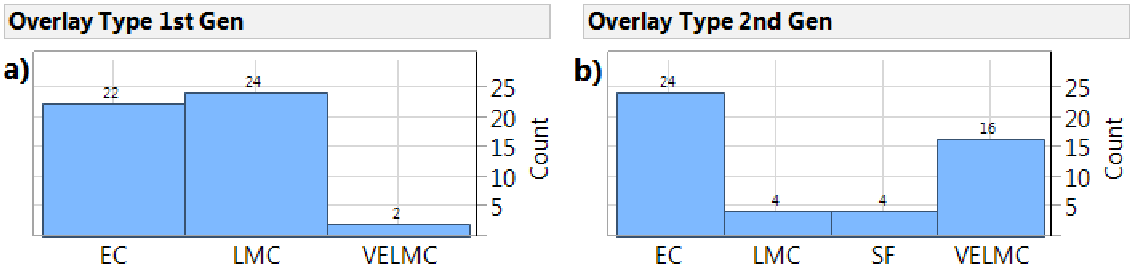


Figure 28. Histograms of Frequency of Overlay Types: (a) first-generation overlay; (b) second-generation overlay. EC = epoxy concrete; SF = silica fume; LMC = latex-modified concrete; VELMC = very-early-strength latex-modified concrete.

Figure 29 shows the one-way analysis between first-generational EC and LMC overlays. The two VELMC overlays were not used for this analysis, since they were overlaid with EC overlays to address the occurrence of cracks alone. This analysis shows that there was no significant difference between the performances of these two overlays in general. The LMC overlays lasted an average of 21.7 years, compared to an average of 19.5 years for EC overlays.

Figure 30 shows the active age of the second-generation overlays as of 2018.

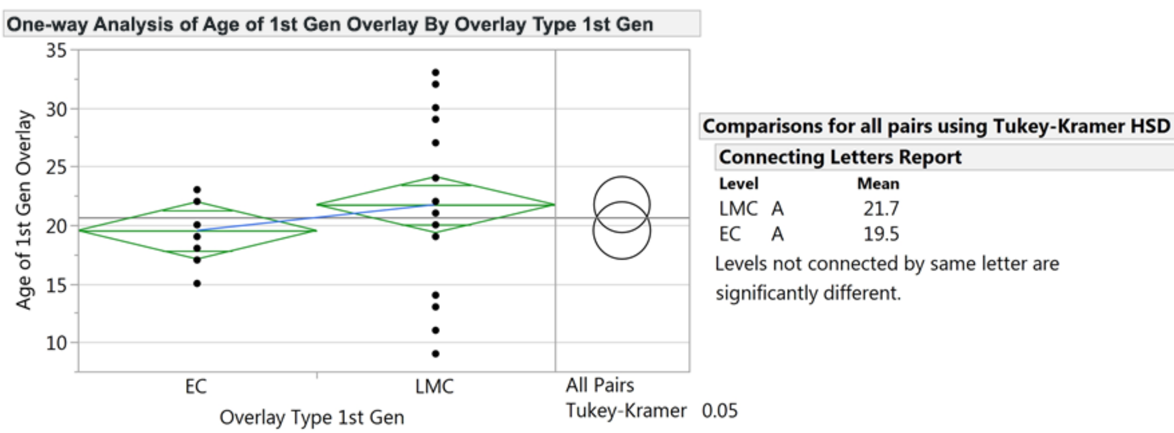


Figure 29. One-way Analysis of Age of First-Generation Overlay and Corresponding Overlay Type. EC = epoxy concrete; LMC = latex-modified concrete.

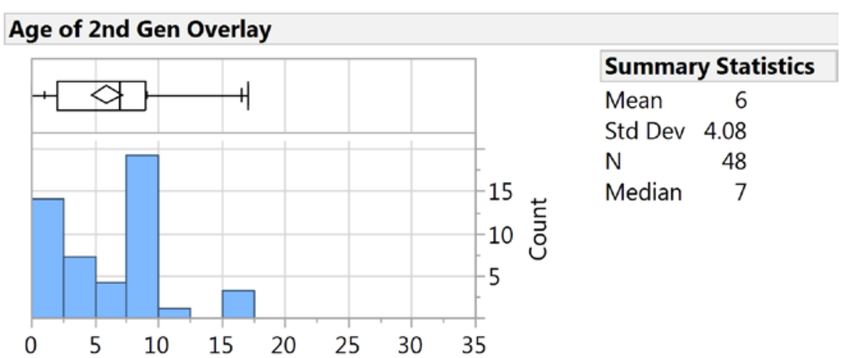
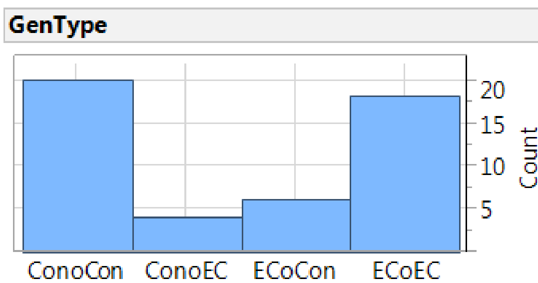


Figure 30. Histogram of Age of Second-Generation Overlays

In general, there were four scenarios depending on the overlay type being replaced and the overlay type being newly applied. For notation purposes, rigid overlays were simply referred to as concrete overlays.

1. Concrete overlay replaces concrete overlay (ConoCon).
2. Concrete overlay replaces epoxy concrete overlay (ConoEC).
3. Epoxy concrete overlay replaces concrete overlay (ECoCon).
4. Epoxy concrete overlay replaces epoxy concrete overlay (ECoEC).

Figure 31 shows the distribution of the four scenarios of multi-generational overlays. It can be inferred that the most common practices with regard to second-generation overlaying were rigid concrete overlays replacing existing rigid concrete overlays (42%) and EC overlays replacing existing EC overlays (38%).



Frequencies

Level	Count	Prob
ConoCon	20	0.42
ConoEC	4	0.08
ECoCon	6	0.13
ECoEC	18	0.38
Total	48	1.00

Figure 31. Histogram of Multi-Generational Overlay Profiles. ConoCon = concrete overlay replaces concrete overlay; ConoEC = concrete overlay replaces epoxy concrete overlay; ECoCon = epoxy concrete overlay replaces concrete overlay; ECoEC = epoxy concrete overlay replaces epoxy concrete overlay. For notation purposes, rigid overlays were referred to as concrete overlays.

Modeling Durability of First-Generation Overlays

Age of bridge deck at the time of second-generational overlay is an indication of the performance of the first-generation overlay and other related exposure factors. Multiple regression modeling was performed for the age of bridge deck at the time of second-generation overlay to see which factors influenced it the most. However, this method can be used only for cases where the dependent variable is entirely known. For example, only overlays that have reached their end of service life can be used; overlays that are still in service cannot be modeled. Regression modeling cannot differentiate between an active overlay and an overlay that reached end of service life. Thus, the model included the following factors for 44 overlays:

- Annual Average Daily Traffic
- Annual Average Daily Truck Traffic Percentage
- Chloride Application Rate
- Length of Bridge
- Deck Width
- Year – Deck Built
- First Generation Overlay Type
- Superstructure Material (MATERIAL_TYPE)

- Superstructure Design Type
- Highway Type (KIND_HWY)
- Presence of Stay-in-place Form
- Aspect Ratio (Longest Span Length ÷ Deck Width).

