Weathering Steel Performance Data Collection

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FOREWORD

The Federal Highway Administration published the existing guidance on the application of uncoated weathering steel (UWS) structures as technical advisory (TA) 5140.22 in 1989 (FHWA 1989). This document gave broad guidance on situations where UWS should not be used or else used with caution. As stated in the TA, "Further work is needed to quantify and understand the performance of UWS in a variety of circumstances and conditions." This report details a study conducted with the FHWA Long-Term Bridge Performance (LTBP) Program that contributes toward that goal, particularly considering longer term performance of UWS structures than was available at the time of the writing of the 1989 TA.

The scope of this present effort included soliciting owner feedback on contemporary UWS issues, compiling a comprehensive national database of UWS structures and their environments, evaluating a subset of these structures using field work protocols developed herein, conducting laboratory analysis of field samples, reviewing owners' inspection reports of UWS structures, and performing a statistical analysis of the UWS database. As a result, quantitative combinations of influential parameters (including climate, geography, geometry, and traffic volume) that were consistently associated with inferior environments for UWS bridges in coastal and heavy deicing environments were identified. Additionally, the UWS database is posted as a "special project" on the LTBP InfoBridge™ portal (FHWA 2022b) for future analysis. This research will be of interest to owners and bridge designers who are involved with the specification or maintenance of UWS structures, material scientists, and those interested in the long-term performance of highway infrastructure.

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Director, Office of Infrastructure
Research and Development

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16. Abstract

The Federal Highway Administration technical advisory (TA) 5140.22, *Uncoated Weathering Steel in Structures*, issued on October 3, 1989, gave broad guidance to bridge owners on the use of uncoated weathering steel (UWS), covering environments where UWS should be used with caution and detailing guidance. This guidance was mainly qualitative, which is largely adequate for detailing guidance, but quantitative guidance on environments of concern is needed to achieve consistently good performance of UWS bridges. Researchers for this study addressed this need through two parallel efforts: a field evaluation program of bridges, accompanied by laboratory analysis of field samples, selected using a statistically driven process, and a statistical analysis of the performance and associated environments of all known UWS bridges in the United States. As a result, the researchers provided quantitative recommendations for two environments of concern: coastal environments, as well as highway overpasses with heavy deicing agent use on the underpassing roadway.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS AND VARIABLES

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AC	alternating current
ADT	average daily traffic
ADTT	average daily truck traffic
Al	aluminum
avg	average
Ca	calcium
$CaCl_2$	calcium chloride
CAUS	Climate Atlas of the United States
Cl^-	chloride ion
CoRe	commonly recognized
CPS	counts per second
CV	cross-validation
ENC	Electronic Navigational Charts
EVS	Extracted Vector Shoreline
Fe	iron
FeOOH	iron oxyhydroxide
FHWA	Federal Highway Administration
G:A	ratio of goethite to akaganeite
G:AM	ratio of the sum of goethite to the sum of akageneite and magnetite and/or maghemite
G:L	ratio of goethite to lepidocrocite
GL:A	ratio of the sum of goethite and lepidocrocite to akageneite
GL:AM	the ratio of the sum of goethite and lepidocrocite to the sum of akageneite and magnetite and/or maghemite
GIS	geographic information system
H&W	highway and waterway
IC	ion chromatography
ICDD	International Center for Diffraction Data
LF	linear feet
LTBPP	Long-Term Bridge Performance Program
max	maximum
MBEI	*Manual for Bridge Element Inspection*
Mg	magnesium
$MgCl_2$	magnesium chloride
min	minimum
MLR	multivariate linear regression
MM	maintenance manual
Mn	manganese
MSE	mean squared testing error
MSV	modestly severe value
NA	not applicable

NaCl	sodium chloride
NBE	national bridge element
NBI	National Bridge Inventory
NEO	NBI, environmental, and owner variables
NO_3^-	nitrate
NOAA	National Oceanic and Atmospheric Administration
OCS	Office of Coast Survey
OS	other steel
PDF	powder diffraction file
PPE	performance prediction equation
ppm	parts per million
RSE	residual standard error
S	sulfur
SCOBS	Subcommittee on Bridges and Structures
SCR	superstructure condition rating
SCR_P	predicted superstructure condition rating
Si	silicon
SME	subject matter expert
SO_4^{-2}	sulfate
TA	technical advisory
TOW	time of wetness
UT	ultrasonic thickness
UWS	uncoated weathering steel
XRD	x-ray diffraction

Variables

I	XRD intensity
I_X	relative intensity of compound X
j	index for labeling the fold number in M_{kj}
k	index for labeling the number of variables used in M_{kj} and MSE_k
K	number of clusters in *k*-means clustering analysis
M_{kj}	MLR model for k variables and fold j
MSE_k	mean squared testing error for using k number of variables
r	number of variables in MLR equation
R^2	coefficient of determination
X	relative percentage of each compound
X_i	variable in MLR equation
Y	dependent variable in MLR equation
ε	error
β	coefficients in MLR equation
ΣI_i	sum of the relative intensities of all compounds

CHAPTER 1. INTRODUCTION

OVERVIEW OF WEATHERING STEEL

Weathering steel is produced by alloying additional elements (2 percent or less of various combinations of copper, phosphorus, chromium, silicon (Si), and nickel) with traditional steel, which causes the corrosion resistance of the steel to be significantly increased. The behavior of unpainted weathering steel exposed to appropriate environments is fundamentally different from that of traditional steel. In contrast to the formation of exfoliating layers of iron oxide (rust) on traditional steel, weathering steel is intended to form a protective oxide coating that inhibits future corrosion of the steel. This increase in corrosion resistance allows weathering steel to be used without the need for paint or other coatings in many situations. Consequently, uncoated weathering steel (UWS) is a cost-effective material for bridges from both initial and lifecycle cost perspectives.

The current understanding is that for UWS to function as intended, it should not be subjected to excessive moisture or excessive levels of chloride (Cl^-) or sulfate (SO_4^{-2}) contaminants. The current understanding of excessive moisture is typically based on the concept of wet-dry cycles. However, it should be emphasized that corrosion happens in the presence of moisture. If UWS is exposed to moisture, it must also be exposed to a drying cycle. The opposite is not true: if UWS is used in a consistently dry environment, no corrosion occurs, and a wetting cycle is not needed. When UWS is exposed to moisture, the relative proportion of wetting and drying periods needed for the protective coating to develop is not well established. However, a time of wetness above 60 percent is often used as an estimate for a limit above which poor performance may occur. In assessing the environments of bridges with poor performance relative to this time of wetness threshold, the researchers found that this factor was one of several associated with poor UWS performance in some cases, but time of wetness above 60 percent is a very extreme condition and does not fully explain field observations.

Of potential contaminants, Cl^- (from both runoff of waterborne deicing salts and proximity of the structure to marine environments with high atmospheric Cl^- levels) are typically more concerning in the United States than SO_4^{-2} levels from pollution, which generally are not high enough to have a detrimental effect. The Federal Highway Administration (FHWA) advises that unpainted weathering steel will perform satisfactorily in the United States in atmospheric Cl^- levels averaging up to at least 1×10^{-6} oz/in^2/d (FHWA 1989). The United Kingdom Standard BD/7/01 recommends that unpainted weathering steel should not be used when the sulfur trioxide level exceeds an average of 5×10^{-6} oz/ in^2/d (a value rarely exceeded in the United States) (Highways Agency 2001). However, the accuracy of these limits is not well established.

STATE OF PRACTICE OF UNCOATED WEATHERING STEEL

UWS was first introduced to the United States bridge market in the mid-1960s (Albrecht and Naeemi 1984). In the 1980s, some States began to experience less than desirable performance of their UWS bridges, as some bridges were corroding much faster than anticipated. This situation prompted FHWA to issue technical advisory (TA) 5140.22 on October 3, 1989, currently entitled *Uncoated Weathering Steel in Structures*, hereafter referenced as the “UWS TA” for brevity

(FHWA 1989). This TA gave broad guidance to bridge owners on the use of UWS on two main topics: environments where UWS should be used with caution (e.g., coastal, high-humidity, or industrial environments; grade separations; and low-level water crossings) and detailing guidance. The UWS TA also stated: “Further work is needed to quantify and understand the performance of UWS in a variety of circumstances and conditions.”

Presently, approximately 2,000 UWS bridges are constructed per decade in the United States, based on data received from bridge owners. Most of these are performing well or satisfactorily, but exceptions continue to exist. The exceptions sometimes relate to accelerated corrosion on a relatively small, localized area of the structure. Such issues are easily avoided by following appropriate detailing guidance, as given in the UWS TA, and maintaining leaking joints. On the other hand, some bridges exhibit poor performance throughout the structure. This report focuses on this type of situation, which is herein termed the “overall performance” of the structure, meaning performance not associated with known problematic details, such as leaking joints and details that trap moisture.

OBJECTIVES AND SCOPE

This study was commissioned through the Long-Term Bridge Performance Program (LTBPP) to provide a better understanding of the performance of UWS and assist in revising the UWS TA with quantified data (FHWA 1989; Friedland et al. 2007). The scope of work for this project was organized into three discrete phases:

- Phase 1—Developmental phase (2011–2012).
- Phase 2—Pilot data collection phase (2012–2014).
- Phase 3—Extensive data collection phase (2018–2023).

The years listed parenthetically in the preceding list reference the period of performance of each of these phases. This information provides context for some of the decisions and methods used in this study, as further described in later chapters.

The following chapters discuss the tasks performed throughout these phases:

- Chapter 2—Owners were engaged to better understand the current use and performance of UWS and the most critical contemporary UWS issues being faced in practice. This task was performed during phase 1 and assisted in determining the scope and focus of the later phases of research.

- Chapter 3—A national UWS database of over 10,000 UWS bridges was created by obtaining and linking the national inventory of UWS bridges to information from the National Bridge Inventory (NBI) (FHWA 2022a); climate and other geographic-dependent data; and information from owners on their maintenance and deicing agent practices.

- Chapter 4—One primary function of this database was to enable bridges to be selected for further evaluation based on a statistically driven process. This process involved creating groups of bridges for a given geographical area (typically within a 50-mi radius of one another), which are termed bridge clusters. Four bridge clusters were evaluated in phase 2, and seven were evaluated in phase 3. These selections enabled the bridges selected for further evaluation to capture a comprehensive breadth of scenarios of interest encountered throughout the United States.

- Chapter 5—A field-test protocol for unpainted weathering steel highway bridges was determined, piloted, implemented on at least three bridges per cluster, and refined. This process provided data for a quantitative update to the UWS TA (FHWA 1989). Because this process was refined throughout the research, the field evaluations in phase 2 were slightly different in some cases than in phase 3, as greater knowledge of the most important data to collect was developed. Specific instances where this occurred and affected the data presented are noted where relevant in later chapters.

- Chapter 6—A desk study of owner inspection reports for selected UWS bridges within each cluster was performed. This study typically involved the evaluation of 10–20 bridges within each cluster, allowing for a more thorough evaluation of the range of UWS performance that existed than was possible to determine based on the scope of the field work.

- Chapter 7—Data on owners' practices with respect to general maintenance practices, bridge-washing practices, and deicing agent use were collected and input into the UWS database. These factors are of interest because the corrosion mechanism of UWS is highly influenced by the presence of Cl^-. Thus, the quantities of Cl^--containing deicing agents applied in the structures' environments could have a direct correlation with UWS performance. Furthermore, maintenance practices aimed at removing or mitigating the presence of Cl^- could have a beneficial effect on UWS performance. Therefore, collecting data on these topics provided context for the observed UWS performance.

- Chapter 8—An analysis of the UWS database was performed to determine the most influential parameters affecting UWS performance from a statistical perspective. Two separate statistical models were created: one for highway overpasses, and one for coastal environments, based on the owners' input described in chapter 2. This analysis provided additional context and a mathematical basis for the interpretation of the field (chapter 5) and desk study (chapter 6) results.

- Chapter 9—Final recommendations for a quantitative update to the UWS TA were developed based on a synthesis of all the above tasks. These recommendations were largely based on the correlations between field performance and various site and environmental parameters that were revealed by the work described in chapter 5 and chapter 6, as further informed by the statistical analysis presented in chapter 8.

- Chapter 10—Conclusions of this research and recommendations for future work were developed.

CHAPTER 2. OWNER INFORMATION ON UNCOATED WEATHERING STEEL PERFORMANCE

SCOPE

LTBPP State coordinators (representing each State, District Columbia, and Puerto Rico, for a total of 52 representatives) provided data for the primary purpose of identifying UWS bridges that are generally exhibiting inferior overall performance for the purpose of selecting bridges for further evaluation. Overall performance was defined as performance physically distanced from problematic details, leaking expansion joints, etc. To better understand the context of the data received from this query, the research team requested information on the historical use and perceptions of UWS within each agency. Specifically, the researchers asked the following questions. Not all questions were applicable to any given agency, depending on their practices:

1. Does your agency have bridges using unpainted weathering steel in its inventory? If so, does your agency continue to construct bridges using unpainted weathering steel?
2. Briefly describe your general perception of the overall performance of unpainted weathering steel in highway bridges within your agency. By "overall performance," we are interested in performance away from problematic details such as leaking joints, details that trap moisture and debris, etc.
3. Identify which of your bridges using unpainted weathering steel are exhibiting the worst overall performance (approximately one to three bridges would be most helpful to us).
4. For the bridges identified in question 3, briefly elaborate on the condition of these bridges and the environment (i.e., climate, physical surroundings, exposure to deicing agents) in which they are located.
5. Briefly describe the reasons why your agency does not use unpainted weathering steel in highway bridges.

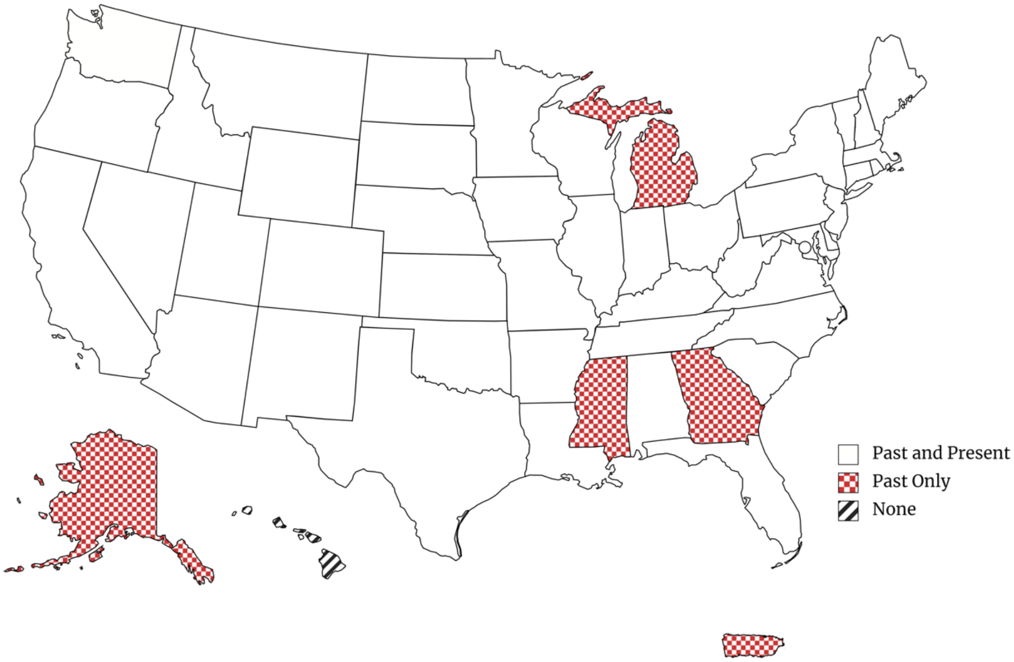
At the same time, the team requested a listing of the UWS bridges inventoried by each agency to assemble the national database of UWS bridges, described in chapter 3.

DATA RECEIVED

As a result of the cooperation of all State coordinators, the researchers obtained a 100-percent response rate from the agencies. However, not all respondents answered every question. Generally, these questions were left blank, and the sample size for that question decreased accordingly, unless other means were available to answer the question.

Use of Uncoated Weathering Steel in Bridges

Figure 1 summarizes the responses regarding the use of UWS in bridges (question 1 from the list), showing all agencies except for Hawaii have UWS bridges. The reasons cited for the lack of use of UWS in Hawaii's bridges were a combination of maintenance issues with steel structures in general and past performance issues of UWS in other applications in Hawaii. Five agencies indicated they have discontinued their use of UWS, with each providing one or more reasons, including poor performance ranging from isolated to local to widespread problems (Mississippi, Alaska, and Michigan, respectively); perceived maintenance requirements (Georgia); aesthetics (Mississippi); and availability (Puerto Rico).



Original map © 2023 MapChart. Modified by FHWA to show UWS use.

Figure 1. Map. Agencies' use of UWS (MapChart 2023).

The listings of UWS bridges provided by the owners revealed more than 10,000 UWS bridges are in the United States. This number represents 2 percent of the national highway bridge population. After a more detailed review of the data within each agency, the researchers found that value varies between 0 and 15 percent within State agencies.

Performance of Uncoated Weathering Steel Bridges

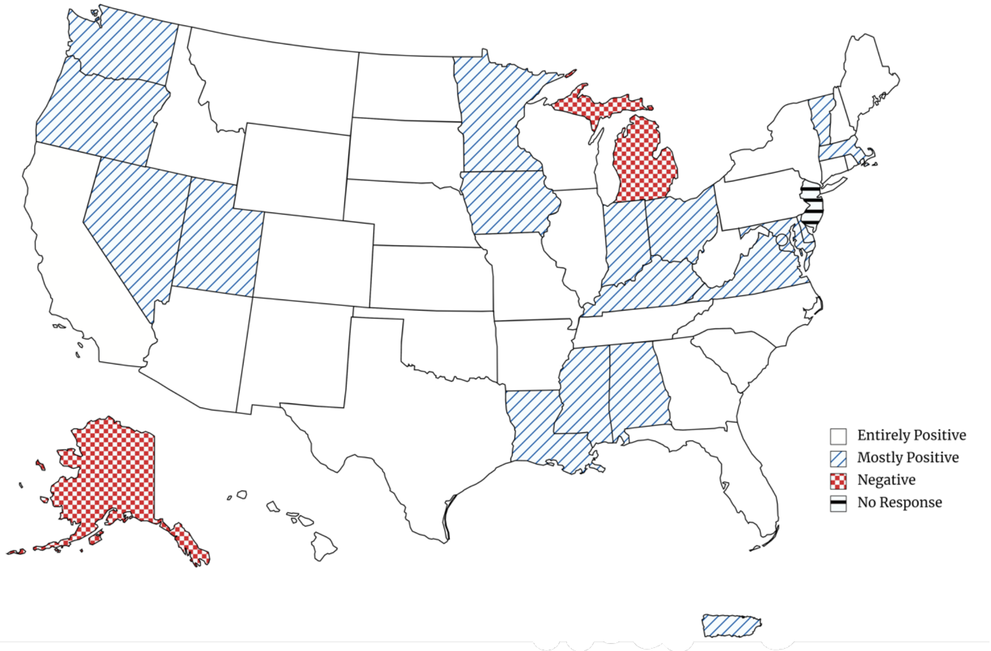
The data received from owners were used to assess the performance of UWS bridges qualitatively and quantitatively, as discussed in the following subsections.

Qualitative Performance

The free responses to the question inquiring about general perceptions of overall performance of UWS (question 2 from the list at the beginning of this chapter) were categorized into the following three clear categories that emerged as the results were reviewed:

- Entirely positive—No overall performance problems with UWS were indicated.
- Mostly positive—A generally positive perception of UWS performance was indicated, but some drawbacks were also mentioned.
- Negative—A response indicated a negative perception of UWS performance.

Based on these definitions, figure 2 shows the numerical and geographical analysis of the 50 responses to question 2. Agencies not reporting data for this question are shown with a horizontal striped pattern in figure 2. Subsequent figures will also represent a lack of data in this way.



Original map © 2023 MapChart. Modified by FHWA to show UWS perception.

Figure 2. Map. Owners' perception of the performance of UWS within their agency (MapChart 2023).

Figure 2 shows that 96 percent of the respondents had a positive perception of the performance of UWS, including 58 percent of the respondents who mentioned no problems with UWS performance. However, 38 percent of respondents reported some drawback to UWS performance, typically associated with various specific environments or situations. The two States with a negative perception of UWS were Michigan and Alaska. Michigan has a history of problems with UWS and thus a long-standing moratorium on UWS bridges such that no UWS bridges have been constructed since the guidance contained in the UWS TA was published (Culp and Tinklenberg 1980). Alaska has a total population of four older UWS bridges containing timber decks, which is now a discouraged practice.

Looking at the geographical distribution of the responses to question 2 regarding the perceived performance of UWS showed that UWS is perceived to perform best in the western half of the continental United States, with only Washington, Oregon, Nevada, and Utah expressing any reservations regarding the performance of UWS over this broad geographical region. Perceptions of the performance of UWS in the eastern half of the United States are more varied. While UWS generally has a good reputation in this area, the regions reporting concerns were the northern gulf coast, Mid-Atlantic, northern Midwest, and New England. The two agencies (Alaska and Michigan) expressing negative perceptions regarding the performance of UWS are located in northern climates.

Quantitative Performance

As a relatively simple means to assess the performance of this extensive inventory of UWS bridges, the research team compiled the NBI superstructure condition rating (SCR) of each structure. The SCR is an integer value from zero to nine that qualitatively describes the overall condition of girders, cross-frames, bearings, etc., with zero being the worst condition (failed) and nine being the best condition (excellent) (FHWA 1995). In this report, SCR is used as a simple indicator of performance (for reasons discussed in the remainder of this section). Chapter 8 contains equations that were developed to predict the SCR as a function of various influential parameters. The results of these equations are labeled SCR_P, for predicted SCR. All other mentions of SCR in this report reference SCR values from the NBI (FHWA 2022a).

The SCR rating takes several factors into consideration, including fatigue cracks and other visual signs of overstressed members, damage resulting from vehicular impacts, missing bolts in structural connections, and corrosion. From the review of numerous owner inspection reports of specific structures, the team observed that corrosion is the most common, but obviously not the only, cause of decreasing SCR. Thus, when reviewing these ratings for an extensive sample size of UWS bridges, the researchers hypothesized that these ratings would give a general quantitative indication of UWS performance in various scenarios.

To more rigorously evaluate the hypothesis that SCR can be used to assess general UWS performance, the research team organized the data in table 1 based on the qualitative performance described by each agency's responses to question 2 (from the list at the beginning of chapter 2, which asked owners to comment on the performance of UWS within their agency). For example, the agencies that had an entirely positive perception of UWS performance were collated, the UWS bridges within those agencies identified, and their respective SCR categorized and summed. For conciseness in managing the large volume of resulting information, the SCR were bracketed into the ranges shown in table 1.

Table 1. Summary of performance of national UWS bridge inventory.

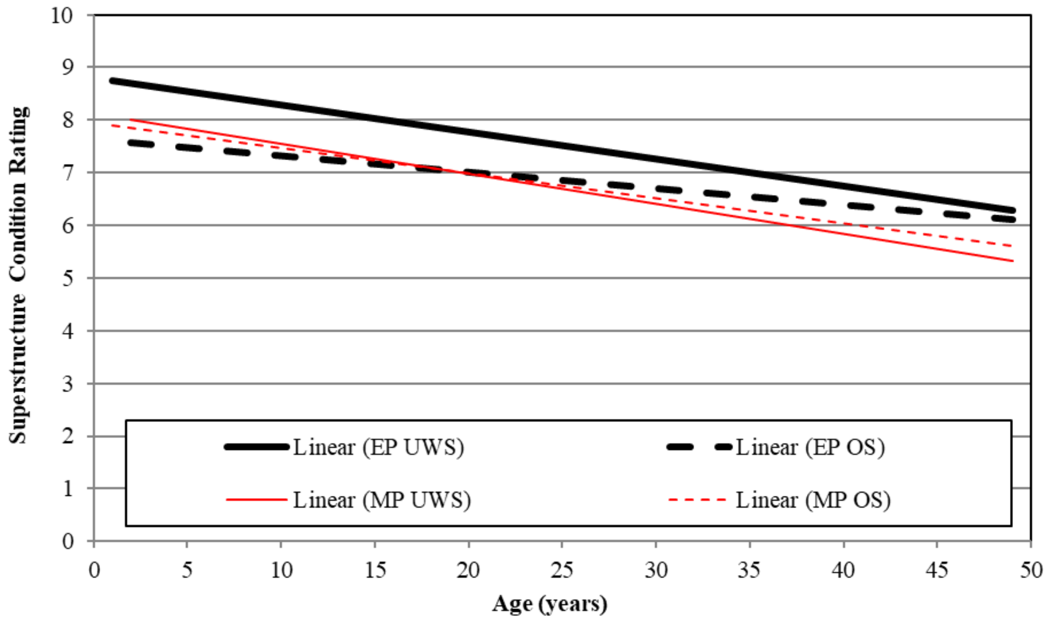
Qualitative Performance Description	SCR 0–3 (percent)	SCR 4–5 (percent)	SCR 6–7 (percent)	SCR 8–9 (percent)
Entirely positive	0	2	24	39
Mostly positive	0	2	17	11
Negative	0	1	4	1
Total	0	4	45	50

Note: Numbers have been rounded to the nearest integer.

The data in table 1 support that a relationship exists between SCR and the local owners' experiences with UWS. Specifically, table 1 shows that the majority of the UWS bridges within the agencies indicating entirely positive performance of UWS have an SCR of either 8 or 9; the majority of the bridges in agencies indicating mostly positive performance of UWS have an SCR of either 6 or 7; and in agencies with a negative perception of UWS performance, the majority of UWS bridges have an SCR of 6 or 7 with the remainder of the inventory in these agencies being more balanced between the other SCR categories (has lower SCR on average) than in other agencies. Comparing the data in the entirely positive, mostly positive, and negative categories shown in table 1, the team observed that the performance categories with higher percentages, and therefore more experience with UWS, are generally observing better UWS performance. However, this observation may be skewed due to potential differences in ages of the UWS population within each category.

The summary data for the total inventory in the last line of table 1 indicated that, on a national level, UWS bridges perform quite well, with 50 percent of the total inventory of UWS bridges having an SCR of either 8 or 9. Also, 45 percent of the UWS bridges have a rating of 6 or 7, 4 percent have a rating of 4 or 5, and 0 percent (rounded to the nearest integer; however, a small number exists) have a rating of 1 to 3. The very low SCR (values of 0 to 3) associated with these UWS bridges were not found to be a direct result of UWS or corrosion-related issues; instead, they were most commonly related to unarrested fatigue cracks in the sample of bridges for which detailed information was obtained.

Figure 3 provides a temporal analysis of the data in table 1 and compares the performance of UWS bridges to other steel (OS) bridges. Here, the SCR versus age for UWS bridges in two representative agencies was plotted relative to the OS bridges in these same agencies. OS bridges were identified based on the superstructure material type listed in the NBI and then removing the bridges previously identified as UWS from the larger population of steel bridges (FHWA 2022a). Age was calculated relative to 2013 (the latest available data at the time this analysis was performed) but otherwise calculated in the manner described in the Year Built and Year Reconstructed subsection in chapter 3.



Source: FHWA.

Figure 3. Graph. SCR versus age—UWS versus OS bridges.

To constrain the figure 3 data analysis to a feasible scope, agencies were first categorized based on the qualitative performance categories used in figure 2 and table 1. Then one agency from the entirely positive category and one agency from the mostly positive category were selected as representative agencies (New York and Virginia, respectively). Neither of the negative category agencies was evaluated, since neither of these agencies owned any UWS bridges that had been designed since the UWS TA was published in 1989 (FHWA 1989). The selections of representative agencies in the relevant categories were based on how closely the distribution of UWS SCR within the agency matched the averages for the agency's category in table 1 while also having a statistically significant number of UWS bridges over at least 20 yr old so long-term performance could be observed.

The linear curve fits to the data in figure 3 were based on data with a large amount of scatter (average regression coefficient of 0.25, where 1.00 represents a perfect data fit and 0.00 represents no correlation), which was expected, given the significant number of variables that factor into a single integer-valued SCR for any given structure. Also as expected, a trend of decreasing SCR with increasing age was observed. Thus, as a simple means to aid in data interpretation, these linear trend lines provide a simple means for comparing the given datasets. The team evaluated higher order equations, but they did not provide significantly improved fits to the data relative to their higher complexity.

In assessing the data in figure 3, the team first made a comparison between the trend lines and the qualitative performance categories to evaluate the validity of this approach. This comparison shows that the trend lines for the UWS datasets do correspond to the qualitative performance indicated by the owners of these bridges, with the trend line for the entirely positive UWS category being consistently above the trend line for the mostly positive UWS dataset. This comparison is also interesting relative to the fact that the OS datasets in these two agencies display similar trends in SCR versus age, but a more appreciable difference in UWS SCR versus age is present. The fact that the two OS datasets are more similar to one another than the two UWS datasets are similar to each other could be a result of differing design or maintenance practices, and a more thorough evaluation of this possibility in future work would be valuable. Climate differences may also possibly contribute to this difference based on the fact that the agency representing the entirely positive category is in an area that receives significantly more snowfall than the agency representing the mostly positive category, while other climatic variables are similar.

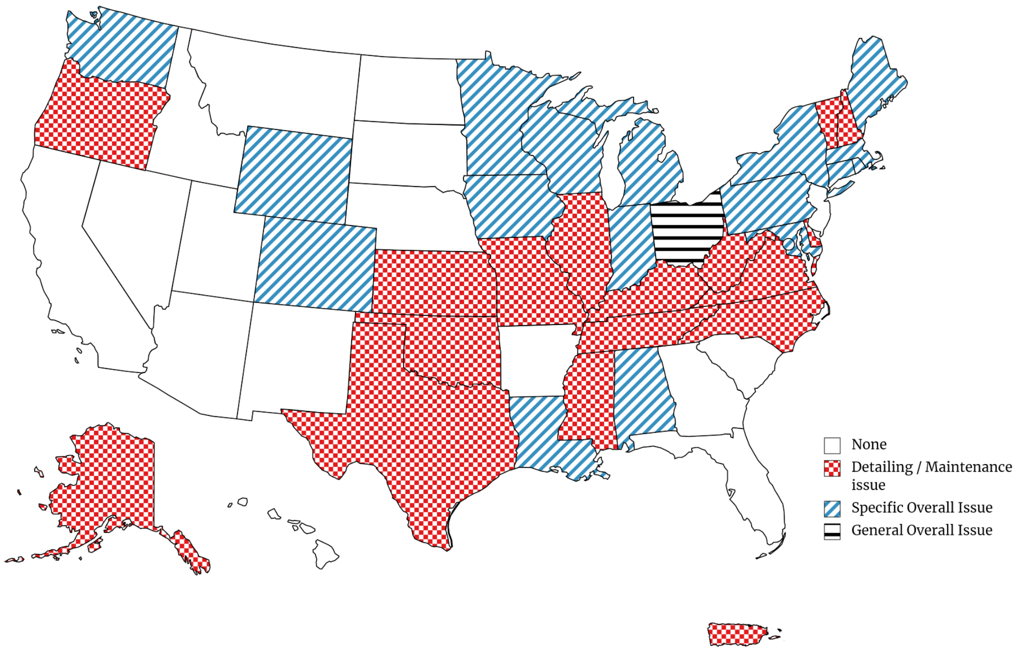
In comparing the performance of the UWS and OS datasets in figure 3, the team generally concluded that UWS bridges perform better or on par with OS bridges. Specifically, the team observed that in the entirely positive category, the performance trend of the UWS dataset is consistently superior to the performance trend of the OS dataset. This difference is most significant for younger bridges, although even UWS bridges designed before the UWS TA was published outperform their OS counterparts.

For the mostly positive performance category, the researchers also observed that the UWS bridges display good performance relative to their OS counterparts. For these two datasets, the trend lines are quite similar: the UWS trend line is slightly superior to the OS trend line for ages of 1–25 yr, and the OS dataset is slightly superior otherwise. However, this finding should be viewed in light of two facts. The first is that even though data are plotted here for ages of 1–49 yr, relatively few (only 9) UWS bridges older than 35 yr old are in the agency being represented here. Thus, data for these structures are not statistically significant in light of the total number of bridges considered in this figure. The second fact is that 25 yr (based on age relative to 2013, at the time this data analysis was performed) have passed since FHWA first published the UWS TA (FHWA 1989). Thus, design or maintenance practices implemented since that time could possibly change these trend lines, when calculated, as the newer bridges in this population age in the future.

Performance Concerns for Specific Uncoated Weathering Steel Bridges

The responses from requests to identify and describe bridges with overall performance issues (questions 3 and 4 from the list at the beginning of chapter 2) are summarized in figure 4. Here the responses were placed into four categories:

1. An answer directly expressing that the agency had no bridges with an overall performance issue with the UWS.
2. A listing of one or more bridges whose inferior performance reportedly stemmed from known problematic details, such as leaking joints, timber decks, etc. (i.e., a detailing and/or maintenance issue).
3. A description of one or more specific bridges with an overall performance issue related to UWS.
4. General information implying an overall performance issue without identifying any information on specific bridges and their environments.



Original map © 2023 MapChart. Modified by FHWA to show bridge performance.

Figure 4. Map. Type of issues affecting bridges with worst overall performance in each agency (MapChart 2023).

Responses relating to detailing and/or maintenance issues were somewhat unexpected, since a clear definition of "overall performance" was provided to focus responses to these questions accordingly. In at least some cases, the responses stated that these agencies simply had no bridges with inferior overall performance, and thus the next most relevant information was provided. However, the frequency with which such issues were reported makes clear that these issues are far from trivial.

Figure 4 shows that if the third and fourth categories (of those in the list at the beginning of chapter 2) are considered together as agencies reporting an overall performance issue, approximately one-third of the agencies falls into each of these three categories: no issues, detailing/maintenance-related issues, and overall performance issues. When the geographic distribution of the bridges in each of these three categories is considered, it is not surprising that there are similarities between the trends shown here and those shown in figure 2, which pertains to the general perception of the performance of UWS within each agency. Specifically, figure 4 reinforces that UWS bridges have no significant overall performance issues in the majority of the western United States and the southeast. The agencies reporting overall performance issues are generally located in northern climates in the eastern United States. This region also has the lowest perception of the performance of UWS, as shown in figure 2. Other agencies reporting overall performance issues are those along the northern gulf coast (which again is consistent with figure 2) and three States in the western half of the United States: Washington, Colorado, and Wyoming. Figure 4 also shows that several UWS bridges in the southeastern quadrant of the United States have specific corrosion problems; however, these problems are attributed to detailing or maintenance issues, which typically consist of failed joints.

The purpose of question 4 (from the list at the beginning of chapter 2) was to determine the condition and information that might inform the cause of said condition of the bridges identified as having inferior overall performance in question 3. Of the 18 agencies (figure 4) identifying UWS bridges with overall performance issues, the descriptions of the environment in which these structures are located were categorized by the number of times various keywords appeared. This analysis revealed that deicing agents were by far the most common issue affecting this group of bridges, with this issue being mentioned by 12 agencies. The only other recurring keyword was related to coastal locations of bridges, which was mentioned by five agencies. In three instances, the combined effects of coastal locations and deicing agents were mentioned.