Figure 32 shows the best model after uninfluential factors were eliminated through a stepwise forward selection process. This analysis identified AADTT% as a strong influential factor in the degradation of the first-generation overlays. The model presented in Equation 2 shows that LMC overlays are expected to last approximately 2.6 years longer than EC overlays.

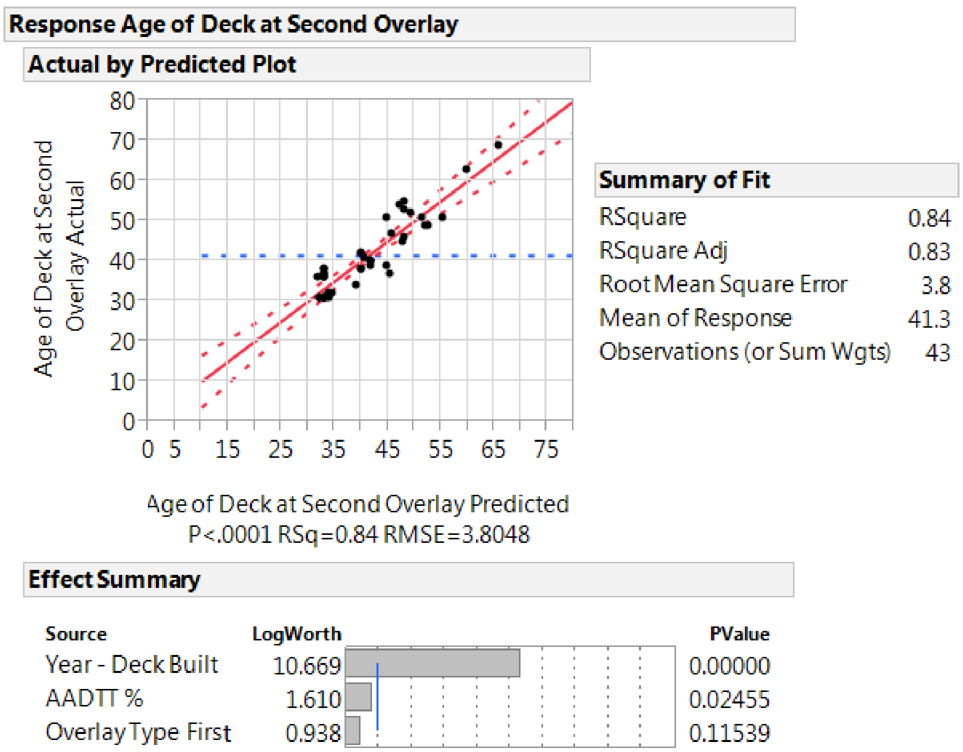


Figure 32. Multiple Regression Model: Age of Bridge Deck at First Overlay

$$\begin{aligned} &\mathit{Age\ of\ Bridge\ Deck\ at\ Second\ Generation\ Overlay} \\ &\quad = 1903.3 - 0.94 * Year_{Deck} - 0.19 * AADTT \\ &\quad + \begin{cases} -1.32 = EC\ Overlay\ (first - generation) \\ +1.32 = LMC\ Overlay\ (first - generation) \end{cases} \end{aligned} \quad \text{[Eq. 2]}$$

where

$Year_{Deck}$ = year in which bridge deck was built including reconstructions
$AADTT$ = annual average daily truck traffic, in percentage.

The analysis included only EC and LMC overlays because from the pool of bridge decks under study, only EC and LMC overlays were replaced or overlaid once.

Service Life of Overlays

Because of the disadvantage of the regression analysis regarding the inability to use the age of active overlays in the model, the models in the previous sections were conducted only for bridge decks for which overlays had reached the end of their service life. However, the performance of 44 first-generation overlays is biased, since they have all reached the end of service life. Including 44 second-generation overlays, 133 bridge deck overlays are still in service. Thus, the actual number of overlays studied in this effort was 177 (133 active overlays + 44 replaced overlays), disregarding the generation. The dataset of 177 overlays can be used for estimation of service life using the statistical method of survival analysis.

Survival Analysis

Survival analysis is a set of statistical methods used for predicting the time for an event to occur. The method is used in engineering, health sciences, anthropology, social engineering, and other fields where the concerned events can be end of service life, failure, death, disease, divorce, unemployment, expiration of food, and other such events. This method has two major advantages over regression modeling:

1. Survival analysis uses censoring when some of the observations do not reach their anticipated event within the study period. For these observations, the method uses a technique called "right censoring," which considers their survival time to be at least as long as the study period and accepts the prospect that the event could happen in the future.

2. Regression modeling can result in negative time to an event, whereas survival analysis restricts positive projection, making it technically appropriate for analyzing overlay life.

Overlay Life

Survival analysis involved two input parameters: time to the event of interest or to the end of the study period without experiencing the event, and the status of the event. Kaplan-Meier estimation, a nonparametric survival method, was used to analyze the overlay life. This method calculates the yearly survival probability of the overlays. The result of this analysis is the mean service life of overlays, which is calculated by taking integration of the survival function developed using survival fitting. The calculation of survival distribution is presented in Equation 3, and the calculation of mean survival time of overlays is presented in Equation 4.

$$\hat{S}(t_i) = \prod_{j=1}^{i} \left(1 - \frac{d_j}{n_j}\right) \qquad \text{[Eq. 3]}$$

$$\hat{\mu} = \sum_{i=1}^{D} \hat{S}\,(t_{i-1})(t_i - t_{i-1}) \qquad \text{[Eq. 4]}$$

where

$\hat{S}(t_i)$ = survival distribution at time t_i
$\hat{\mu}$ = estimated mean survival time
d_i = number of failed overlays at t_i
n_i = number of surviving overlays prior to t_i
t_i = time in years.

Figure 33 shows the Kaplan-Meier survival fit plot for thin overlays (EC) and rigid overlays (LMC, SF, and VELMC). The rigid overlays were combined because of the similarity in removing contaminated base concrete and resetting the deck damage at the time of overlay construction and since no significant differences were found among the three rigid overlay types.

Table 9 shows the summary of the survival analysis. Number Failed is the count of overlays that reached their service life, and Number Censored is the count of overlays that are active at the end of the study period without being replaced for survival analysis. From Figure 33 it is clear that rigid overlays outperformed thin overlays in terms of service life, although there were overlaps in the confidence intervals. The width of the blocks is an indication of the variability of the overlay performance at any one surviving percentage.

The projected mean service life, as shown in Table 9, for thin overlays was 20.9 years and for rigid overlays was 25.9 years. The standard error is the standard deviation of the sampling distribution; the lower the standard error, the higher the precision. To increase the precision of the estimation by twofold, the standard error should be halved, which in turn means that the sample size must be quadrupled.