It became clear after reviewing, organizing, and compiling the responses that three dominate categories are associated with performance concerns: deicing agents, coastal environments, and deicing agents combined with a coastal environment. Consequently, this research focused on the deicing agent and coastal environments initially and throughout the research (in phase 2) and the combined influence of deicing agents and coastal environments in phase 3. All other UWS bridges reported with overall performance issues are unique to various individual State agencies (Pennsylvania, Washington, and Wyoming) and were, therefore, deemed to be of lesser importance to achieving the overall objective of informing general design guidelines on a national basis.

CHAPTER 3. UNCOATED WEATHERING STEEL DATABASE

A key component of this study was creating a national database of UWS bridges. This step was necessary in order to associate various geographic and climate variables with each bridge site and to assess the correlations between these parameters and performance. Creating the national database of UWS bridges consisted of two main parts. The first part identified which bridges comprise UWS. Because this information is not tracked in a consistent manner, this step required the efforts described in the following section. The second main part compiled data for each identified UWS bridge. Three main types of data are described in the following sections: data available in the NBI, which is typically geometric and traffic-related site features; location-based data, which generally refers to the climate in which the bridge is located; and data on owners' practices, which is aggregated on a per-agency basis as described subsequently (FHWA 2022a).

NATIONAL INVENTORY OF UNCOATED WEATHERING STEEL BRIDGES

The first step in compiling the UWS database was simply identifying the bridges of interest. While the NBI is a thorough list of bridges in the United States, this database does not include a specific item that identifies a bridge as constructed of UWS (FHWA 2022a). Consequently, NBI records cannot be directly searched for UWS bridges. Instead, UWS bridges were identified by requesting that each LTBPP State coordinator provide a listing of all known UWS bridges in the agency's inventory. The agencies were asked to provide the structure/bridge identification number of each UWS bridge in their inventory, and most also provided additional details about the bridges, which aided in data verification.

The team received inventories from 50 agencies (representing 48 States, Puerto Rico, and District of Columbia). Multiple agencies conveyed that the first-hand knowledge of inspectors in district agencies was used to compile the list of their UWS bridges. Alternatively, one agency conveyed that they record paint type, so the combination of no paint type and steel was inferred to be a UWS bridge. The data are thus potentially vulnerable to some inaccuracies or omissions as a result. While no method was available to perform a comprehensive quality control review of the accuracy of the data, all bridges were checked for reasonableness of the latitude and longitude (as further explained subsequently) as this parameter was key for associating the bridges with environmental and weather-related data. Hundreds of bridges were also spot checked for data accuracy. This check revealed some of the State inventories that were received contained bridges that were ultimately found to be painted steel and bridges that were built before UWS bridges were introduced in 1964 (Albrecht and Naeemi 1984). While such data quality issues exist, they are believed to be relatively infrequent relative to the nearly 10,000 UWS bridges identified through this process.

NATIONAL BRIDGE INVENTORY DATA

The NBI provides information (physical attributes, location, etc.) on all State and Federal bridges in the United States and was used to gather data for the UWS database (FHWA 2022a). Details on each of the items of interest in the NBI are provided subsequently. These are a subset (from over 100 items in the NBI) that are most likely to affect overall UWS bridge performance based on the current understanding of UWS performance. Note, however, the full NBI records for each bridge are included in the database.

The items that require further explanation to fully comprehend the data presented elsewhere in this report are described in the following subsections. In summary, these items are record type (which indicates whether the route on or under the bridge is being described), latitude, longitude, year built and reconstructed, average daily traffic (ADT), average daily truck traffic (ADTT), service under the bridge, vertical underclearance, navigational vertical clearance, minimum lateral underclearances on right and left, and SCR. These items and their relevance to UWS performance are explained in the following subsections in the order that they appear in the NBI records. The item numbers that appear in parentheses after each heading refer to the NBI item numbers using the official *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, hereafter abbreviated as the NBI coding guide in the discussion that follows (FHWA 1995). In some cases, some synthesis of the raw NBI data was necessary in order to efficiently report and consider these items of interest, as subsequently described. All NBI data reported herein were based on the 2019 NBI records, the most currently available reporting year when the database was finalized.

Record Type (Item 5A)

Each bridge in the NBI has an identification number, and all the NBI data associated with that bridge are known as the "NBI record(s)" for that particular bridge (FHWA 2022a). All bridges have at least one record that contains the majority of the information about the bridge and the route that the bridge carries. One or more additional records may be included for a structure corresponding to one or more routes the bridge may cross. Item 5A=1 indicates the primary record containing the details of the structure and the route carried by the structure. Additional records describe the routes going under the structure and are referred to as secondary records or underrecords. Item 5A=2 specifies a single route going under the structure, and information about this route is contained in this record. Additional routes being crossed by the structure are labeled with alphabetic characters beginning with "A" and continuing through "Z" as needed. Only information that is relevant to the inventory route is contained in the secondary records (FHWA 1995).

Item 5A was used to determine whether the NBI record was the primary record or a secondary record for the UWS database. The majority of the needed information was contained in the primary records, but (as will be detailed in the ADT and ADTT Under the Structure subsections) the secondary records also contained critical ADT information used in the UWS database.

Latitude and Longitude (Items 16 and 17)

The latitude and longitude from items 16 and 17 give the geographic coordinates of the bridge location in degrees, minutes, and seconds and were used in geographic information system (GIS) software to accurately map the bridges and ultimately associate them with the geography-dependent variables (e.g., climate data as discussed in the Location-Based Data subsection). The latitude and longitude values from the NBI records were converted to decimal degrees and plotted in GIS using World Geodetic System 84 (NGA Office of Geomatics 2023) as the reference coordinate system. The bridge coordinates reference the beginning of the bridge in the direction of the route or another location that is comparable with each agency’s linear referencing system (see FHWA 1995).

Occasionally, a bridge had latitude and longitude values that did not coincide with the actual bridge location. These errors were detected by plotting the bridge latitude and longitude on Google® Earth™; plotting could also be performed using GIS, but Google Earth was adopted for this purpose at the early stages of this research. The researchers used two different methods to find coordinate discrepancies. First, if the bridges of a specific agency were not located within the State boundaries, the team concluded that the bridge latitude and longitude coordinates for the bridge were incorrect. The second method used the “features intersected” and “facility carried” entries from the NBI records; if these entries did not coincide with what the bridge was carrying and intersecting on Google Earth, the team concluded that the latitude and longitude values were incorrect. Values that were found to be in error were manually changed using http://itouchmap.com/latlong.html to correct the inconsistencies (Apple® 2022). This website was used to obtain the latitude and longitude based on the intersection of the route carried and feature intersected. This website was used rarely, except for the data from one agency for which a significant number of inconsistences were found.

Year Built and Year Reconstructed (Items 27 and 106)

Age is an important consideration for all UWS bridges since there is a direct relationship between age and structural deterioration. Because the age of interest is the age of the UWS components rather than the age of the structure as a whole, the team considered the year built (item 27) and year reconstructed (item 106) entries in the NBI (FHWA 2022a). Since knowing whether the UWS components of these structures were built during the initial construction or the reconstruction is not possible, an assumption must be made. Therefore, the more recent of these two dates was used in statistical analyses of the resulting UWS database. This action is both conservative (i.e., it would overestimate the decrease in superstructure rating that occurs over time, if this assumption is incorrect, and the reconstruction refers to more minor upgrades such as deck replacement) and most consistent with actual practice, i.e., girders are often replaced during a reconstruction. The researchers then calculated the age of the structure relative to 2019 (the year of the NBI data used) for the purposes of the final analysis of the UWS database (age for phases 1 and 2 was calculated relative to 2013 as this study was completed before 2019; in other instances where 2013 is the reference age, these instances are specifically noted). Often, when specific bridges of interest were identified, the team determined the exact age of the UWS components through additional correspondence with the owners in these cases, but obtaining this information was not feasible for every structure in the UWS database.

After compiling the database, the team observed that a small number of bridges were included with year built and year reconstructed (where applicable) values before the date when UWS is first known to have been used in highway bridges (i.e., 1964) (Albrecht and Naeemi 1984). The UWS used during the 1940s and 1950s contained a steel that was alloyed with different amounts of copper, phosphorus, chromium, nickel, and Si than the 1964 UWS. Thus, its patina formation properties were different than “modern” UWS (Mathay 1993). Consequently, bridges constructed or reconstructed before 1964 were excluded from all subsequent data analyses but were retained in the overall database for future reference.

Average Daily Traffic and Average Daily Truck Traffic Under the Structure (Items 5A, 29, and 109)

The ADT and ADTT underneath the structure was a primary parameter of interest for evaluating the effects of deicing agents because salt spray from the cars and trucks traveling under the bridges can collect on the girders, adding a corrosive solution to the superstructure. In the NBI, the ADT underneath the structure is expressed via the secondary record types identified with a "2" or "A" through "Z" alphabetic character in item 5A, each representing the ADT on a specific route under the structure (FHWA 2022a). To aggregate the multiple ADT values into a single value to facilitate data analysis, the researchers summed these ADT values in item 29 for these record types. Hence, this sum represents the volume of traffic on the inventory routes under the structure. This quantity was selected based on the rationale that whether there was a high volume of traffic on a single route under the structure or a large sum of traffic on multiple routes under the structure, both could increase the percentage of steel in the advanced condition states. This ADT sum was used as a metric to compare to UWS performance, as further explained in chapter 6. ADTT under the bridge was obtained by multiplying the percentage of truck traffic (item 109) by the ADT under the bridge. Occasionally, the data for a bridge crossing a highway, according to item 42B described in the following subsection, did not include an ADT beneath the structure. In this situation, the ADT and ADTT were left blank.

Service Under the Bridge (Item 42B)

The type of service under the structure was used to classify the crossing under the bridge. This information is of interest because a highway crossing may experience salt-spray from traffic beneath the structure, and waterway crossings in marine environments are more susceptible to Cl^- exposure. Item 42B indicates the following service types, individually and in combination: highway, waterway, railroad, pedestrian, bicycle, relief for waterway, and other (FHWA 1995).

Vertical Underclearance and Navigational Vertical Clearance (Items 54B and 39)

The vertical underclearance is of interest for bridges crossing over roadways treated with deicing agents because lower clearances increase the potential for deicing agents to be transferred to the structural elements of the bridge. Alternatively, bridges with low crossings over bodies of water are vulnerable to extended periods of wetness due to flooding or condensation of water vapor. Coastal bridges' exposures to atmospheric Cl^-, which lead to corrosive settings, are also likely to increase as vertical clearance over water decreases. Thus, the clearance over roadways and bodies of water is a relevant variable affecting UWS performance.

Highway and railroad vertical underclearance values in item 54B are expressed in hundredths of a meter but are herein converted to feet for the purposes of consistently providing English units throughout this report. According to the NBI coding guide, the vertical underclearance is measured from the travel lanes on a roadway or the tracks on a railroad, to the superstructure's underside (FHWA 1995). If the underclearance is greater than 100 ft, then a value of 99.99 can be entered by the inspector. The lowest, most critical value is recorded. If the crossing type is not a highway or railroad, then a value of 0 is recorded (FHWA 1995). This value of 0 is the common entry for bridges over waterways.

Item 39 is used to report vertical underclearance for bridges that cross waterways. Specifically, this item refers to vertical navigational clearances over waterways. According to the NBI coding guide, the minimum clearance in item 39 is to be measured above a datum ("that is specified on a navigational permit issued by a control agency") and, like vertical underclearance, reported to the nearest hundredth of a meter, but converted to feet herein (FHWA 1995). On reviewing the NBI records, the researchers observed that neither a vertical underclearance nor a navigational vertical clearance was provided for the majority of bridges that crossed waterways. Inquiries with selected State coordinators to attempt to determine other possible means for determining this data led to the conclusion that this information cannot be determined from existing records within these representative agencies. Therefore, the vertical clearance over nonnavigable bodies of water cannot be determined for most bridges.

Minimum Lateral Underclearance on Right and Left (Items 55 and 56)

The minimum lateral underclearances are of interest as they may contribute to the so-called tunnel effect, defined by FHWA (1989) as a "combination of narrow depressed roadway sections between vertical retaining walls, narrow shoulders, minimum vertical clearances, and deep abutments adjacent to the shoulders." The above-mentioned conditions prevent the air currents from dissipating the "salt spray" generated by deicing salts on underpasses, which was discussed in the previous subsection. The smaller the lateral underclearance, the greater the corrosive effect of the salt-spray and chemical concentrations is likely to be on the structural members.

According to the NBI coding guide, the minimum lateral underclearance to the right and left is measured from the centerline of the respective right/left side track of a railroad and the respective right/left edge of the roadway (excluding the shoulder) for highways to the nearest substructure unit, rigid barrier, or toe of slope (FHWA 1995). The clearance should be measured (to the nearest tenth of a meter) from the right/left edge of the through roadway since ramps and accelerating or turning lanes are not considered. If a railroad and highway are beneath the structure, the lessor of the two measurements is recorded. If the underclearance is greater than 100 ft, then a value of 99.9 is noted. A value of 0, indicating not applicable, is recorded if the crossing is other than a highway or railroad (FHWA 1995). These items are referred to as "right lateral underclearance" and "left lateral underclearance" for brevity herein.

Superstructure Condition Rating (Item 59)

The SCR is an integer value from 1 to 9 (or the letter "N" for culverts) that is meant to describe the overall physical condition of the superstructure members (girders, cross-frames, bearings, paint, joints, etc. as applicable for each structure) (FHWA 1995). The value is influenced by multiple bridge characteristics, including visual signs of overstressed members such as plastic deformations or fatigue cracks, damage resulting from vehicular impacts, missing bolts in structural connections, and corrosion. Corrosion is of most interest to this study, but obviously is not the only cause for a low superstructure rating. Thus, these ratings can provide general information on possible UWS performance; however, it should be noted that on review of detailed data from several agencies, the researchers observed that corrosion is by far the most common factor affecting the SCR. However, very low SCR (values of 1–3) associated with some UWS bridges are not a result of UWS or corrosion-related issues, but some other form of deterioration or distress.

LOCATION-BASED DATA

The UWS database includes three types of location data: climate (e.g., weather), atmospheric chemical concentration, and distance to the coast (categorized as geographic data). These data were compiled from existing sources, and then GIS software was used to connect the relevant values of each of these datasets to a value for each bridge in the UWS database. The specifics of this data and the GIS methodology are discussed in the following subsections.

Climate Data

The climatic data comprise:

- Snowfall.
- Humidity.
- Time of wetness (TOW).
- Temperature.
- Fog.
- Precipitation.
- Wind.

In some cases, multiple metrics exist for a given category of data. For example, the temperature data consist of information such as average number of days below freezing temperature, average daily mean temperature, and average daily maximum temperature.

The majority of the climate data (snowfall, humidity, temperature, fog, precipitation, and wind) was obtained from the Climate Atlas of the United States (CAUS) (National Oceanic and Atmospheric Administration (NOAA) 2002). This source documents these data at numerous stations throughout the United States and provides the latitudes and longitudes of these weather stations. These location data were used in GIS to associate the various snowfall, temperature, fog, precipitation, and wind values to each bridge based on its location data. These data generally consist of 30-yr averages of average monthly and annual data. A similar process was used to associate TOW data to specific bridges. In addition to the CAUS, other datasets that were considered are described in the following subsections. This consideration does not include the MERRA2 data used in the InfoBridge™ database, as this project began before such data were added to InfoBridge (FHWA 2022b).

Humidity

Two datasets are available for relative humidity. One of these is the NOAA humidity dataset, in which the relative humidity is reported as an average percentage in the morning and afternoon for monthly and annually (NOAA 2008). The locations of the 265 stations in this dataset are dispersed unevenly, with more stations along the west and east coastal States and fewer stations in the central United States. The other dataset is contained in the CAUS (NOAA 2002). In this dataset, the average relative humidity is given as a value within a range (typically of 10-percent relative humidity) corresponding to an alphabetical category label for each station monthly and annually. For instance, if the average relative humidity over a particular month at a particular station is 70 percent, then it would fall within category G, which indicates an average relative humidity between 66 and 75 percent. In this quantification system, "A" represents the lowest humidity, and increasing levels of humidity are indicated by categories "B," then "C," etc.

An important advantage of this latter dataset is that it is synthesized to create GIS contours that connect the latitudes and longitudes of stations with relative humidity values that fall within a specified range. Those stations are connected by vectors creating polygons, or "contours," which distinguish the small pockets of high humidity from the larger contours of lower humidity. Therefore, there is a high probability that the humidity information that could be associated with the bridges would accurately depict the bridge's climate, although expressed as a range rather than a specific value. In contrast, the NOAA data do not contain contours, and thus judgment would be required by the research team to determine how to best associate a specific bridge with the station data (e.g., choose closest station or interpolate between multiple stations with various geographical relationships to the point of interest). Since this step has already been done by climate experts in the CAUS dataset, this dataset was ultimately used to classify the humidity at specific bridges.

To combat the fact that the relative humidity is bracketed over a range in the selected dataset, the monthly data were used to describe the humidity at each bridge. For example, a bridge site may be described as being in category H in January, category G in February and March, and category F for the remaining 9 mo of the year. The months in each category were counted and concatenated to create humidity labels such as "9F, 2G, 1H" for the example scenario.

In later data analysis (described in the following subsection), this information was represented by a relative "humidity score." To create this score, the minimum and maximum humidity values for any bridge in the UWS database were first recorded, where the minimum was found to be 2 mo in B, 2 mo in C, 5 mo in D, and 3 mo in E, while the maximum value was found to be 12 mo in I. Each alphabetical category was then assigned a numerical weight. Because the lowest value of monthly humidity recorded was B and the highest was I, a numeric scale of 1–8 (B=1, C=2, … I=8) was used. This scale was intended to weight the intensity of monthly humidity numerically. Then a single humidity value was assigned to each bridge by multiplying the number of months in each category by the weighted value associated to that letter and summing each of these totals. For example, the bridge with the minimum humidity has a humidity value of 33 on this scale; the humidity value of 2B, 2C, 5D, and 3E is numerically equated to $2\times1+2\times2+5\times3+3\times4=33$. Similarly, the maximum value of 12 mo in I has a value of $12\times8=96$. The final step was to normalize these values on a 0 to 1 scale for convenience. With a maximum value of 96, and a minimum of 33, the "humidity score" of any bridge is expressed by the ratio of (weighted_value–33) to (96–33). Thus, greater humidity scores indicate more severe environments. Furthermore, even though precise values for humidity are not given in this dataset, by including the monthly data, humidity typically varies throughout the geographic area represented by a bridge cluster.

Time of Wetness

The TOW data, reported in hours per year, was compiled by Chase from a variety of different sources.[1] Chase analyzed and documented the results for 1,020 stations throughout the United States. However, the team observed that within specific localized regions of interest (i.e., the clusters that will be discussed in chapter 4), the TOW data sometimes had little variation, making it difficult to apply for the purpose of classifying differences within a population. Consequently, TOW was considered a secondary variable in this study.

Atmospheric Chemical Concentration Data

Chemical concentration data include atmospheric concentrations of:

- Chloride (Cl^-).
- Nitrate (NO_3^-).
- Sulfate (SO_4^{-2}).

Hereafter in this report, elements and compounds are referenced by the standard chemical symbols noted parenthetically in the above list.

Yearly datasets for Cl^-, NO_3^-, and SO_4^{-2} concentrations (converted to parts per million (ppm) for the purposes of consistently providing English units throughout this report) are available online from the National Atmospheric Deposition Program through the National Trends Network (NADP 2019). There are 199 monitoring sites, located throughout the United States, that measure these chemical concentrations. The stations' latitudes and longitudes are documented, and these locations were used to associate chemical concentration values to each bridge based on its location data using GIS.

Geographic Data

The remaining location-based data were generally classified as "geographic data" and are the distance-to-the-coast data. Two "digital vector shoreline" datasets are available from NOAA's Office of Coast Survey (OCS) shorelines: the Extracted Vector Shoreline (EVS) and the Electronic Navigational Charts (ENC®) (NOAA 2012a, 2012b). Both of these shoreline datasets were evaluated as a means for defining the coastline in the GIS analysis such that distance to the coast from each relevant bridge could be determined.

EVS represents the shoreline by outlining the "land plate" and excluding the "marsh areas." While no clear definition of land versus marsh could be obtained from the source, it states that the data are not "tidally referenced." Other details on the methodology used to create this dataset are also available from NOAA OCS. Note that the EVS is not maintained and does not represent the most current nautical charts (NOAA 2012a).

The ENC shoreline was created from charted information and original "source" information. According to NOAA (2012b), "The ENC shoreline is collected for navigational waters and

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[1] Personal communication with S. Chase, research professor, University of Virginia, 2012.

accurately depicts the tidally influenced shoreline including waterways and tidal creeks." It also includes other information relevant to navigation, such as obstructions and channel limits.

Ultimately, the research team chose the ENC data since the data are maintained and updated regularly, whereas the EVS data are not maintained or representative of the current nautical charts. NOAA OSC also stated that ENC is the "newest and most powerful electronic charting product" (NOAA 2012b). Further details on the difference between the two datasets and the justification for choosing ENC over EVS can be found in Kaur (2014).

Geographic Information System Methods

Associating all the location-based data types reviewed in the preceding subsections with each bridge in the UWS database required several steps that are detailed in Kaur (2014). This subsection highlights the use of several GIS tools that were used to associate the various data types with specific bridges and to create the bridge clusters (i.e., groups of bridges subjected to more thorough analysis, as introduced in chapter 1 and further explained in chapter 4).

The "match option" determined the condition used to match chemical concentration and climate data to each bridge location. When the chemical concentration and climate data existed at discrete points (e.g., weather stations), the "closest" option was used to match the closest chemical or weather station to each bridge site as well as associate the chemical and weather data to each bridge site. For climate data that consisted of polygons (i.e., the humidity dataset utilized), the "intersect" option matched the contour data overlapping with each bridge site to the respective bridge site (Esri® 2012). The "near" tool was used for coastal bridges to determine their distances to the coastline.

The buffer tool was generally used to create a specified radius (50 mi, generally) around reference bridges (see chapter 4) to create bridge clusters. The radius distance was specified in the "buffer distance" field. A circle of the identified radius then circumscribed the reference bridge, and the bridges within the radius were then identified and extracted by using the circle from the "select by shape" function. All the records within the specified radius were then highlighted in the attributes table (a table with information about the features that were joined or related through the various GIS tools) (ESRI 2012). These records were then copied to a spreadsheet, where the data were further organized. An additional method that was useful for selecting bridges was selecting all the bridges within a State boundary when an agency of interest motivated the cluster selection rather than a specific reference bridge of interest. To do this, all the bridges within the State boundary were selected on the attribute table and exported to a spreadsheet.

OWNERS' PRACTICES

The researchers sought information on typical maintenance practices and deicing agent use from each LTBPP State coordinator. This exercise and the resulting data are described in chapter 7. Specifically, the chapter 7 section, Input Data for the UWS Database, describes the types of maintenance and deicing agent information that was included in the UWS database.

CHAPTER 4. SELECTION OF BRIDGES FOR STUDY

After the UWS database was compiled and organized (as described in chapter 3), it was used to aid in selecting appropriate bridges for further evaluation, as described in this chapter. This process was also largely based on the information received from the LTBPP State coordinators that was reviewed in chapter 2.

METHODOLOGY OVERVIEW

The process of selecting bridges for further study began with identifying general locations of interest. These locations are termed “clusters,” which are further described in the Clusters subsection. Bridges in these locations were then sorted into different types with respect to the level of analysis to which the bridges would be subjected. These bridge types are described in the Bridge Types subsection. The final subsection to this section then describes the process of sorting bridges into these categories.

Clusters

The overarching organization of the bridge selections was based on forming bridge clusters. Clusters are simply groups of bridges within geographic proximity to one another, which is typically defined by a 50-mi radius. The scope of work of this phase of research was to evaluate 11 bridge clusters (4 in phase 2 and 7 in phase 3). Each cluster was intended to have 10—20 bridges, but some clusters have more.

The research team established two different categories for the clusters, as described by table 2. One category was related to climate, and the other was related to bridge condition. The climate-related categories focused on the two environments of most widespread concern based on the owner information discussed in chapter 2: highway overpasses over roadways heavily treated with deicing agents and bridges in coastal environments. The intersection of these two effects for bridges along the northern coastlines was also evaluated.

Table 2. Overview of cluster locations and categories.

Condition	Deicing	Coastal	Deicing+Coastal
Inferior	1. Maryland+ Virginia	7. Louisiana+ Mississippi	10. Connecticut
Inferior	2. Minnesota	8. North Carolina	—
Inferior	3. Iowa	—	—
Good	4. New York	9. Texas	11. New Hampshire
Good	5. Colorado	8. North Carolina	—
Good	6. Ohio	—	—

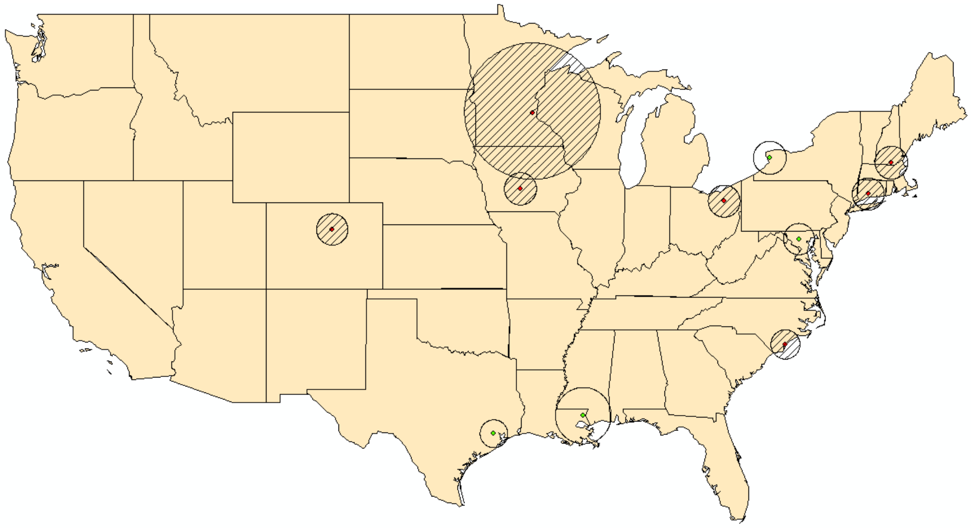
—No additional bridges in this category.

Two condition-related categories were examined: “inferior” and “good” performing. The inferior category attempted to capture the most extreme performance situations of the worst performing bridges. The good performing category attempted to capture not only good performing bridges, but bridges that were performing well despite being located in a harsh environment at an advanced age. Specifically, the good clusters were identified via filtering the UWS inventory for bridges with high age and SCR while also being in environments with high ADT and snowfall.

The inferior performing reference bridges were identified by the information received from owners that was described in chapter 2. This longer list of bridges with performance concerns was filtered to focus on bridges that were highway overpasses and locations that appeared to have the worst UWS performance based on the data available for review. General considerations for all cluster selections also included the presence of a significant number of UWS bridges in the local region (ideally within a 50-mi radius), agencies that collected element-level inspection data (as further described in chapter 6), the presence of some of the clusters used in this study that overlapped with the clusters being used in the larger LTBPP program, and geographic diversity to the extent possible.

Note that table 2 shows two States simultaneously for some cases. In these cases, the first State listed is the location of the reference bridge. The second State listed is within the 50-mi radius of that reference bridge, and some bridges in the cluster are located in this State. Table 2 also contains one duplicate entry, listing North Carolina as both an inferior and good performing coastal cluster. This circumstance is because, after the team evaluated the other coastal clusters in phase 2, only North Carolina had more than 10 bridges within 50 mi of the coast that were at least 20 yr old. Also, some bridges along the coast in North Carolina performed significantly better, and others in the same general location performed significantly worse, than the remainder of the coastal bridge population (as quantified by SCR relative to age). Therefore, North Carolina is appropriately considered as both an inferior and good performing cluster.

Figure 5 maps the location of the center of all clusters and shows the radius used for each cluster. These radii are generally 50 mi but were increased where necessary to provide a large enough population of bridges to study and/or to provide more variation in environments within a cluster. Hatched circles represent the seven phase 3 clusters, and open circles represent the four phase 2 clusters.



Original map © 2023 MapChart. Modified by FHWA to show cluster locations.

Figure 5. Map. Cluster locations (MapChart 2023).

Bridge Types

The research team considered four different classifications of bridges in this study. In decreasing order of the level of detail in which these four types of bridges are evaluated, they are as follows:

- Reference bridges.
- Field bridges.
- Cluster bridges.
- Proximate bridges.

These types are described as follows:

- Reference bridges are those with the most detailed field evaluation because they are of greatest interest due to having exceptionally good or inferior performance relative to their environment. These bridges also typically form the geographic center of a cluster. Reference bridges are also evaluated based on inspection reports. Reference bridges are a subset of the field bridges.

- Field bridges are other bridges subjected to field evaluation. In phase 2, the reference bridge for each cluster was sampled at a larger number of locations relative to the other field bridges. In phase 3, the field sample locations were optimized, and the reference bridges and other field bridges were sampled in the same manner and to the same extent as described in chapter 5. Field bridges were also evaluated based on inspection reports. Field bridges are a subset of the cluster bridges.

- Cluster bridges are those that are evaluated based only on inspection reports. Cluster bridges are a subset of the proximate bridges.

- Proximate bridges are other bridges located within a specific distance of the other bridge types that have an age within a defined range of interest. Proximate bridges are only defined by the information compiled in the UWS database.

Bridge Selection Process

In the majority of cases, the sequence of selecting bridges for each of the four bridge types was as follows. The reference bridges were typically the known starting point and are identified based on information from bridge owners and/or statistical evaluation of data in the UWS database. Then proximate bridges were identified using GIS, using distance from the reference bridge as the selection criteria. Next, cluster bridges were selected as a subset of the proximate bridges based on a rigorous statistical process described in a subsequent subsection. Once the cluster bridges were identified, inspection reports for each of these structures were requested from their owners, and the UWS condition of each of these structures was reviewed. The statistical classification of the influential parameters of the bridges in the cluster were reviewed and used as the basis for selecting the field bridges.

In other cases, a specific reference bridge was not identified at the outset. Instead, a particular geographic region of interest was first identified, and then the proximate bridges were identified, followed by the cluster, field, and reference bridges. Additional details on the bridge selection process are in the following subsections, listed in the typical sequence of the selections.

Reference Bridges

The selection of reference bridges was based on either a bridge identified by owners as one exhibiting poor UWS performance relative to other UWS bridges within the same agency, by filtering parameters of interest from the UWS database to identify bridges with extremely good or inferior performance relative to their environment, or by using some combination of the prior two methods to identify potential candidates for which inspection reports were requested and then used as the primary basis for the selection.

Proximate Bridges

Proximate bridges were identified by selecting the coordinates of the reference bridge as the center of a circle of a prescribed radius (typically 50 mi, but 100 mi was used in the poor performing coastal cluster to encompass more bridges and more severe environments) in GIS. GIS was then used to identify all the bridges within the circle thus circumscribed. This list was then filtered to remove bridges that were built (or reconstructed) before 1964 or were less than 20 yr old.

Cluster Bridges

The two subsequent subsections describe sorting the proximate bridges into categories and using these categories to select cluster bridges.

Categorization of Cluster Bridges

The rationale for choosing the cluster bridges from the larger population of proximate bridges falling within the specified distance of the reference bridge was based on a statistical analysis of selected parameters for each bridge within a given cluster. The main ideas of this process were to enable varying only one parameter at a time within the dataset, while also having redundancy in the data.

This process began with identifying the parameters of greatest interest, which are those hypothesized as having the greatest effect on UWS performance based on prior experience and research. Table 3 identifies these parameters for the coastal clusters to be the two variables of distance to the coast and humidity. Atmospheric Cl^- concentration was also considered for the coastal clusters, but within the geographic bounds of a given cluster, this effect was more readily captured by distance from the coast. Table 4 identifies the parameters of greatest interest for the deicing clusters to be the five variables of ADT under the structure, vertical underclearance, average annual snowfall, humidity, and atmospheric Cl^- concentration. Table 4 also emphasizes that highway crossings were the focus of these clusters, but railroad and/or waterway crossings were sometimes included when these bridges were of particular interest.

Table 3. Parametric combinations for coastal clusters.

Combination	Distance to Coast	Humidity
1	Low	High
2	Low	Low
3	High	High
4	High	Low

Table 4. Parametric combinations for deicing clusters.

Combination	Crossing	ADT of Crossing	Vertical Under-Clearance	Humidity	Annual Snowfall	Atmospheric Cl^-
1	Highway	High	Low	High	High	High
2	Highway	High	Low	High	High	Low
3	Highway	High	Low	High	Low	High
4	Highway	High	Low	High	Low	Low
5	Highway	High	Low	Low	High	High
6	Highway	High	Low	Low	High	Low
7	Highway	High	Low	Low	Low	High
8	Highway	High	Low	Low	Low	Low
9	Highway	High	High	High	High	High
10	Highway	High	High	High	High	Low
11	Highway	High	High	High	Low	High
12	Highway	High	High	High	Low	Low
13	Highway	High	High	Low	High	High
14	Highway	High	High	Low	High	Low
15	Highway	High	High	Low	Low	High
16	Highway	High	High	Low	Low	Low
17	Highway	Low	Low	High	High	High
18	Highway	Low	Low	High	High	Low
19	Highway	Low	Low	High	Low	High
20	Highway	Low	Low	High	Low	Low
21	Highway	Low	Low	Low	High	High
22	Highway	Low	Low	Low	High	Low
23	Highway	Low	Low	Low	Low	High
24	Highway	Low	Low	Low	Low	Low
25	Highway	Low	High	High	High	High
26	Highway	Low	High	High	High	Low
27	Highway	Low	High	High	Low	High
28	Highway	Low	High	High	Low	Low
29	Highway	Low	High	Low	High	High
30	Highway	Low	High	Low	High	Low
31	Highway	Low	High	Low	Low	High
32	Highway	Low	High	Low	Low	Low
R	Railway	—	—	—	—	—
W	Waterway	—	—	—	—	—

—Not considered.

The parameters of greatest interest for the deicing+coastal clusters were the combination of the parameters considered in table 3 and table 4. Because six unique variables (one additional variable relative to table 4) were present, there were 64 parametric categories for highway crossings (a high and low distance-to-the-coast version of each category listed in table 4) plus two additional categories for railroad and waterway crossings for a total of 66 categories.

Then the research team compiled the values of each of these variables for the bridges in each cluster and calculated the median values for the cluster. Next, the value of each variable for each bridge was classified as "high" or "low" relative to the median to, theoretically, equally divide the population into each category. Values equal to the median were considered "low," meaning that a precisely equal distribution did not always occur. Each bridge was then sorted into one of the categories described by the combination of high and low values for each parameter, as described by table 3 and table 4. In all cluster types, combination 1 represented the most severe environment, and the last combination represented the least severe environment. Table 3 and table 4 are organized as follows: the theoretical worst-case scenario is labeled combination 1, then the parameters are independently varied, beginning with the parameters listed on the right side of the tables and working toward the left.