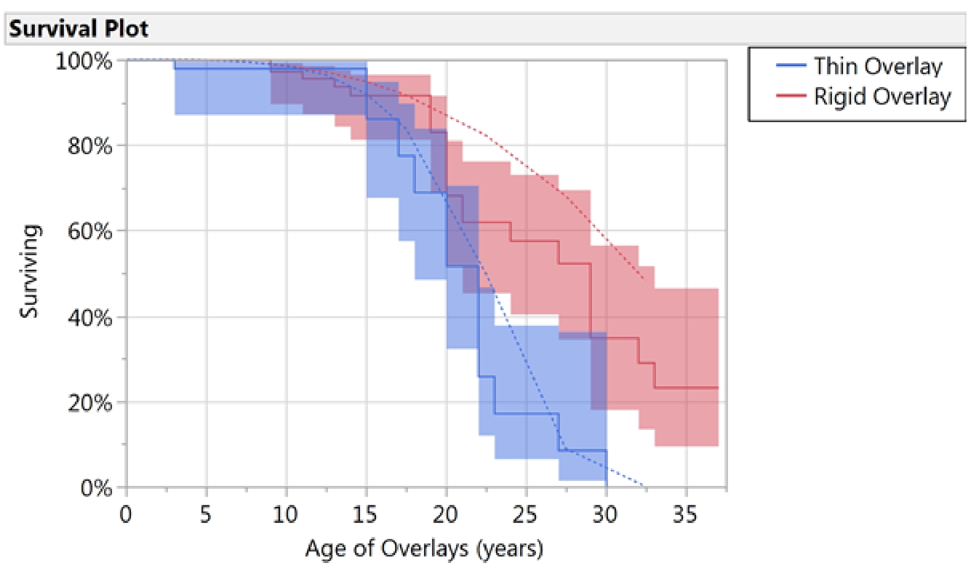


Figure 33. Kaplan-Meier Survival Plot for Age of Thin and Rigid Overlays

Table 9. Summary of Kaplan-Meier Survival Analysis

Group	Number Failed	Number Censored	Mean Survival Time of Overlays (yr)	Standard Error (yr)
Thin overlay	22	47	20.9	0.95
Rigid overlay	22	86	25.9	1.14
Combined	44	133	23.8	0.84

Table 10 shows the median, lower, and upper 95 percent confidence limits and times for 25 percent and 75 percent failure probabilities for the projected service life of rigid and thin overlays. It is clear that rigid overlays have a wider variation in service life (21 to 32 years) whereas thin overlays have a more predictable service life (18 to 22 years), taking 95 percent confidence intervals. The greater variation in the service life of the rigid overlays compared to the thin overlays is most likely related to the deck condition at overlay. Rigid overlay decks have significantly more damage prior to overlay than the thin overlays, thus indicating that damage at overlay influences overlay performance.

Tables 11 and 12 present the predicted survival risk and the number of overlays predicted to fail through every year of the service life of thin and rigid overlays, respectively. The Number Censored shows the number of overlays that were active at that particular age in the dataset.

Table 10. Quantiles of Kaplan-Meier Survival Analysis

Group	Median Time (yr)	Lower 95% (yr)	Upper 95% (yr)	25% Failures (yr)	75% Failures (yr)
Thin overlay	22	18	22	18	23
Rigid overlay	29	21	32	20	33
Combined	22	20	27	20	29

Table 11. Survival Risk Tabulation for Thin Overlays

Age of Overlay (yr)	Survival (%)	Failure (%)	Survival Standard Error (yr)	Number Failed	Number Censored	Number At Risk
0	100%	0%	0	0	0	69
1	100%	0%	0	0	2	69
2	100%	0%	0	0	17	67
3	98%	2%	0.02	1	2	50
4	98%	2%	0.02	0	5	47
7	98%	2%	0.02	0	2	42
8	98%	2%	0.02	0	7	40
9	98%	2%	0.02	0	5	33
12	98%	2%	0.02	0	2	28
14	98%	2%	0.02	0	1	26
15	86%	14%	0.066	3	2	25
17	78%	22%	0.083	2	0	20
18	69%	31%	0.093	2	0	18
20	52%	48%	0.102	4	0	16
22	26%	74%	0.091	6	0	12
23	17%	83%	0.078	2	1	6
26	17%	83%	0.078	0	1	3
27	9%	91%	0.072	1	0	2
30	0%	100%	0	1	0	1

Table 12. Survival Risk Tabulation for Rigid Overlays

Age of Overlay (yr)	Survival (%)	Failure (%)	Survival Standard Error (yr)	Number Failed	Number Censored	Number At Risk
0	100.0%	0.0%	0	0	0	108
0	100.0%	0.0%	0	0	2	108
1	100.0%	0.0%	0	0	4	106
2	100.0%	0.0%	0	0	2	102
3	100.0%	0.0%	0	0	3	100
4	100.0%	0.0%	0	0	9	97
5	100.0%	0.0%	0	0	7	88
6	100.0%	0.0%	0	0	2	81
7	100.0%	0.0%	0	0	3	79
8	100.0%	0.0%	0	0	3	76
9	97.3%	2.7%	0.019	2	7	73
10	97.3%	2.7%	0.019	0	3	64
11	95.7%	4.3%	0.025	1	5	61
12	95.7%	4.3%	0.025	0	4	55
13	93.8%	6.2%	0.03	1	5	51
14	91.7%	8.3%	0.036	1	2	45
15	91.7%	8.3%	0.036	0	3	42
16	91.7%	8.3%	0.036	0	1	39
17	91.7%	8.3%	0.036	0	3	38
18	91.7%	8.3%	0.036	0	3	35
19	83.1%	16.9%	0.058	3	1	32
20	68.3%	31.7%	0.076	5	1	28
21	62.1%	37.9%	0.081	2	2	22
22	62.1%	37.9%	0.081	0	3	18
23	62.1%	37.9%	0.081	0	1	15
24	57.6%	42.4%	0.087	1	0	14
25	57.6%	42.4%	0.087	0	1	13
26	57.6%	42.4%	0.087	0	1	12
27	52.4%	47.6%	0.093	1	1	11
29	34.9%	65.1%	0.103	3	0	9
32	29.1%	70.9%	0.101	1	0	6
33	23.3%	76.7%	0.096	1	0	5
37	23.3%	76.7%	0.096	0	4	4

Thus, survival analysis provided a reliable estimation of the service life of overlays and the risk of failure associated with age.

Effect of Deck Damage Prior to Overlay on Future Performance of Overlays

Based on availability, bridge engineers allocate funds years in advance for the rehabilitation of bridge decks that have the most need. Because of the nature of this process, it is possible that in the interim, bridge decks undergo either a higher degree of damage or less change. There is a conjecture that the degree of damage in a bridge deck at the time of the first overlay might affect the service life of the overlay. One of the challenges is the high variability in the data on damage quantities. Deterioration detection by an inspector is often visual in nature and may include subjective estimations for damage quantities. Thus, the actual damage in a bridge deck could be quite different from the reported values in the inspection reports. This was evident when several inspection records were reviewed, especially when damage quantities changed abruptly and changed back in a consecutive report or when reported damages disappeared without any indication of repairs and reappeared in a later report. However, it may be possible to determine the actual damage at overlay from the final reconstruction plans, but they are not always available.

Multiple regression modeling for rate of first overlay damage using forward stepwise selection was attempted with the following factors:

- Annual Average Daily Traffic
- Annual Average Daily Truck Traffic Percentage
- Chloride Application Rate
- Deck Damage Percentage at Overlay
- Length of Bridge
- Length of Longest Span
- Roadway Width
- Superstructure Material
- Superstructure Design Type
- Skew Angle
- Highway Type
- Presence of Stay-in-place Form
- Aspect Ratio (Longest Span Length ÷ Deck Width).

However, the regression process yielded no valid models, indicating that none of the factors or combinations of factors produced a statistically significant relationship with the rate of damage of the overlays. This was also attempted for the four subsets of overlays, but the results were very weak regression models. However, there are other ways to assess relationships between these factors.

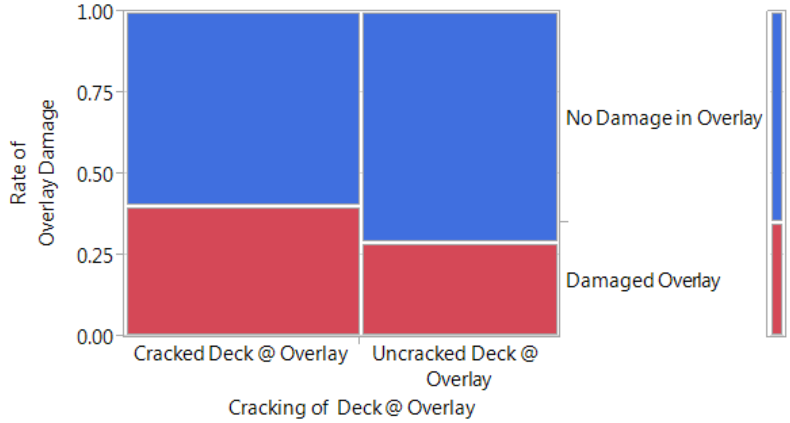
A robust statistical method to determine if the degree of deck damage at the time of overlay has any effect on the rate of future damage in the overlays themselves is the use of Pearson's chi-square test. This test uses categorical data, so the deterioration data were converted into presence and absence of deterioration, indicating presence of deterioration and no deterioration, respectively.

The null hypothesis for this test states that there is no dependence between the amount of deck damage at the time of first overlay and the rate of damage of the overlays themselves.

Figure 34 shows the mosaic plots that indicate the relationship between the two factors in categorical form. The rate of damage of overlays, calculated up to the most recent inspection, was compared with deck cracking prior to overlay (Figure 34a), deck surface wear prior to overlay (Figure 34b), and deck damage prior to overlay (Figure 34c). The rate of cracking in overlays was not compared with the deck deterioration prior to overlay, since cracking of overlays is likely a combination of overlay construction issues related to curing and material issues related to water content. In addition, active cracking in the deck prior to overlay would theoretically lead to cracking of overlays; however, no data on the active cracks are available to make that comparison.

Contingency Analysis of Rate of Overlay Damage By Cracking of Deck @ Overlay

Mosaic Plot



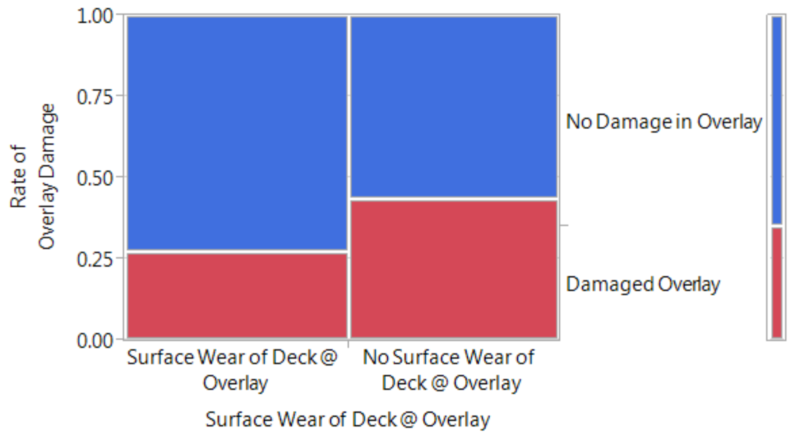
Tests

N	DF	-LogLike	RSquare (U)
114	1	0.824	0.01

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	1.648	0.20
Pearson	1.635	0.20

Contingency Analysis of Rate of Overlay Damage By Surface Wear of Deck @ Overlay

Mosaic Plot



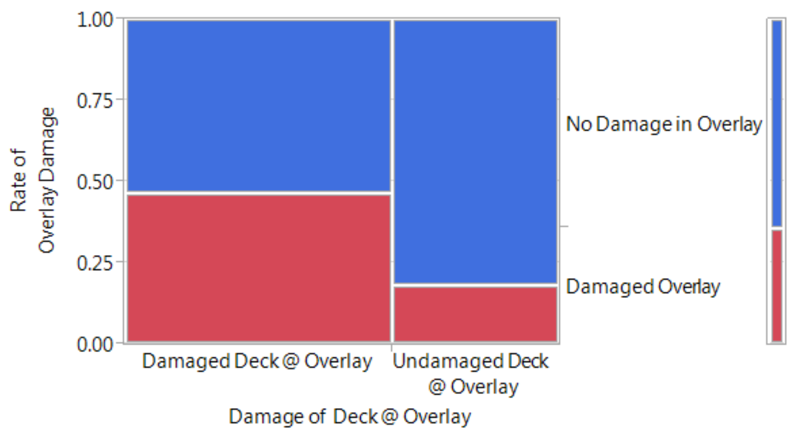
Tests

N	DF	-LogLike	RSquare (U)
114	1	1.713	0.02

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	3.425	0.06
Pearson	3.410	0.06

Contingency Analysis of Rate of Overlay Damage By Damage of Deck @ Overlay

Mosaic Plot



Tests

N	DF	-LogLike	RSquare (U)
115	1	5.011	0.07

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	10.021	0.0015*
Pearson	9.481	0.0021*

Figure 34. Independence Test: Rate of Damage in Overlay vs. (a) Cracks in Deck at Overlay, (b) Surface Wear of Deck at Overlay, and (c) Damages in Deck at Overlay

The rate of surface wear in overlays was not compared with deterioration of the deck prior to overlay, since issues with surface wear would be related to the overlay material and construction.

The width of the x-axis is proportional to the number of data points in that category. Pearson's chi-square test gives a p-value of 0.0021, which is much smaller than 0.05 (95% confidence) for deck damages; however, higher p-values were obtained for cracks and surface wear. A very small p-value indicates that the null hypothesis can be rejected, which means there is dependence between the degree of deck damage at the time of overlay and the degree of damage the overlays have undergone.

This indicates that there is a correlation between deck damages prior to overlay and the rate of damage of overlays. However, for understanding the correlation between overlay types and prior deterioration of decks, this analysis was conducted for the four overlay types.

EC Overlays

Figure 35 shows the mosaic plots for EC overlays. The rate of damage of overlays, calculated up to the most recent inspection, was compared with deck cracks prior to overlay (Figure 35a), surface wear prior to overlay (Figure 35b), and deck damages prior to overlay (Figure 35c). Pearson's chi-square test results are shown to the right side of the mosaic plots. Small p-values reject the null hypothesis and show that there is significant dependence between the two factors.

Figure 35 shows that there is significant dependence between presence of deck cracks and damages prior to overlay and the rate of overlay damage for EC overlays. In fact, for every EC overlaid deck with no cracks and no damages prior to overlay, no damages were observed at the latest inspection, irrespective of the age of the overlay. This is a major finding regarding EC overlay behavior.

To confirm the generality of these results, a comparison between the age of overlays for damaged and undamaged decks was performed. Figure 36 shows the comparison between the ages of EC overlays as of 2018 for zero and nonzero damage. There is no statistical difference between the two datasets. This finding supports the conclusion that EC overlays constructed on decks with no cracks and no damages would last longer without having damages themselves compared to EC overlays constructed on decks with non-zero damage.