Selection of Specific Cluster Bridges

After determining the parametric categorization of the reference bridge, the team then attempted to choose an additional bridge with the same parametric categorization as one cluster bridge (for redundancy in the data) and pairs of bridges that represented varying one parameter at a time relative to the reference bridges for the remaining cluster bridges. For the coastal clusters, which had fewer categories, the researchers made an effort to include at least three bridges in each category of interest, which resulted in a greater ability to assess repeatability and redundancy and a greater capability for matching multiple specific parametric values among various cluster bridges. In some cases, single parameter variations relative to the reference bridge were not possible, so variables were varied relative to other cluster bridges to maintain the single parameter variation concept. If this process did not naturally result in including combination 1, bridges from this category were also included when they existed. The least severe category was also included when bridges in this category existed, to represent the full range of environments within a cluster.

In cases where more bridges were assigned to a category of interest than were reasonable to include based on the intended cluster size, the researchers made several additional considerations. Based on these combined considerations, the individual influences of each variable were theoretically more readily apparent. First, an effort was made to select bridges that were as similar to the reference bridge (or other bridges in the same parametric category as the reference bridge) as possible, with only the parametric value that was intended to be varied by the category under consideration being varied. In other words, the goal was not only that the "high" or "low" designation was kept constant except for one variable, but the specific values within those categories also remained as constant as possible. For example, if the reference bridge had an ADT of 70,000 and an annual snowfall of 23 inches, when cluster bridges with different humidity values were sought, bridges that had similar values of ADT and snowfall were prioritized. This consideration of keeping constant parameters as consistent as possible also extended to parameters other than those listed in table 3 and table 4, such as age or environmental parameters of secondary importance. An additional consideration with respect to age was the team selected older bridges whenever they existed (with a minimum age of 20 yr used whenever possible), which both serves as a worst-case scenario and was most likely to lead to detecting any differences in performance in differing environments.

The median ±1 standard deviation was also computed and used to identify bridges as “very high” or “very low” to reveal bridges with more extreme parametric values. These bridges were given higher priority when making final cluster bridge selections because any influences of these parameters would be theoretically more readily observed in these cases.

An additional consideration in selecting specific cluster bridges was the SCR. Since SCR was treated as a dependent variable, the researchers generally made no effort to select bridges with a specific SCR. However, if multiple bridges populate the same parametric combination category, then the team evaluated the average SCR of the bridges within that category, and thus made an effort to choose cluster bridges that were representative of this average when selecting cluster bridges to represent that parametric combination category. Other criteria for including bridges in the clusters included those with exceptionally good or inferior performance and those that would improve the fit of the SCR versus age relationship of the cluster bridges relative to the population of bridges that they were intended to represent.

A final consideration in the choices of specific cluster bridges to populate the categories of interest was the owner of the bridge. When there were different owners within a cluster with different levels of detail in their inspection reports, those with more detailed reporting were prioritized. This data-driven decision making process led to a list of typically 10–20 cluster bridges, as listed later in the Selected Bridges section of this chapter.

Field Bridges

Typically, three field bridges were included in each cluster: the reference bridge and two additional bridges. Field bridges were selected after the team requested and evaluated the inspection reports of all cluster bridges. Condition state information for the UWS members and joints was considered, as well as photos of UWS performance. Two bridges were then selected as additional field bridges (in addition to the reference bridge of the cluster): one generally representing the best condition bridge within the cluster and the other representing the worst condition bridge within the cluster. Here, best and worst were assessed based largely on the percentages of the girders and other UWS elements in various condition states, which is considered relative to age and severity of the parametric category.

For example, if two bridges had all the superstructure in condition state 1 (the best condition), but one bridge had more snowfall than the other, and all other parameters were equal, then the bridge with greater snowfall was considered “best.” In identifying the “worst” cluster bridge, the research team assessed information from the inspection reports to determine whether advanced condition states were the result of leaking joints or other known problematic details. Bridges where these appeared to be the sole cause of advanced corrosion were eliminated from consideration as field bridges. Bridges with extensive portions of the steel painted, e.g., all fascia girders, were also removed from consideration as field bridges.

SELECTED BRIDGES

The following two subsections describe the bridges selected as reference and field bridges and cluster bridges, respectively.

Reference and Field Bridges

Table 5 describes the environment and condition of the field bridges, which includes reference bridges. Note some structure numbers have been truncated for brevity. In one case (Maryland+Virginia cluster), an additional field bridge (relative to the typical group of three field bridges) was included. This addition was made because logistical considerations resulted in the need for alternate choices for field work. However, resources were ultimately available for including the preferred and alternate choices.

Cluster Bridges

Table 6 summarizes the number, environment, and condition of the cluster bridges by reporting the minimum (min), maximum (max), and average (avg) value of each of the primary parameters of interest for each cluster. The number of bridges is also reported, which is generally between 10 and 20, except for the deicing+coastal clusters. These clusters included a larger number of bridges due to the greater number of parameters involved and, therefore, parametric categories that were desirable to populate.

Table 5. Characteristics of field bridges.

Cluster	Structure No.	Crossing Type	Distance to Coast (mi)	ADT Under Structure (count)	Vertical Under-Clearance (ft)	Normalized Humidity Score (unitless)	Snow (inches)	Atmospheric Cl^- (ppm)	Age (yr)[1]	SCR (unitless)
CO	E-16-JZ	Highway	NA	18,300	19.7	0.29	62.6	0.045	28	7
CO	E-16-JW	Highway	NA	62,500	16.4	0.29	62.6	0.045	31	8
CO	E-16-JX	Highway	NA	84,000	16.4	0.29	62.6	0.045	31	8
CT	4382	Highway	2.9	48,400	16.6	0.54	31.9	0.315	32	6
CT	5796	Highway	0.6	11,600	15.7	0.54	47.4	0.315	26	7
CT	3830	Highway	2.2	19,400	16.2	0.54	31.9	0.315	37	6
IA	041331	Highway	NA	88,500	17.2	0.57	34.8	0.066	11	7
IA	042711	Highway	NA	78,360	24.0	0.57	34.8	0.066	10	8
IA	004111	Highway	NA	73,990	18.2	0.57	34.8	0.066	12	8
LA+MS	238…961	Waterway	0.1	—	—	0.81	—	0.372	38	7
LA+MS	244…671	Waterway	0.2	—	—	0.70	—	0.372	32	5
LA+MS	625…011	Waterway	17	—	—	0.62	—	0.372	34	7
MD+VA	6260	Highway	NA	237,529	16.3	0.57	23.4	0.217	26	7
MD+VA	84010	Highway	NA	59,922	16.4	0.57	27.8	0.217	27	7
MD+VA	82010	Highway	NA	71,700	16.4	0.57	22.4	0.217	39	6
MD+VA	00013	Highway	NA	4,180	16.4	0.57	22.4	0.296	32	5
MN	04019	Highway	NA	9,700	16.1	0.60	53.1	0.030	34	5
MN	62861	Highway	NA	130,000	16.1	0.56	52.9	0.057	40	6
MN	19811	Highway	NA	53,000	16.3	0.56	44.3	0.057	35	7
NC	190083	Rail	4.2	—	—	0.65	—	0.328	33	5
NC	1290058	Highway	2.1	—	—	0.67	—	0.717	28	8
NC	1290057	Highway	2.4	—	—	0.67	—	0.717	28	8
NH	111…900	Highway	2.1	65,610	16.1	0.73	59.2	0.750	14	8
NH	017…300	Highway	28	3,900	14.6	0.54	68.2	0.180	36	6
NH	017…700	Highway	18	21,000	17.4	0.54	55.4	0.180	20	8
NY	1072562	H&W	NA	22,015	14.3	0.63	92.2	0.073	31	8
NY	1071860	Highway	NA	33,156	16.4	0.63	92.2	0.073	30	7
NY	1071880	Highway	NA	70,941	16.9	0.63	92.2	0.073	30	8

Cluster	Structure No.	Crossing Type	Distance to Coast (mi)	ADT Under Structure (count)	Vertical Under-Clearance (ft)	Normalized Humidity Score (unitless)	Snow (inches)	Atmospheric Cl^- (ppm)	Age (yr)[1]	SCR (unitless)
OH	7701977	Highway	NA	23,599	15.6	0.65	49.2	0.101	39	8
OH	7701993	Highway	NA	26,000	15.3	0.65	49.2	0.101	40	8
OH	7805934	Highway	NA	7,832	15.2	0.59	40.1	0.100	21	5
TX	120…023	Waterway	0.1	—	—	0.79	—	0.565	34	7
TX	121…177	Highway	3.4	—	—	0.62	—	0.565	33	8
TX	121…152	Highway	20	—	—	0.63	—	0.565	23	7

[1] For consistent reporting, age listed is relative to 2013, when phase 2 clusters were established.

—No data to report.

NA = not applicable; H&W = highway and waterway.

Table 6. Summary of cluster bridges.

Cluster[1]	Distance to Coast (mi)	ADT Under Structure (count)	Vertical Under-Clearance (ft)	Normalized Humidity Score (unitless)	Snow (inches)	Atmospheric Cl^- (ppm)	Age (yr)[2]	SCR (unitless)
CO min	—	62,500	16.4	0.29	62.6	0.045	28	3
CO avg	—	95,200	18.3	0.29	62.6	0.045	32	7
CO max	—	183,000	26.2	0.29	62.6	0.045	33	8
CT min	0.0	1,020	13.9	0.54	26.3	0.217	13	5
CT avg	5.8	33,518	17.3	0.54	42.1	0.288	32	7
CT max	22.3	161,900	30.0	0.57	100.1	0.315	44	8
IA min	—	5,900	16.3	0.57	23.8	0.066	7	7
IA avg	—	53,060	18.2	0.57	32.8	0.066	13	8
IA max	—	94,500	24.0	0.57	34.8	0.066	14	9
LA+MS min	0.1	—	—	0.62	—	0.372	27	4
LA+MS avg	10.9	—	—	0.68	—	0.372	34	7
LA+MS max	89.8	—	—	0.81	—	0.372	38	8
MD+VA min	—	4,180	16.3	0.54	15.7	0.217	23	5
MD+VA avg	—	84,936	19.5	0.57	22.0	0.257	30	7

Cluster[1]	Distance to Coast (mi)	ADT Under Structure (count)	Vertical Under-Clearance (ft)	Normalized Humidity Score (unitless)	Snow (inches)	Atmospheric Cl⁻ (ppm)	Age (yr)[2]	SCR (unitless)
MD+VA max	—	237,529	52.5	0.62	27.8	0.296	40	8
MN min	—	300	16.1	0.56	34.2	0.030	24	5
MN avg	—	40,196	18.7	0.58	49.3	0.056	32	7
MN max	—	135,600	39.9	0.73	56.0	0.105	43	8
NC min	2.1	—	—	0.57	—	0.328	28	5
NC avg	9.4	—	—	0.64	—	0.561	30	7
NC max	32.2	—	—	0.67	—	0.717	33	8
NH min	0.1	100	10.2	0.54	55.4	0.154	14	6
NH avg	14.4	43,977	16.2	0.61	60.9	0.366	30	7
NH max	33.1	79,000	23.3	0.73	68.2	0.750	41	9
NY min	—	3,850	14.3	0.56	60.4	0.049	22	5
NY avg	—	18,928	19.3	0.63	97.4	0.069	31	8
NY max	—	70,941	58.2	0.65	153.6	0.073	42	9
OH min	—	2,931	15.1	0.59	40.1	0.070	9	5
OH avg	—	19,491	16.0	0.62	47.8	0.099	35	6
OH max	—	92,927	23.0	0.65	57.2	0.101	46	8
TX min	0.0	—	—	0.62	—	0.565	20	5
TX avg	4.7	—	—	0.63	—	0.565	26	7
TX max	12.4	—	—	0.79	—	0.565	34	8

—No data to report.

[1] Number of bridges in each cluster are as follows: CO = 10, CT = 21, IA = 14, LA+MS = 15, MD+VA = 21, MN = 20, NC = 10, NH = 28, NY = 20, OH = 16, TX = 17.

[2] For consistent reporting, age listed is relative to 2013, when phase 2 clusters were established.

CHAPTER 5. FIELD DATA

FIELD DATA COLLECTION METHODS

Five types of field data were collected:

- Photos.
- Tape adhesion tests.
- Rust samples.
- Section loss measurements via ultrasonic thickness (UT) testing.
- Pit depth measurements (where applicable).

These data were collected as discussed in the following subsections and were based on existing LTBPP protocols for evaluating steel superstructure corrosion (FLD-OP-SC-002 as amended in appendix A through appendix D with modifications specific to UWS) and labeling procedures (FLD-OP-SC-003) (Hooks and Weidner 2016). For the bridges evaluated in phase 2, these data types were collected at numerous locations. These data were then evaluated to determine the most informative locations for data collection, and these data was collected at a smaller number of locations in phase 3, as discussed in the following subsections.

Sampled Locations

A minimum of 12 locations were sampled in each field bridge. In phase 3, these locations were standardized to include three points on two different girders at two different cross sections of the bridge. For highway crossings, one cross section was over the shoulder of the roadway, and the other was over a right travel lane of the roadway. These same cross sections were prioritized in phase 2. For rail crossings, one cross section was near the abutment, and the other was as close to the rail as possible, considering logistics and safety. For water crossings, one cross section was the visually estimated center of the waterway, and the other was over vegetation (if possible) or soil if no vegetation exists at the site, otherwise, the cross section was near the abutment.

Within each bridge cross section, one exterior girder and the adjacent interior girder were sampled. For highway crossings, these girders were on the side of the bridge facing oncoming traffic in the lanes over which the sampled cross section is located. The three locations sampled on each girder cross section were the top surface of the bottom flange on both sides of the web and the side of the web facing traffic (if applicable) at approximately one-third of the height of the web above the bottom flange.

Each of these sampled locations was represented by a 4-inch by 6-inch surface area, marked by white chalk on the surface of the girder using a cardboard template. Each sampled location was also numerically labeled in ascending order for record-keeping purposes. The location of this sampled area was measured and recorded relative to the nearest joint or abutment, the ground, and the girder geometry.

Data Types

This section describes the five types of data that were collected as a standard part of the field work. In addition, other data types that were considered in preliminary work and the reasons these were not used in the final field protocols are described in this section.

Two general categories of photos were taken: overview and sample location. The following six standard overview photos were taken at each bridge:

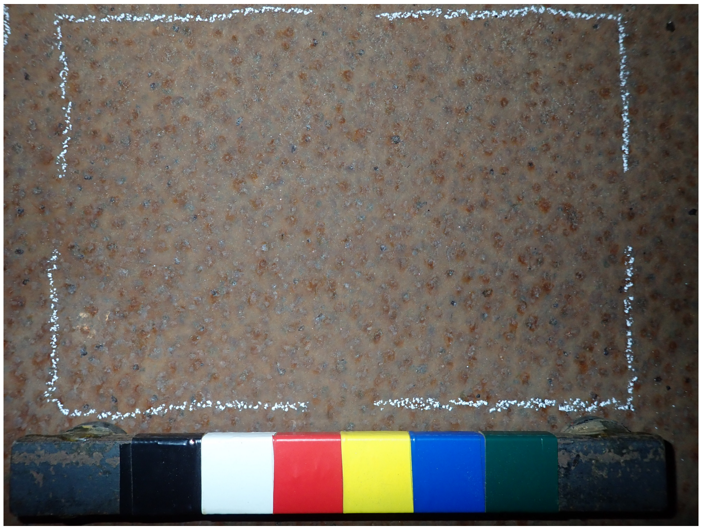
- A wide-view photo of the bridge showing the full length of an exterior girder. This photo was taken from a distance of approximately 100 ft back from the bridge, but within the limits of site traffic control, or on the shoulder of the road if necessary.
- A photo showing the ends of all girders at a typical bearing location.
- A wide-view photo of interior girders for a typical span.
- A closeup photo of a typical splice plate on a fascia girder (if applicable).
- A closeup photo of a lateral bracing to girder connection (if applicable). This photo focused on bolted connections, such as between cross-frame members and transverse stiffeners serving as lateral bracing connection plates, in areas where any pack rust was developing, if applicable.
- At least one photo depicting the general environmental exposure of the structure (e.g., over water or traffic conditions).

A sketch was created showing the location and viewing angle from which each overview photo was taken relative to the bridge. This step was to facilitate comparison with any future site visits of these same structures.

Photos at two slightly different scales were also taken at each sample location. An example of the first, wide view, photo is shown in figure 6, which shows that this photo was framed to include the entire perimeter of the sampled area as well as the sample location label and a magnetic bar wrapped with different colors of tape. The purpose of this magnetic bar was to provide a means for standardizing the color in different lighting conditions in potential future image recognition analysis. Figure 7 shows an example of the second sample location photo, which was taken at a higher zoom to provide more information on the visual appearance of the UWS surface condition. The wide-view sample location photo was also taken before the closeup sample location photo because the presence of the location label in the wide-view photo aided in organizing the photographic log.

Source: FHWA.

Figure 6. Photo. Example of standard wide-view photo of sampled locations.



Source: FHWA.

Figure 7. Photo. Example of standard closeup view photo of sampled locations.

Tape Adhesion Test

The tape adhesion test included adhering a 4- to 5-inch-long piece of clear packaging tape (with a minimum adhesive strength of 55 oz/inch) to the surface of the UWS girder. Tape adhesion was determined based on specifications provided by the manufacturer based on testing performed in accordance with ASTM D3330 or similar methods (ASTM 2004). Next, a rubber "J" roller was used to roll over the tape with 10 passes, using firm pressure. Then the tape was slowly peeled off with a shallow angle between the tape and the steel surface. The tape sample was then adhered to a clean sheet of white paper to be used for image processing to quantify the size and distribution of the corrosion by-products that adhered to the tape.