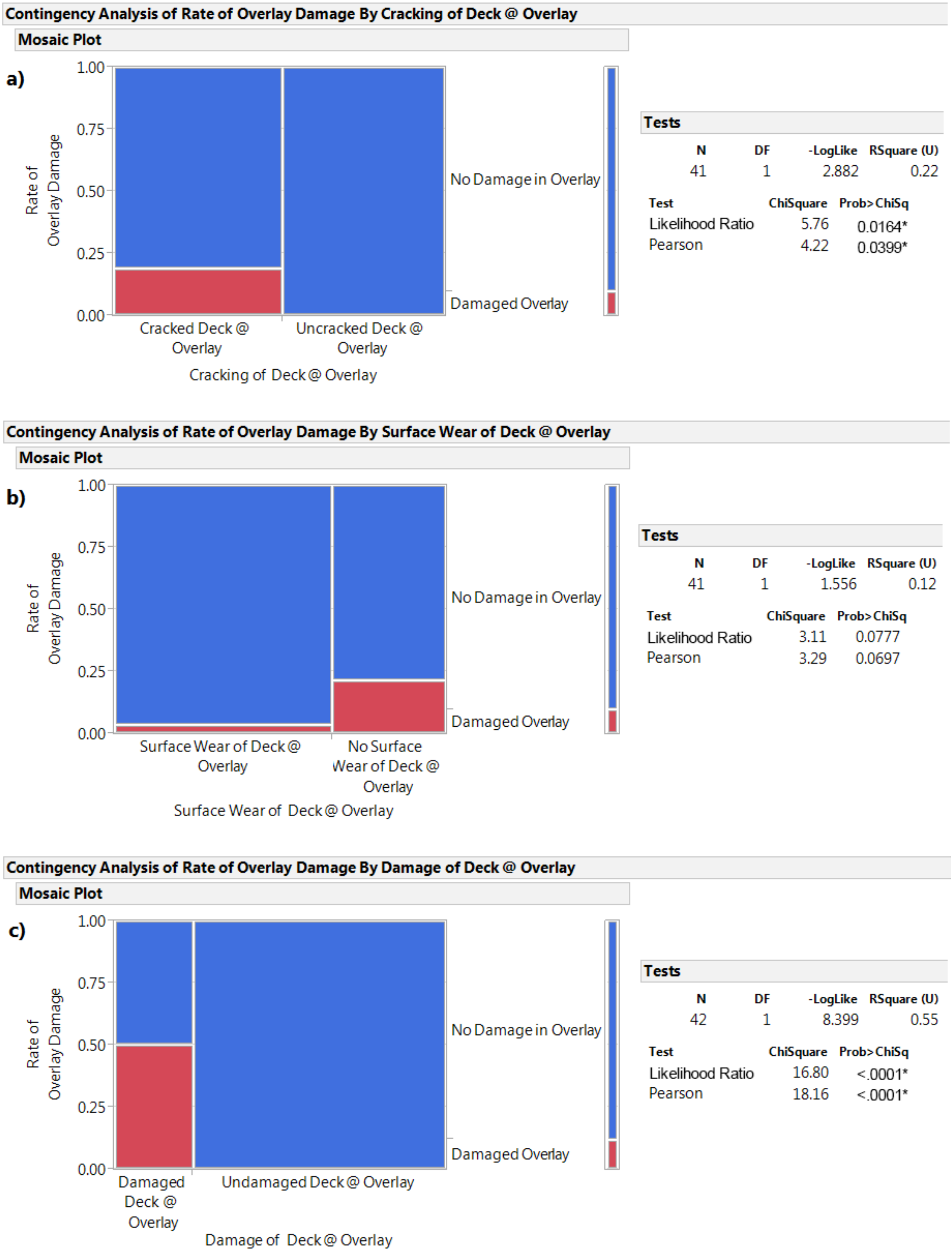


Figure 35. Independence Test: Rate of Damage in Epoxy Concrete Overlays vs. (a) Cracks in Deck at Overlay, (b) Surface Wear of Deck at Overlay, and (c) Damages in Deck at Overlay

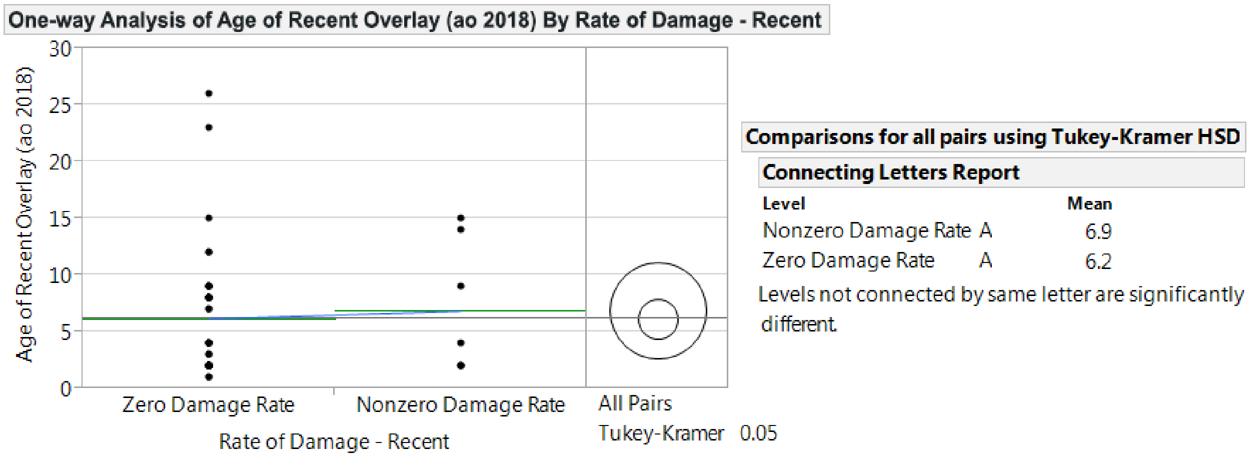


Figure 36. One-way Analysis of Age of Epoxy Concrete Overlays and Rate of Overlay Damage

LMC Overlays

Figure 37 shows the mosaic plots for LMC overlays. The rate of damage of overlays, calculated up to the most recent inspection, was compared to deck cracks prior to overlay (Figure 37a), deck surface wear prior to overlay (Figure 37b), and deck damages prior to overlay (Figure 37c). No significant dependence was found among the three pairs of parameters; p-values were large (p-value > 0.05 = 95% significance level).

The dataset did not include undamaged decks prior to LMC overlay (Figure 36c); thus, no strong conclusion could be reached. This could be a typical observation with rigid concrete overlays, since LMC overlays are not typically applied for decks with no visible damages.

SF Overlays

Figure 38 shows the mosaic plots for SF overlays. The rate of damage of overlays, calculated up to the most recent inspection, was compared with deck cracks prior to overlay (Figure 38a), deck surface wear prior to overlay (Figure 38b), and deck damages prior to overlay (Figure 38c). No significant dependence was found among the three pairs of parameters, since p-values were large (p-value > 0.05 = 95% significance level), even though mosaic plots for cracks and surface wear appeared to have some correlation. The high p-values indicated that the correlations were not significant. This might be because SF overlay construction involves removal of the chloride-contaminated top concrete surface, which would also remove the existing delaminations, patches, and cracks. This might act as a reset for the bridge decks in terms of damage accumulation.