Rust Samples

Rust samples were collected by scraping the surface of the girders. Approximately 0.18 oz of rust were collected for later laboratory analysis by scraping the surface with a stainless steel chisel and/or wire brush and collecting and sealing the rust into a clear, plastic bag. If not enough rust could be collected from within the marked area, rust was also collected from the surrounding area. Each bag was marked with the bridge and sample reference number.

Section Loss and Pitting Depth

The researchers calculated section loss estimates by measuring plate thicknesses at a minimum of two locations for each field bridge: one representing a typical situation and one representing a girder location judged to be in the most corroded location. Plate thickness were measured using a UT gauge.

Before the measurement, the oxide layer was removed by a power grinder in a 0.75-inch-diameter area until the bare metal was exposed only on the highest points of the corroded surface, leaving any depressions filled with oxide. Approximately one-third of the ground surface was intended to have a metallic appearance. Then, a coupling agent was applied to the surface of the steel. The UT gauge probe was then moved around the ground area, and the smallest reading was recorded as a reasonable estimate of the plate thickness.

The location of the measurement was noted and then later compared to the nominal thickness of the plate according to the structural drawings at the measured location. If the field measurement was less than the nominal plate thickness, the difference between these two values was recorded as estimated section loss. This estimate was likely a lower bound estimate because original plate thicknesses are typically greater than the nominal specified plate thickness by a small margin. The depth of any pitting was measured using a lever pit gauge.

Preliminary Data Types

The team also evaluated several additional field data types. Those not mentioned previously in the four preceding subsections were abandoned from future use based on the phase 1 assessment of their capabilities for providing useful data in an efficient manner that maximizes the productivity of field-testing time. The data types that were abandoned, and the reasons for doing so, are summarized by table 7.

Table 7. Preliminary data types that were abandoned in final field protocols.

Measurement	Summary of Experience	Limitation
Temperature	Limited value	Limited value.
Tooke gauge for rust thickness measurement	Impractical	Surface roughness prohibited a clean scratch.
Micrometer	Impractical	Requires clean steel surface; inaccurate results.
Linear polarization resistance	Impractical	Difficult to use on vertical and rough surfaces.
Electrochemical impedance spectroscopy	Impractical	Electromagnetic interference; time-consuming; difficult to use on vertical surfaces.
AC resistance using Nilsson soil resistance meter	Impractical	Difficult to use on vertical and rough surfaces.
Visual assessment of color per SSPC standard (SSPC 2000)	Impractical	Inconclusive.
Color meter	Impractical	Inconclusive.
In situ residual salt concentration (swab, Chlor Rid, and Bresle methods)	Impractical	Time-consuming; inaccurate results.
SO_4^{-2} field test kit	Impractical	Time-consuming; inaccurate results.
Knife adhesion test	Impractical	Time-consuming; brittle rust layers complicated measurement.

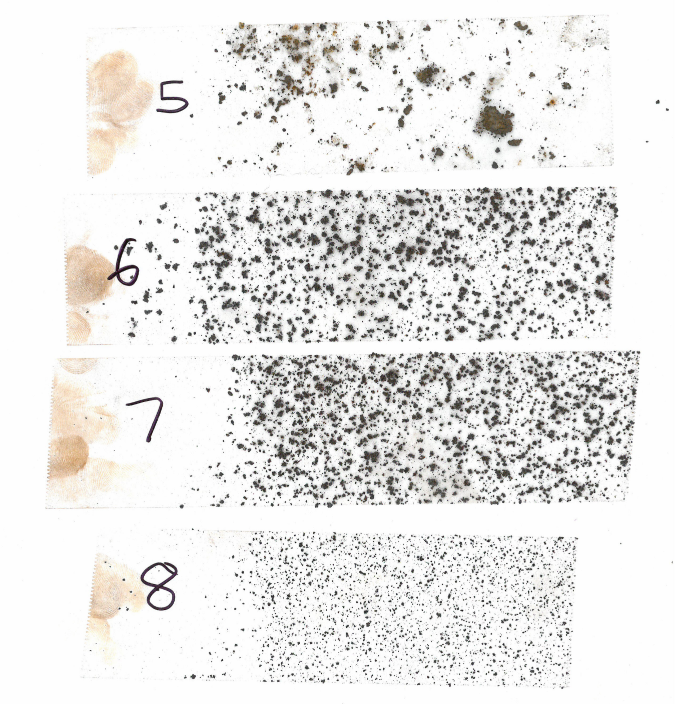
AC = alternating current; SSPC = SSPC International.

FIELD SAMPLE ANALYSIS METHODS

Of the five types of data collected in the field, two of them required laboratory or computational analysis. The tape adhesion test samples were analyzed using an image recognition algorithm, as described in the subsequent subsection. The rust samples were subjected to two laboratory analysis procedures: an ion chromatography (IC) test to determine the Cl^- concentration absorbed in the oxide layer and an x-ray diffraction (XRD) analysis to determine the specific species of iron (Fe) compounds forming the rust layer. These procedures are also further described in this section.

Tape Adhesion Analysis for Corrosion Particle Sizes

Figure 8 provides examples of the different visual appearances of the tape adhesion tests. Some samples show little or no rust on the tape and particles that are very small. Other images show an almost uniform coverage of small- or medium-sized rust. Still others show nonuniform distributions of larger conglomerations of rust particles. To quantitatively represent these varied results and then compare and contrast them, an image recognition algorithm was developed.



Source: FHWA.

Figure 8. Photo. Example tape adhesion specimens.

Two measures for characterizing the tape adhesion results were the spatial density of rust and the size and distribution of rust particles in the sample. The data analysis program MATLAB® has many built-in functions, i.e., a toolbox for image processing, that were ideally suited for analyzing digital images such as this (MathWorks® 2023). To automatically process the tape samples, the team wrote a MATLAB script to determine rust spatial density and distributions of particle size. The procedure to determine rust spatial density was as follows:

1. The tape sample was first scanned and converted into a digital image using a scan resolution of 300 dots/inch.

2. The image was converted into black and white using the MATLAB function "im2bw." White pixels were denoted by a "1," and black pixels were denoted by "0." The threshold value, a number between 0 and 1, that determines when a grayscale pixel was converted to black or white was set equal to the average of the result of the "graythresh" function and 0.25. This optimized value was determined by comparing a number of converted black and white images with the actual tape sample image and choosing the value that yielded the best agreement.

3. The pixel dimensions of the image were determined using the “size” function.
4. The number of pixels that are black (assumed to rust) was determined using the “find” function.
5. The rust spatial density was calculated as the number of black pixels divided by the total number of pixels in the image.

The MATLAB program then continued to determine the size and distribution of rust particles by performing the following functions:

6. The binary image was inverted so that black pixels were equal to “1” and white pixels were equal to “0.”
7. Connected regions of black pixels were identified and labeled using the function “bwlabel.” A region was considered connected when a perimeter of white pixels surrounded it. A connected region was assumed to be a rust particle.
8. The area, in pixels, of each connected region/particle was determined using the function “regionprops” with the “area” argument.
9. The area of each connected region (i.e., particle) was calculated by converting the area in pixels to square inches. The scale factor was determined by scanning a penny of known area and dividing it by the computed area of the penny in pixels.
10. The area of each region (i.e., particle) was converted into an equivalent circular area. The diameter of the equivalent area was assumed to be the equivalent rust particle diameter.
11. The particle areas were then sorted in bins of increasing size: 0 to 1/32 inch, 1/32 to 1/16 inch, 1/16 to 1/8 inch, 1/2 to 1 inch, and greater than 1 inch. The percentage of particles of each bin was then calculated by summing the areas in each of the bins and presenting this as a percentage of the total. The sum in all bins was equal to the spatial density calculated in the first portion of the algorithm.

The program has other capabilities to help the user better understand and evaluate its operation. A minimum threshold for equivalent diameter may be set so that the program will ignore all particles it detects with an equivalent diameter less than the set threshold. Second, an RGB (red, green, blue color model) image of the labeled binary image can be displayed. This display allows the user to view, via color distinction, the image as a collection of individually recognized particles. Lastly, the program can print “bounding boxes” around each individual particle, which has two main functions. Primarily, because precise color distinction is difficult with the naked eye, it helps the user better distinguish where some particles end and others begin. Secondarily, the program does not apply bounding boxes to particles it was ordered to ignore by the minimum threshold. This feature allows the user to easily see which particles the program is ignoring.

Ion Chromatography Analysis

IC tests were conducted using an ion chromatograph calibrated per ASTM D4327 on all the rust samples that were collected (ASTM 2017). The IC tests were conducted to sample Cl^-, SO_4^{-2}, and NO_3^- ions absorbed in the rust samples. These soluble salts were of interest because they may affect the rate and type of rust development. Note that quantification of insoluble salts was beyond the scope of this study due to the need for acidic solutions that require stringent safety procedures to perform such testing. Furthermore, because insoluble salts do not exist in an ion state, they have no electrochemical effects on corrosion.

The procedure used to prepare the samples for the IC analyses is described as follows, in accordance with ASTM C114 (ASTM 2018):

1. Grind the rust sample finely with a mortar and pestle so that all material can fit through a No. 20 (0.033 inch) or smaller sieve.
2. Blend samples thoroughly before weighing.
3. Weigh the sample to the nearest 0.00004 oz. Use 0.071 oz or more if enough sample is available. If the sample is less than 0.018 oz, note the actual weight in the comments of the data collection table. Note that samples of 0.071 oz or more require dilution in step 7, and those less than 0.071 oz do not. Therefore, the analyst should make temporary notes of sample weights for this purpose.
4. Transfer the sample into a beaker and add 0.34 fl oz of deionized water, cover the beaker with laboratory film, and let it sit for 16 to 24 h.
5. Swirl the sample, then transfer it into a 0.31-fl oz centrifuge tube and centrifuge at 4,000 rpm for 2 min.
6. Remove the supernatant from the sample tube without transferring solid material. Filter the supernatant through a syringe filter (i.e., $8\times10-6$ inch nylon membrane) into a clean 0.51-fl oz centrifuge tube.
7. Refer to the temporary notes made in step 3. If the mass of the sample is 0.071 oz or more, add 0.17 fl oz of filtered sample to a 1.7-fl oz volumetric flask and dilute to 1.7 fl oz.
8. Mix the sample thoroughly by inverting the centrifuge tube or flask.
9. If there is 0.51 fluid ounces of the sample or greater, transfer 0.17-fl oz of the sample into each of three 0.17-fl oz IC vials . If there is less than 0.51 fluid ounces of the sample, equally divide the sample into three 0.17-fl oz IC vials.
10. Load the IC sample vials into the autosampler and begin the IC analysis.

The IC analysis was conducted in accordance with ASTM D5085 (ASTM 2002). The setup and parameter settings for the analysis were as follows:

- Metal trap column to catch metals to protect IC from damage.
- Anion exchange column: AS20.
- Guard column: AG20.
- Eluent gradient: 10 mM NaOH hold for 4 min, ramp from 10 to 45 mM at 8.5 min, and hold for 4 min.
- Effluent flow rate: 0.034 fl oz/min.
- Temperature: 30 °C.
- Detection: Electrical conductivity cell.

X-Ray Diffraction Analysis

This section begins with providing a brief background on XRD for readers unfamiliar with the usefulness of this analysis method. The means for preparing and processing the XRD samples are then discussed. This section concludes with describing the methodical qualitative and quantitative methods that were developed in this work for analyzing the XRD results from UWS samples.

Background

A commonly used method for quantifying the relative proportions of specific species of Fe oxyhydroxides (FeOOH) within a rust sample is XRD analysis. This method involves grinding corrosion products into powder form and then subjecting the powders to short-wave radiation. Because this wavelength is comparable to the distances between atoms, the waves either pass between atoms or are reflected by an atom. Furthermore, because the lattice arrangement (positioning and spacing between atoms) of each species of FeOOH is different, different species of FeOOH result in different relative intensities of the reflected waves as the angle of incidence between the wave and the sample is varied. Comparing diffraction patterns of a sample to existing XRD standards (discussed in the following Qualitative Analysis subsection) allows crystalline structures to be identified (International Center for Diffraction Data 2022). The relative composition of different compounds within a sample can then be determined using methods such as the semiquantitative phase analysis or Rietveld analysis method (Hubbard and Snyder 1988; Izumi 1993).

Furthermore, prior work has suggested relationships between various ratios of these compounds and protective ability. For example, Yamashita and Misawa (1998) suggested the protective ability of the rust layer can be assured if the ratio of goethite to lepidocrocite (G:L) exceeded 2. Dillmann, Mazaudier, and Hoerlé (2004) later refined this concept to consider the ratio of goethite plus magnetite to lepidocrocite plus akaganeite when studying the corrosion of Fe artifacts. Hara et al. (2007) proposed another version of this concept where the ratio of goethite to the sum of lepidocrocite, akaganeite, and wustite greater than 1 was concluded as being protective.

Sample Preparation

The XRD analysis performed in this study involved four primary steps: sample preparation, sample processing, qualitative analysis of results, and quantitative analysis of results. The specific procedures used for sample preparation were:

1. Grind approximately 0.035 oz of the rust sample with a mortar and pestle to a fine powder (e.g., with the ability to pass through a No. 45 or smaller sieve) to randomize orientation.
2. Place the rust sample on a glass slide and smear uniformly using a second glass slide to achieve a flat upper surface.

Sample Processing

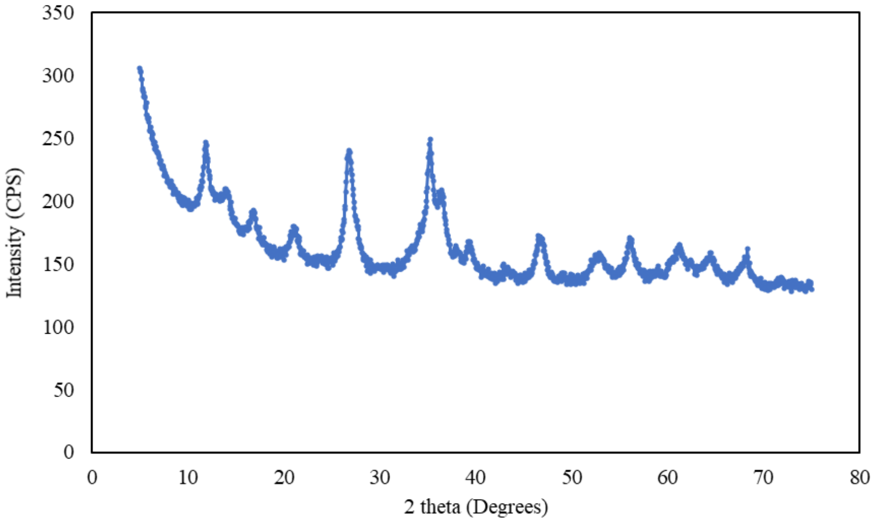
The samples were processed using an XRD machine with the following characteristics and settings:

- Copper source radiation tube.
- Divergence slit of 0.047 inch.
- Anti-scatter slit of 0.71 inch.
- Power-level maximums of 40 kV and 40 mA.
- Start angle of 5.0000 degrees.
- Stop angle of 75.0000 degrees.
- Degree increment size of 0.0500 degree.
- Scan time per increment of 2.000 s.
- Scan type of "coupled 2 theta/theta."
- Scan mode set to "continuous" and the autorepeat option used to repeatedly process specimens for a minimum of 8 h to continually refine the scan due to the efflorescence caused by the copper radiation source on the Fe sample.
- Starting position of theta and detector set at 0 degrees.
- *x*-, *y*-, and *z*-coordinates centered on the specimen.

The results of this process were data giving the intensities of the reflected x-rays as the angle of incidence between the x-ray source and the sample was varied. Before performing the qualitative analysis, the research team used DIFFRAC.EVA software (version 3.1) to perform background subtraction (Bruker 2014). This step was akin to removing noise from the sample, which occurred because of the efflorescence of the sample. An example of the output from the XRD software (in terms of counts per second) before and after background subtraction is shown in figure 9 and figure 10, respectively. The background subtraction settings used were as follows:

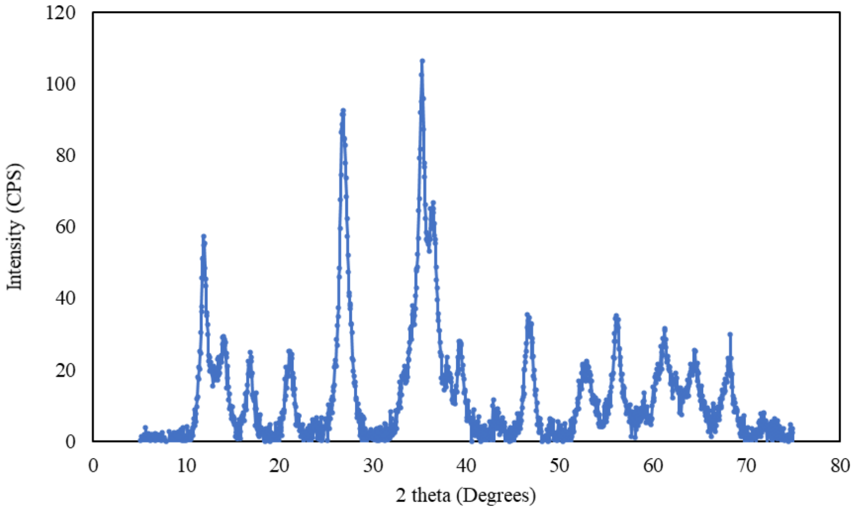
- Curvature of 0.018 was used in most cases. This value is conservative and common. In some cases, a larger value of 0.275 was necessary to remove the background intensities.
- Threshold of 1.000 was used.

User interpretation was necessary to make meaningful conclusions from this data. In this study, both a qualitative and a quantitative interpretation of these data were performed. The qualitative interpretation involved identifying the Fe compounds present in the sample, whereas the quantitative interpretation calculated the proportions of those compounds.



Source: FHWA.
CPS = counts per second.