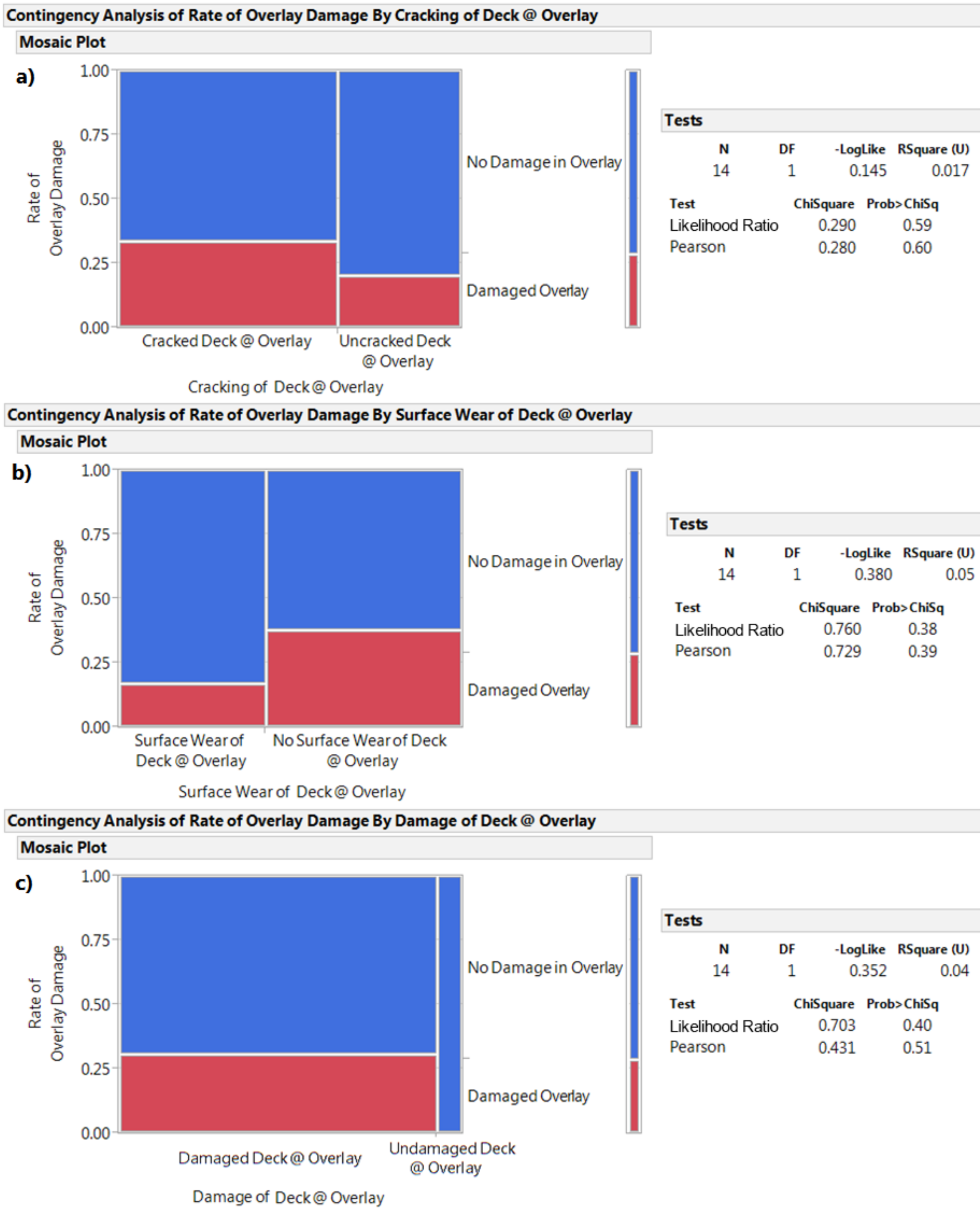


Figure 37. Independence Test: Rate of Damage in Latex-Concrete-Modified Overlays vs. (a) Cracks in Deck at Overlay, (b) Surface Wear of Deck at Overlay, and (c) Damages in Deck at Overlay

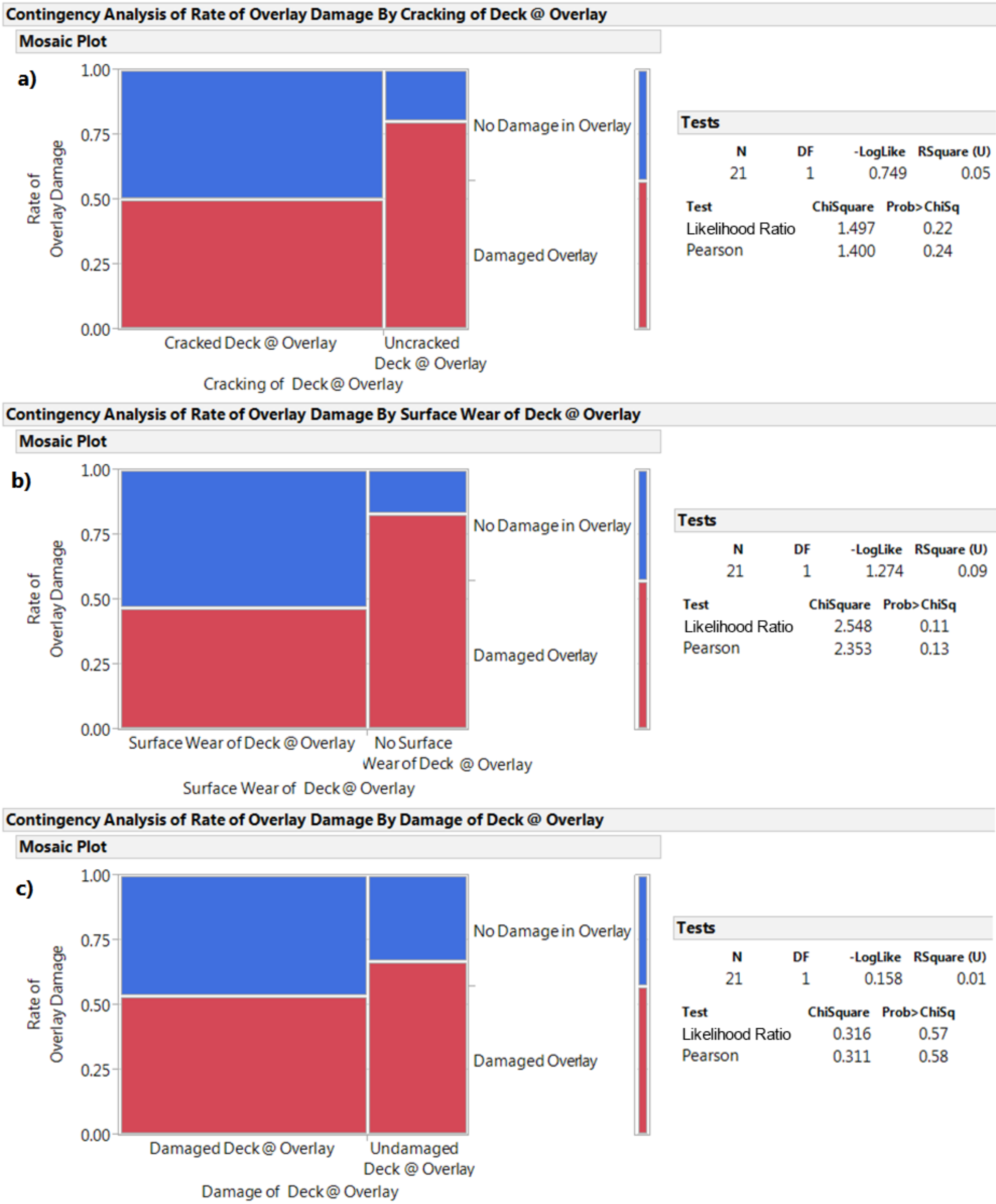


Figure 38. Independence Test: Rate of Damage in Silica Fume Overlays vs. (a) Cracks in Deck at Overlay, (b) Surface Wear of Deck at Overlay, and (c) Damages in Deck at Overlay