Figure 9. Graph. Example output from XRD software without background subtraction.

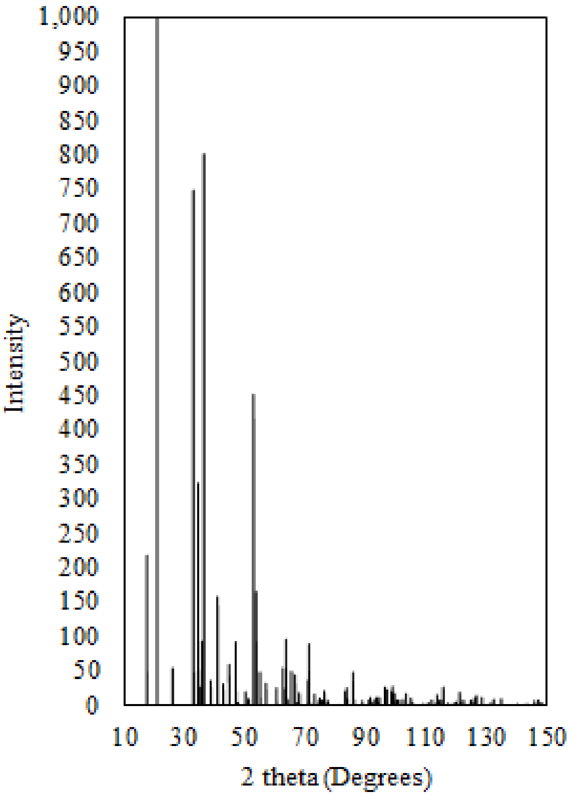


Source: FHWA.

Figure 10. Graph. Example output from XRD software with background subtraction.

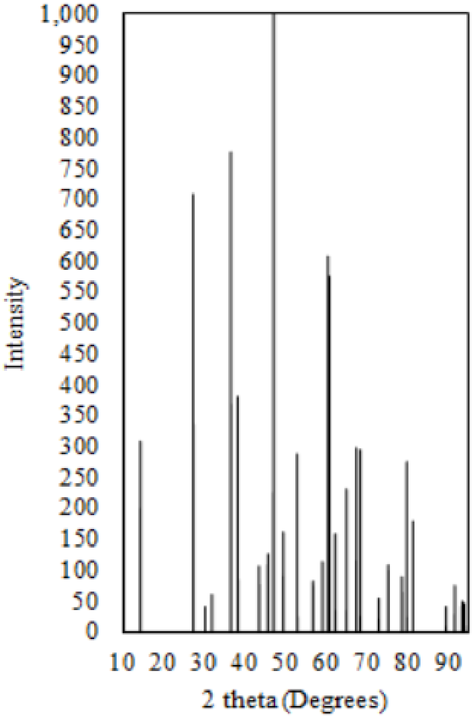
Qualitative Analysis

The qualitative analysis was performed by comparing the diffraction pattern output (intensities versus angle of incidence) from the XRD software to the corresponding diffraction pattern of various compounds. When an unknown is a mixture, the diffraction pattern is a simple sum of the diffraction pattern from each compound. Diffraction pattern standards for individual compounds exist for a vast array of compounds. The diffraction pattern standards used in this study were the powder diffraction files (PDFs) that are maintained and periodically updated by the International Center for Diffraction Data (ICDD) (2022). Examples of these standards for selected compounds of interest are shown in figure 11 through figure 13. Furthermore, in some cases, multiple XRD standards exist for a given compound. Therefore, figure 11 through figure 13 indicate the specific PDF shown, according to the labeling used by the DIFFRAC.EVA software used in this study (Bruker 2014). To systematically compare the XRD output to the PDF standards to identify the compounds present in each sample, the team used four primary steps in the qualitative analysis, described as follows.



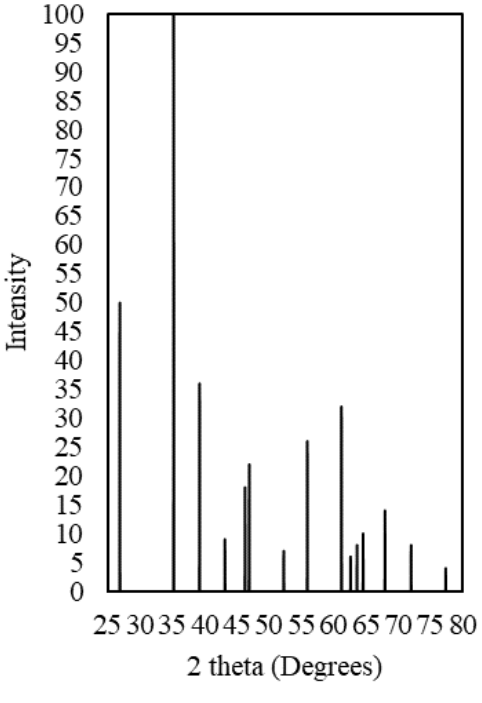
Source: FHWA.

Figure 11. Graph. XRD standard for goethite (PDF 01-073-6522).



Source: FHWA.

Figure 12. Graph. XRD standard for leprodocrocite (PDF 00-060-0344).



Source: FHWA.

Figure 13. Graph. XRD standard for akaganeite (PDF 00-060-0614).

1. The compounds of interest were identified. They included two categories of compounds: Fe compounds known to be common to UWS (based on prior literature, e.g., Morcillo et al. 2014) and compounds composed of elements other than Fe that may have been introduced into the sample based on field conditions. Table 8 lists the Fe compounds that were considered. To identify other elements that may have been included in the sample, wavelength dispersive x-ray fluorescence was conducted on four randomly-selected specimens. This analysis revealed that the eight elements listed in table 9 (i.e., Fe, chlorine (Cl), Si, manganese (Mn), sulfur (S), aluminum (Al), calcium (Ca), and magnesium (Mg)) comprised at least 1 percent of at least one of the four specimens selected for preliminary analysis. Therefore, these eight elements were identified as potential elements for consideration in all subsequent XRD analysis. Note table 9 gives the range of each of these eight elements that was contained in the four specimens selected for preliminary analysis.

   The minimum amount of Fe being 83-percent mass of the sample indicated that iron hydroxides (FeOH) and iron oxyhydroxides (FeOOH) were the major components of the four tested rust samples. Therefore, elements other than Fe were only considered when there were values in the XRD results that could not be explained solely by Fe compounds.

Table 8. Fe compounds considered in XRD analysis.

Name	Composition
Goethite	α-FeOOH
Akaganeite	β-FeOOH
Lepidocrocite	γ-FeOOH
Feroxyhite	δ-FeOOH
Ferrihydrite	$Fe_5HO_8 \times 4H_2O$
Hematite	α-Fe_2O_3
Maghemite	γ-Fe_2O_3
Magnetite	Fe_3O_4
Schwertmannite	$Fe_{16}O_{16}(SO_4)_3(OH)_{10} \cdot 10H_2O$
Ferric sulfate	$Fe_2(SO_4)_3$

Table 9. Percent mass of elements resulting from XRF analysis.

Metric	Fe	Cl	Si	Mn	S	Al	Ca	Mg
Maximum	94.66	2.48	4.94	1.19	2.66	1.83	1.37	2.22
Minimum	82.80	0.55	0.69	1.05	0.00	0.00	0.16	0.00

2. The angles corresponding to the highest intensities (i.e., peak angles for brevity) from the XRD standards for the compounds of interest were compiled for each intensity level (i.e., the highest relative intensity is intensity level 1, the next highest relative intensity is intensity level 2, etc.). Numerous PDFs exist for the compounds listed in table 8. To filter this list to a more manageable and more appropriate list, the team considered the database status and discarded PDFs from deleted databases. Then the quality of the PDFs was considered, indicated by ICDD using 1 of 10 labels. Only PDFs receiving one of the three

highest quality ratings were considered, which resulted in 1 (for schwertmannite) to 100 (for magnetite) PDF cards for each Fe compound of interest.

Each PDF was summarized by the highest diffracted intensities (typically the eight maximum intensities) and corresponding angles of incidence (i.e., peak angles). The minimum and maximum peak angles corresponding to each of the eight maximum intensities were then compiled for each compound, as shown in table 10. For compounds where the relative positions of the peak angles for the eight maximum intensities were the same for each PDF for that compound, all PDFs for that compound were summarized easily by reporting the minimum and maximum peak angle corresponding to each intensity level. For example, the peak angles corresponding to the highest intensity of all 22 cards of goethite were between 21.05 and 21.85 (when rounding the minimum down and the maximum up to the nearest 0.05 based on the resolution of the XRD analysis performed in this study). So, these two theta values were summarized directly.

However, oftentimes the peak angles associated with the highest intensities were not in the same relative positions. For example, 9 of the 11 PDFs for lepidocrocite had a peak angle for the first highest intensity between 14.10 and 14.25. One of the remaining PDFs for lepidocrocite had a peak angle for the first highest intensity of 27.05, which fell within the range of peak angles corresponding to the second highest intensity of the majority of the other PDFs for lepidocrocite. In these situations, histograms for the peak angles of each compound were created and manually interpreted to determine the range of peak angles for each maximum intensity reported in table 10.

3. The angles of incidence producing the maximum intensities (i.e., peak angles) in each set of XRD output were identified. The DIFFRAC.EVA software has the ability to automate this step. However, to have greater insight into the peak angles, the raw data with background subtraction was exported to a spreadsheet, and simple functions were used to identify local maxima in each scan. The researchers found that this process generally matched the automated results from the DIFFRAC.EVA software. However, slight differences in the peak angle (up to 0.2 degrees) and, therefore, the corresponding maximum intensities, were sometimes observed. Because of the greater understanding of the manual spreadsheet results versus the more “black box” nature of the DIFFRAC.EVA software, the manually generated list of peak intensities was used.

4. The peak angles in each set of XRD output were compared to the XRD standards to identify the compounds present in the sample. This process began by matching the peak angles from the output to a specific intensity level of one or more compounds (e.g., if a peak angle of 33.20 was measured, this angle was matched to correspond to the third intensity of goethite and first intensity of hematite). A simple code was created to organize this step into a tabular format. An example is shown in table 11, where the first column represents the measured peak angles, the second column lists the corresponding relative intensity, and the remaining columns indicate the intensity level for each compound that corresponds to the measured peak angle.

Table 10. Minimum and maximum peak angles (in degrees) corresponding to peak intensities for compounds considered.

Compound	1st Min	1st Max	2nd Min	2nd Max	3rd Min	3rd Max	4th Min	4th Max	5th Min	5th Max	6th Min	6th Max	7th Min	7th Max	8th Min	8th Max
Lepidocrocite	14.10	14.25	27.00	27.15	36.20	36.90	46.75	47.05	52.70	52.90	60.25	60.90	37.95	38.20	67.35	68.60
Goethite	21.05	21.45	36.50	36.80	33.05	33.35	52.90	53.50	34.55	34.85	58.70	59.15	41.15	41.45	36.00	36.30
Akaganeite	35.15	35.50	26.70	27.00	11.80	12.00	16.75	17.00	38.50	39.25	46.20	46.90	55.85	56.45	61.15	61.20
Hematite	33.05	33.40	35.55	36.80	53.95	54.55	49.40	49.80	24.10	24.95	62.35	62.85	63.90	64.40	40.80	41.15
Maghemite	34.70	35.70	62.85	63.10	29.45	30.30	57.25	57.45	42.15	43.45	52.25	53.90	90.20	90.40	74.45	74.55
Magnetite	35.00	35.85	62.05	64.90	29.70	31.35	56.50	57.65	42.75	43.60	18.05	18.95	88.90	89.90	53.05	54.10
Feroxyhite	62.95	63.20	53.50	54.10	40.40	40.45	35.05	35.25	38.95	39.80	87.35	87.65	117.25	118.10	—	—
Ferrihydrite	35.55	36.40	34.05	34.30	62.05	63.10	18.85	19.80	40.00	40.80	26.00	26.35	56.00	56.30	45.65	46.30
Schwertmannite	35.15	35.20	26.25	26.30	18.20	18.25	61.30	61.35	39.45	39.50	55.25	55.30	63.65	63.70	46.50	46.55
Ferric sulfate	23.75	25.65	14.70	14.85	20.25	21.75	29.70	30.65	32.50	32.95	37.80	38.30	53.40	53.50	—	—

—No data to report.

Table 11. Matching of measured peak angles to standard peak angles (by relative ranking of intensity level)—example data.

Measured Peak Angle (degree)	Relative Intensity (percent)	Lepidocrocite	Goethite	Akaganeite	Hematite	Maghemite	Magnetite	Feroxyhite	Ferrihydrite	Schwertmannite	Ferric Sulfate
36.55	100	3	2	—	2	—	—	—	1	—	—
21.15	72	—	1	—	—	—	—	—	—	—	3
35.25	64	—	—	1	—	1	1	4	—	1	—
33.20	44	—	3	—	1	—	—	—	—	—	—
53.10	39	—	4	—	—	6	8	—	—	—	—
61.35	35	—	—	8	—	—	—	—	—	4	—
34.25	32	—	—	—	—	—	—	—	2	—	—
26.70	31	—	—	2	—	—	—	—	—	—	—
59.05	28	—	6	—	—	—	—	—	—	—	—
40.00	23	—	—	—	—	—	—	—	5	—	—
63.90	22	—	—	—	7	—	2	—	—	—	—
41.20	21	—	7	—	8	—	—	—	—	—	—
46.65	18	4	—	6	—	—	—	—	—	8	—
55.45	17	—	—	—	—	—	—	—	—	6	—
65.50	15	—	—	—	—	—	—	—	—	—	—
57.10	14	—	—	—	—	4	4	—	—	—	—
68.15	14	8	—	—	—	—	—	—	—	—	—
67.35	13	8	—	—	—	—	—	—	—	—	—
71.55	13	—	—	—	—	—	—	—	—	—	—
11.95	13	—	—	3	—	—	—	—	—	—	—
50.65	11	—	—	—	—	—	—	—	—	—	—
14.30	10	1	—	—	—	—	—	—	—	—	—
72.20	10	—	—	—	—	—	—	—	—	—	—

—No relevant information; the measured angle does not correspond to a peak angle for the listed compound.

These data were then interpreted to attempt to reach a conclusion about whether each compound of interest was or was not present in the sample using the following criteria (with the specific compounds that met each criterion for the example shown in table 11 listed parenthetically). Note that these criteria were applied in the listed sequence. This procedure is because of the overlap of some intensity levels of different compounds overlapping at the same peak angle and obscuring conclusions. Thus, eliminating compounds that do not appear in the sample from consideration as quickly as possible simplified the data interpretation. The following criteria were used to reach qualitative conclusions

- If none of the standard peak angles for a given compound appeared in the measured list of peak angles, the team concluded that the compound did not exist in the specimen. (This result did not occur for any of the compounds in the example shown in table 11.)

- If two of the first three peak angles (i.e., the angles corresponding to intensity levels 1 through 3) were not in the list of measured peak angles, then the team concluded that the compound was not present in the sample (e.g., maghemite, feroxyhite, schwertmannite, and ferric sulfate for the example shown in table 11). Theoretically, all the first three peak angles for a given compound should appear in the list of measured peak angles, if the compound was present in a sufficient quantity in the sample. However, this criterion was relaxed in order to account for the possibility of peaks for a given compound being obscured by more dominant peaks and to avoid eliminating potential compounds.

- If only one compound matched a given peak angle, then the team concluded that the compound was present in the specimen (e.g., the peak angle of 14.30 degrees in table 11 indicates that lepidocrocite was present in this sample and, in general, that goethite, akaganeite, magnetite, and ferrihydrite were present in this sample). The number of the top three intensity levels for each compound that matched the measured peak angles was also considered at this stage. If all three of these intensity levels were present, it served as validation that the compound was present.

- For any remaining compounds that were not classified as being present or not present in the sample, the compound was not definitively classified in the qualitative analysis. The quantitative analysis was subsequently used to evaluate the likelihood that these compounds were present in the sample.

Quantitative Analysis

The quantitative analysis consisted of two primary steps.

1. The relative intensities were compiled for each intensity level for each compound of interest from the XRD standards. This step was done in the same way that the peak angles were compiled as described in step 2 of the Qualitative Analysis subsection immediately preceding this subsection. Table 12 shows the results of this synthesis. Since the average values were used for calculation purposes, the average results are presented with the following exceptions. The first exception was that the first relative intensity for

each compound is always assigned a value of 100 percent, despite the fact that the average intensity for the range of angles associated with this intensity may have been less than 100 percent due to different PDFs having different rankings of the angles producing the maximum intensity, as explained in the previous subsection. The second exception was that there was no consensus peak angle for akaganeite, with three different PDFs giving three different peak angles. Therefore, the relative intensity of the first three intensities of akaganeite were all assigned to be 100 percent.

Table 12. Relative intensities (in percent) corresponding to maximum XRD intensities for compounds considered.

Compound	1st Relative Intensity	2nd Relative Intensity	3rd Relative Intensity	4th Relative Intensity	5th Relative Intensity	6th Relative Intensity	7th Relative Intensity	8th Relative Intensity
Lepidocrocite	100	72	59	38	24	29	20	24
Goethite	100	63	40	29	22	19	15	14
Akaganeite	100	100	100	55	29	19	29	32
Hematite	100	72	42	36	30	26	26	20
Maghemite	100	32	35	24	16	10	9	7
Magnetite	100	37	29	28	21	11	9	9
Feroxyhite	100	83	37	44	10	11	15	—
Ferrihydrite	100	75	50	58	52	69	38	59
Schwertmannite	100	46	37	24	23	21	18	12
Ferric sulfate	100	53	57	61	46	16	28	—

—No data to report.