VELMC Overlays

Figure 39 shows the mosaic plots for VELMC overlays. The rate of damage of overlays, calculated up to the most recent inspection, was compared with deck cracking prior to overlay (Figure 39a), deck surface wear prior to overlay (Figure 39b), and deck damages prior to overlay (Figure 39c). No significant dependence was found among the three pairs of parameters, as p-values were large (p-value > 0.05 = 95% significance level), even though mosaic plots for cracks and surface wear appeared to have some correlation. The high p-values indicated that the correlations were not significant. This indicates that the degree of deck damage at VELMC overlay construction has less influence on the performance of the overlay. This might be because VELMC overlay construction often includes deep milling similar to other rigid overlays or hydro-milling, which effectively removes poor, chloride-contaminated concrete from the top surface. Hydro-milling has been in use only since approximately 2010, and its effect needs to be monitored.

Figures 37 through 39 show that all rehabilitative rigid overlays had no correlation with deck condition prior to overlay.

First-Generation Overlay in Multi-Generation Overlay System

Similar to what was described in the previous section, gathering pre-overlay deck damage information for the 44 first-generation overlays was attempted. However, only 23 decks had rehabilitation plans available. The amount of Type B and Type C patching performed on the bridge decks prior to the first-generation overlays was gleaned from as-built rehabilitation plans. Figure 40 shows the relationship between repair percentage prior to overlay and complete age of first-generation overlays. No strong trend was identified. Figure 41 separates LMC and EC overlays and again, no trend was identified. No information about the cracking and surface wear conditions of the decks prior to overlay was available.

Figure 42 shows the distribution of presence of damages in the bridge deck prior to first-generation overlays. There were only two decks with zero damages. Therefore, Pearson’s chi-square test will not provide a significant outcome.

Thus, the smaller sample size of 23 first-generation decks and the absence of variation in the data restricted any meaningful analysis of these data. However, the substantial amount of information gained from the recent overlays enabled the researchers to make significant inferences regarding the selection of overlays in Virginia and their service life performance.

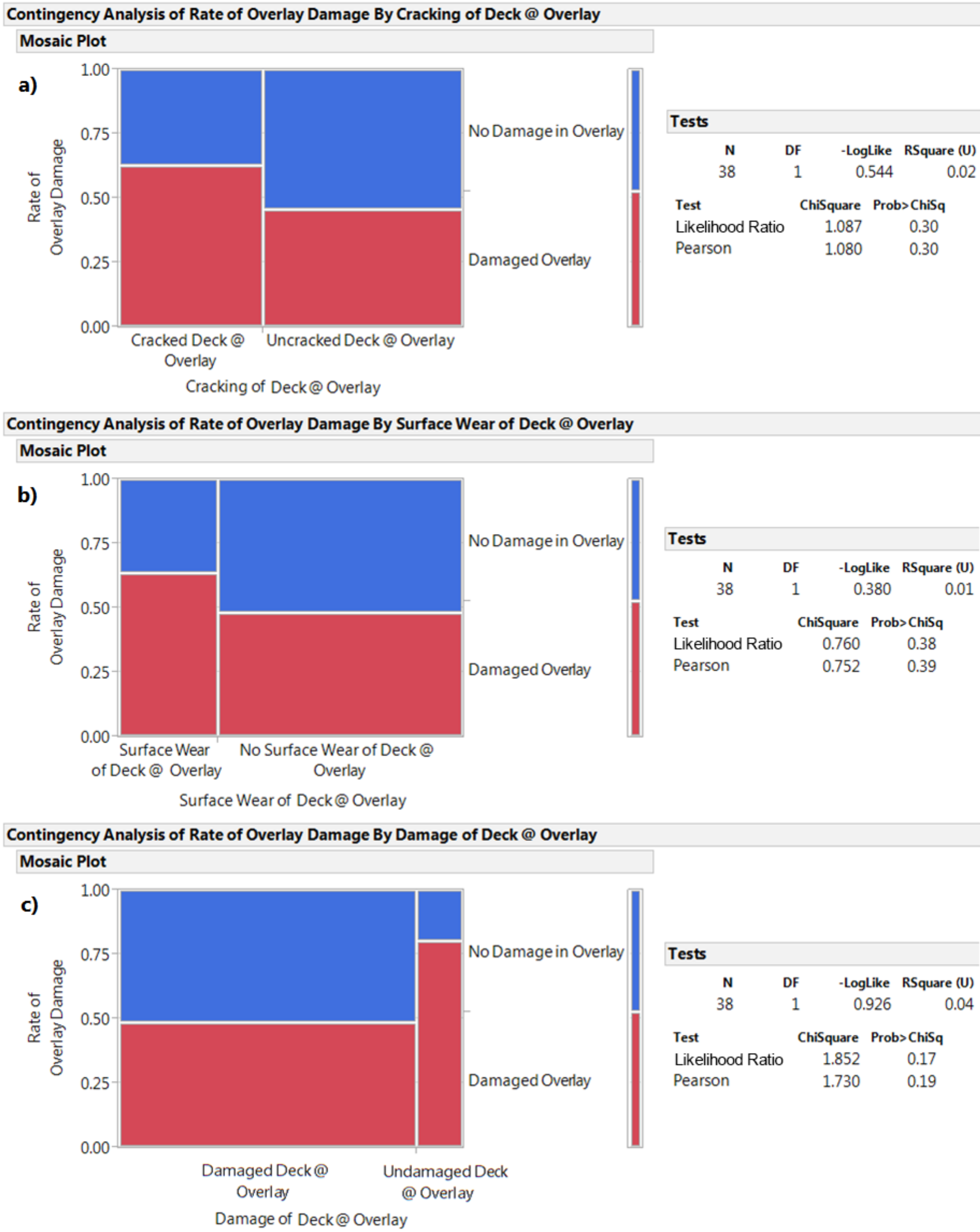


Figure 39. Independence Test: Rate of Damage in Very-Early-Strength Latex-Modified Concrete Overlays vs. (a) Cracks in Deck at Overlay, (b) Surface Wear of Deck at Overlay, and (c) Damages in Deck at Overlay

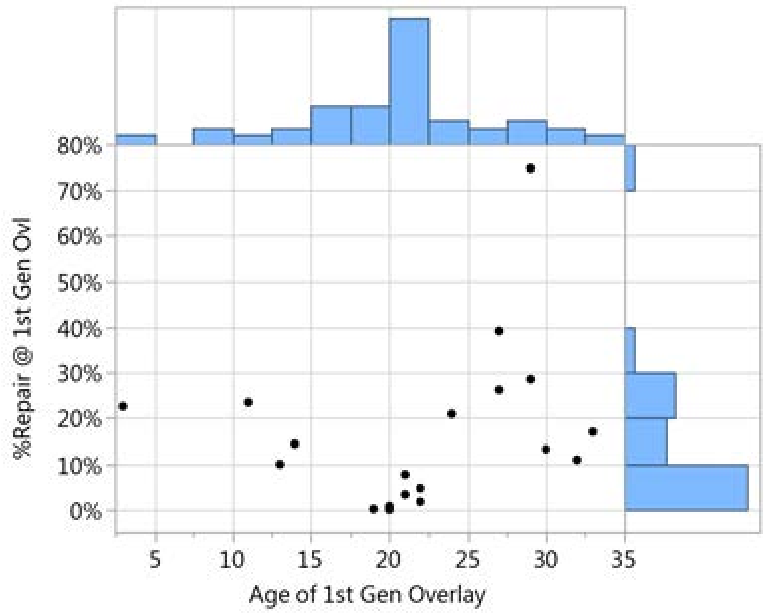


Figure 40. Surface Area Repaired at Time of First-Generation Overlay

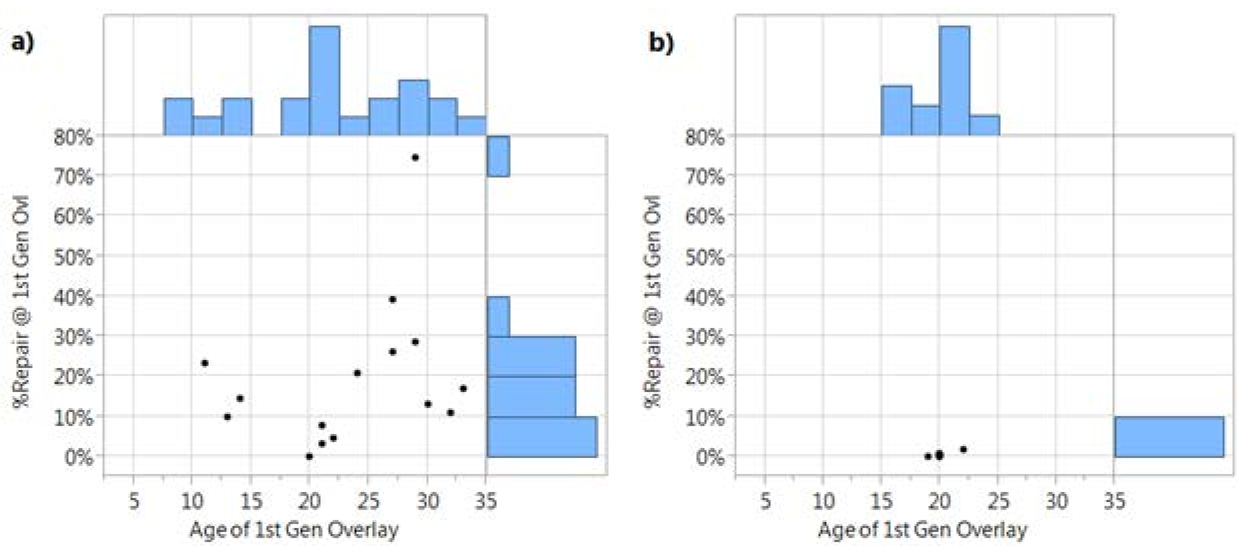


Figure 41. Surface Area Repaired at Time of First-Generation Overlay: (a) latex-modified concrete overlay only; b) epoxy concrete overlay

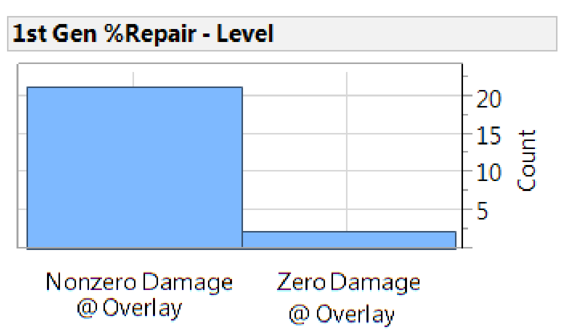


Figure 42. Histogram of Presence of Damages Prior to First-Generation Overlay

Summary of Findings

- Overlays were being placed on recently constructed bridge decks earlier than on older bridge decks.
- Overlays were being placed earlier because of increased deicing salt applications on bridge decks.
- Overlays were being placed on interstate and state highway bridges earlier than on other bridges.
- As a preventive method, EC overlays were predicted to serve for an average of 20.9 years. The range of service life was 18 to 22 years at a 95 percent confidence level.
- As a rehabilitative method, rigid concrete overlays were predicted to serve an average of 25.9 years. The range of service life was 21 to 32 years at a 95 percent confidence level.
- Decks with no damages prior to epoxy overlays had better performing overlays.
- The recent trend of overlay type selection favored EC and VELMC overlays. EC overlays proved to be one of the better performing overlays through VDOT experience. VELMC overlays improved upon LMC overlays by vastly reducing the time of construction and thus have become more suitable for decreased traffic disruption and reduced worker exposure to the field environment.

CONCLUSIONS

- *Bridges built with simply supported concrete superstructures can perform better, requiring overlays later than other types of superstructures.* Regression modeling of the bridge deck characteristics helped in reaching this conclusion.
- *Bridge inspection reports provide subjective, less reliable, and qualitative information about bridge deck condition.*
- *Preventive EC overlays should be used in a preventive sense, as the name suggests, and can be expected to serve in the range of 18 to 22 years. If preventive EC overlays are installed on bridge decks with spalls, patches, or delamination, irrespective of the amount of damage, an increased rate of deterioration in the overlays is likely to follow*.
- *Preventive EC overlays can perform well as second-generation overlays on first-generation EC overlays if there are no patches, spalls, or delaminations on the deck.*
- *Rehabilitative overlays such as LMC, SF, and VELMC overlays can be expected to serve in the range of 21 to 32 years. Future performance of rehabilitative overlays will not be influenced by the presence of bridge deck damage prior to overlay.* This might be because of

the removal of deteriorated concrete before rigid overlay construction. This emphasizes the importance of proper removal of poor quality concrete from bridge decks before overlaying during rehabilitation.

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division should adjust the anticipated service life of overlays in Chapter 32 of the Maintenance and Repair Manual and add recommendations about second-generation overlays*.

2. *The Virginia Transportation Research Council (VTRC) and VDOT's Structure and Bridge Division should conduct a Phase III study to verify the service life performance findings of this study. Phase III will include field evaluations of preventive and rehabilitative overlay types in Virginia as recommended by the technical review panel for the study. In addition, a Best Practices Bridge Inspection Manual should be compiled.*

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, VTRC will work with members of the VDOT Structure and Bridge Division's bridge management team to modify guidance in the *Maintenance and Repair Manual* by December 1, 2019.

With regard to Recommendation 2, VTRC will work with the Technical Review Panel for the Phase III study to agree on the scope of the study by December 2019.

Benefits

As per Recommendation 1, updated guidance in Chapter 32 of VDOT's Structure and Bridge Division's *Maintenance and Repair Manual* from the findings of this study will lead to better service life design and life cycle cost analysis.

As per Recommendation 2, information gained from the Phase I and II studies can be verified in the field to develop a reliable understanding of the performance of overlays.

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