2. The relative intensity of each compound in the specimen was calculated. In general, the research team took three approaches to calculating these values. These approaches are discussed as follows, in order of increasing complexity:

    - The simplest scenario was that for the highest intensity of a given compound, this compound was the only one contributing to the measured relative intensity at the given peak angle. An example of this scenario appears in table 11, where the first intensity level of goethite was the only contribution to the 72-percent relative intensity at the peak angle of 21.15 degrees. In these cases, the measured relative intensity was directly taken as the relative intensity of the associated compound.

    - If the highest intensity of a given compound occurred at the same peak angle as peak intensities of other compounds (the opposite of the scenario described in the preceding scenario), one alternative option was identifying another peak angle of the compound where no other compounds contribute. An example of this option appears in table 11, where at a peak angle of 34.25 degrees, only the second intensity level of ferrihydrite was present. In this case, the maximum relative intensity of the compound of interest was calculated as the ratio of the measured relative intensity to the average value for the given level of intensity. For example, again, using the second intensity level of ferrihydrite in table 11, which corresponded to a 32-percent relative intensity, and dividing this by the average second-level relative intensity of 75 percent from table 12, gave an estimated maximum relative intensity of akaganeite of 32 percent/0.75=43 percent.

- If neither of the previous two scenarios occurred, estimating the individual effects of two or more compounds that have the same peak angles was necessary. This estimation should ideally be done at a peak angle with only two contributing compounds and the relative intensity of one of these was already calculated. An example of this situation occurs in table 11 at a peak angle of 33.20 degrees, where the third intensity level of goethite and the first intensity level of hematite contributed to the measured 44-percent relative intensity. Recalling that the relative intensity of goethite was stated in the first approach as being 72 percent, this information was used to separate the individual effects of the two compounds by calculating the contribution of the known compound at the peak angle of interest as the product of the relative intensity of the compound in the sample and the relative intensity of the intensity level of that compound from table 12. So, returning to the same example, the third intensity level of goethite contributed 72 percent×40 percent=29 percent of the relative intensity at 33.20 degrees. The first intensity level of hematite contributed the balance of 44-percent relative intensity, i.e., 15 percent (44 percent minus 29 percent).

In some cases, both of the previous two approaches were used and compared, given that both involve some approximations. Similarly, the type of relative proportioning described in the last approach above was used to check if the inclusion or exclusion of compounds that were not definitively classified in the qualitative analysis resulted in more reasonable results to make a final determination on these compounds.

The relative percentage of each compound (X) in the specimen was calculated. The relative intensity of each compound (I_X; i.e., relative intensity of compound X) was simply divided by the sum of the relative intensities of all compounds (ΣI_i) to calculate the relative percentage of each compound, as shown by figure 14.

$$Relative\ percentage\ of\ compound\ X = \frac{I_X}{\sum I_i}$$

Figure 14. Equation. Relative percentage of compound.

A final check was to sum the effects of the individual compounds contributing to relative intensity values not used in other calculations. The relative intensity of 100 percent at 36.55 degrees in table 11 is an example. Specifically, the products of the relative intensity of each compound with a peak angle at the measured peak angle of interest (e.g., third intensity level of lepidocrocite, second intensity level of goethite, second intensity level of hematite, and first intensity level of ferrihydrite) and the calculated percentage of those compounds were summed and compared to the measured relative intensity. This comparison gives confidence that the qualitative analysis and quantitative results were reasonable. For example, again using the table 11 example, hematite was not definitively classified as being present or not present in the sample based on the qualitative analysis. However, the quantitative checks demonstrated less error when hematite was assumed to be present in the sample.

FIELD BRIDGE RESULTS

The field bridge results are summarized by table 13 and table 14 and later analyzed in chapter 8. The data are divided among two tables due to the large volume of data, with the adhesion and IC test results in table 13 and the XRD and section loss results in table 14. These tables present a summary of the most relevant metric for each of the types of field data collected. Specifically, from the tape adhesion results, the maximum, minimum, and average percentage of the area occupied by rust particles greater than 1/8 inch is reported. This metric was found to be the metric that most strongly correlated with inspectors' perception of when the UWS condition transitions from condition state 1 to condition state 2. From the IC results, the maximum, minimum, and average Cl^{-} concentration absorbed in the rust sample is presented. This IC metric was selected because Cl^{-} is the ion most strongly correlated with UWS performance.

Table 13. Summary of field data, adhesion, and IC test results.

Cluster	Structure No.	Adhesion Test Max (% area)	Adhesion Test Min (% area)	Adhesion Test Avg (% area)	Absorbed Cl^{-} Max (ppm)	Absorbed Cl^{-} Min (ppm)	Absorbed Cl^{-} Avg (ppm)
CO	E-16-JW	0.6	0.0	0.1	15,544	3,999	8,585
CO	E-16-JX	0.1	0.0	0.0	23,442	2,261	13,437
CO	E-16-JZ	1.6	0.0	0.6	40,054	194	10,438
CT	3830	12.6	1.2	6.8	3,722	229	1,668
CT	4382	18.9	6.7	12.2	5,229	1,003	2,658
CT	5796	9.5	0.0	5.4	2,232	234	1,052
IA	004111	6.9	0.2	3.1	6,328	2,297	4,300
IA	041331	17.1	0.2	5.5	9,697	1,431	5,409
IA	042711	4.0	0.0	1.6	9,307	424	4,813
LA+MS	238…961	20.9	0.0	5.9	243	1	75
LA+MS	244…671	14.4	0.0	3.8	93	1	26
LA+MS	625…011	13.6	0.0	0.6	34	1	6
MD+VA	6260	28.0	0.0	11.1	1,204	43	506
MD+VA	84010	31.6	0.0	15.0	4,572	1,051	2,990
MD+VA	82010	26.7	0.0	12.0	6,190	206	2,092
MD+VA	13	28.7	0.0	9.8	4,064	400	2,039
MN	4019	4.8	0.0	1.3	7,693	798	4,650
MN	19811	7.0	0.0	1.8	10,566	563	4,425
MN	62861	0.0	0.0	0.0	18,795	4,833	9,216
NC	190083	5.7	0.3	1.7	1,146	284	563
NC	1290057	34.2	0.0	11.2	1,092	143	601
NC	1290058	43.2	0.0	17.4	1,438	124	682
NH	111…900	27.2	0.0	5.6	3,895	303	1,898
NH	017…300	4.5	0.0	2.0	3,706	113	1,923
NH	017…700	57.4	1.2	13.6	3,164	426	1,401
NY	1072562	25.7	0	5.6	4,113	756	2,064
NY	1071860	58.3	0.3	13.8	8,713	365	4,175
NY	1071880	25.2	0	5.6	6,538	379	2,339
OH	7700105	14.5	0.2	5.6	7,863	1,758	4,032
OH	7701977	33.3	0.2	11.6	5,805	836	3,343
OH	7701993	17.2	0.0	7.4	7,117	689	3,236
TX	120…023	46.5	0	16.7	997	64	548
TX	121…177	25.3	0	2.3	2,182	83	769
TX	121…152	8.9	0	0.7	1,366	131	481

Table 14. Summary of field data, XRD, and section loss results.

Cluster	Structure No.	G:A Max (unitless)	G:A Min (unitless)	G:A Avg (unitless)	Section Loss Max (inches)	Section Loss Min (inches)
CO	E-16-JW[1]	0.94	0.94	0.94	0.01	0.00
CO	E-16-JX	0.31	0.00	0.13	[2]	[2]
CO	E-16-JZ	0.31	0.11	0.18	0.01	0.00
CT	3830	6.71	0.65	2.20	0.04	0.02
CT	4382	1.87	0.51	1.00	0.04	0.04
CT	5796	2.01	0.51	0.96	0.05	0.01
IA	004111	0.46	0.00	0.33	0.04	0.04
IA	041331	0.46	0.00	0.30	0.06	0.04
IA	042711	0.47	0.00	0.31	0.04	0.02
LA+MS	238…961	—	—	—	—	—
LA+MS	244…671	—	—	—	—	—
LA+MS	625…011	—	—	—	—	—
MD+VA	6260	—	—	—	—	—
MD+VA	84010	—	—	—	—	—
MD+VA	82010	—	—	—	—	—
MD+VA	00013	—	—	—	—	—
MN	4019	0.28	0.00	0.14	0.00	0.02
MN	19811	0.47	0.27	0.35	0.02	0.01
MN	62861	0.46	0.34	0.40	0.06	0.06
NC	190083	8.02	1.28	3.67	0.00	0.00
NC	1290057	10.45	0.69	4.99	0.03	0.02
NC	1290058	11.84	1.21	3.97	0.02	0.02
NH	111…900	1.01	0.00	0.53	NA	NA
NH	017…300	4.52	0.00	1.43	0.02	0.01
NH	017…700	1.66	0.46	0.86	0.04	0.00
NY	1072562	—	—	—	—	—
NY	1071860	—	—	—	—	—
NY	1071880	—	—	—	—	—
OH	7700105	0.55	0.42	0.46	0.07	0.04
OH	7701977	1.51	0.74	1.17	0.04	0.00
OH	7701993	2.29	0.48	1.40	0.03	0.03
TX	120…023	—	—	—	—	—
TX	121…177	—	—	—	—	—
TX	121…152	—	—	—	—	—

—Data not collected for phase 2 bridges.

G:A = ratio of goethite to akaganeite.

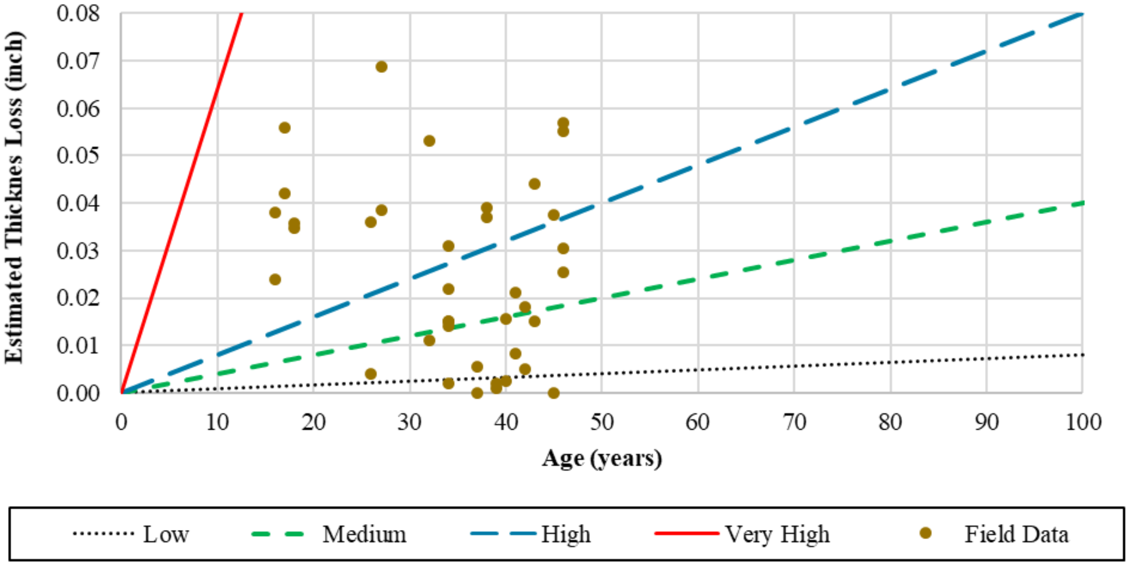
[1] Insufficient rust particles available to perform XRD analysis at more than one sample location.

[2] Section loss estimate not available.

The XRD data are summarized by presenting the ratio of goethite to akaganeite (G:A). Of five different XRD ratios evaluated in the statistical analysis performed in chapter 8, this ratio was found to best distinguish between the performances of different bridges. This finding was logical and consistent with past research, which generally suggests that the two compounds represented in this ratio (G:A) are two of the strongest indicators of good and inferior oxide layer development, respectively. Based on these prior findings, it follows that a relatively high ratio (e.g., value greater than 1) of percentage of goethite to percentage of akaganeite is an indicator of good performance, while a relatively low value of this ratio (e.g., value less than 1) is an indicator of inferior performance. The maximum, minimum, and average values of this ratio are presented in table 14 for each field bridge.

Because section loss was only measured at two locations, only the maximum and minimum of these two metrics are presented in table 14. No significant pitting generally occurred and is thus not included here for brevity.

Among other uses of this data, these results along with photos of each field bridge were reviewed to conclude whether the UWS of each field bridge was in good or inferior condition. This determination was made based on the consensus of the independent review by four subject matter experts (SMEs). Given the many data types (e.g., photos, tape samples, thickness loss, XRD) that exist and their wide variance, researchers independently established their own criteria for the classifications, but photos and thickness loss were key considerations. Because of the reliance on thickness loss, these values are plotted versus age of the structure (at the time of field sampling in 2019) in figure 15. Figure 15 also plots this data relative to the four highest corrosivity categories used by Albrecht et al. (1989): low, medium, high, and very high. These corrosivity categories give a range of thickness losses per year, with the upper bound of each range plotted in figure 15. Performance in the high, medium, low, or very low (not shown) categories is generally viewed as acceptable performance, with minimal thickness losses over the lifespan of a structure. Avoiding the use of UWS in the very high corrosivity category is generally recommended. However, Figure 15 shows that several data points fall in the very high category.



Source: FHWA.

Figure 15. Graph. Estimated section loss from UT measurements versus age.

These good or inferior classifications are compared to more quantitative assessments in chapter 8 and are, therefore, in contrast, termed “subjective classifications,” due to the variable criteria applied by each SME. The subjective classifications of the four SMEs (labeled as P1 to P4) are shown in table 15. In the Summary column, the majority or split opinion on the UWS performance is given. All the SMEs were in agreement on the performance of 12 of the 21 field bridges, and three SMEs were in agreement on 8 additional field bridges, with only 1 bridge having a split opinion, as shown in the last column.

Table 15. Subjective classifications of field bridge performance.

Bridge ID	P1	P2	P3	P4	Summary	Agree (no.)
CT 3830	Inferior	Good	Good	Good	Good	3
CT 4382	Inferior	Inferior	Good	Good	Good/ Inferior	2
CT 5796	Inferior	Inferior	Good	Inferior	Inferior	3
IA 041331	Inferior	Inferior	Inferior	Inferior	Inferior	4
IA 004111	Inferior	Inferior	Inferior	Inferior	Inferior	4
IA 042711	Inferior	Inferior	Inferior	Inferior	Inferior	4
NH 017701460003700	Inferior	Inferior	Inferior	Inferior	Inferior	4
NH 11101120017900	Inferior	Inferior	Inferior	Inferior	Inferior	4
NH 017201120011300	Good	Good	Good	Inferior	Good	3
MN 62861	Inferior	Inferior	Inferior	Inferior	Inferior	4
MN 04019	Inferior	Inferior	Good	Inferior	Inferior	3
MN 19811	Inferior	Inferior	Inferior	Inferior	Inferior	4
CO E-16-JX	Good	Good	Good	Good	Good	4
CO E-16-JZ	Good	Good	Good	Good	Good	4
CO E-16-JW	Good	Good	Good	Good	Good	4
NC 190083	Good	Good	Good	Inferior	Good	3
NC 1290057	Good	Good	Good	Inferior	Good	3
NC 1290058	Good	Good	Good	Inferior	Good	3
OH 7701993	Inferior	Inferior	Good	Inferior	Inferior	3
OH 7701977	Inferior	Inferior	Inferior	Inferior	Inferior	4
OH 7700105	Inferior	Inferior	Inferior	Inferior	Inferior	4

CHAPTER 6. INSPECTION REPORT DATA

This chapter describes the desk study evaluating UWS performance for cluster bridges. This study consisted of reviewing data from the most recent inspection report of each cluster bridge. This chapter describes the data contained within these inspection reports that were reviewed and how these data were used to classify UWS performance.

DESK STUDY METHODOLOGY

This section consists of two subsections describing the two desk study methodology. First the process of systematically reviewing the inspection reports to compile relevant information is described. Then the synthesis of this information to form conclusions relevant to this study is discussed.

Review of Inspection Reports

This section describes the type of information contained in the owners' inspection reports.

Overview of Inspection Reports

After all cluster bridges were identified, as discussed in chapter 4, the researchers requested the most recent inspection reports for each cluster bridge from their owners. Quantitative and qualitative information in these reports was used as the basis for the desk study, as described in the following subsections. In most cases, this information was largely based on the national bridge elements (NBE), a consistent nationwide classification system for bridge elements described in the *Manual for Bridge Element Inspection* (MBEI), which was used by a majority of owners at the time this research was carried out (American Association of State Highway and Transportation Officials (AASHTO) 2011, 2019). These procedures evolved throughout the course of this research with the publication of the first edition of the MBEI in 2011 and the second edition in 2019, as further described in the following subsections. Some inspection reports were instead based on the AASHTO commonly recognized (CoRe) element bridge inspection reporting system, a prior version of the same concept (AASHTO 2001). The team evaluated the differences between the use of these different rating systems and found them to be negligible for the purposes of this research. However, slightly differing types of information were available for different agencies and in phase 2 (completed from 2012 to 2014) compared to phase 3 (completed from 2018 to 2022) as these inspection procedures evolved.

Relevant information based on these reporting systems is described in the next two sections. All agencies also included qualitative text descriptions of UWS condition and associated photos for at least some bridges. A description of how this information was used concludes this section. While the researchers focused on agencies using the CoRe or NBE systems for consistency, a small number of agencies (2 of 13) used neither system. For these agencies, the team relied on qualitative descriptions and photos, in addition to the rating methods specific to those agencies.

NBE and CoRe Elements

The specific NBE and CoRe elements that are related to UWS performance include UWS elements such as girders/beams and various types of drainage devices and joints (e.g., pourable joint seal and compression joint seal), whose performance directly affects the performance of the structural elements beneath them. The NBE rating system also includes the concept of bridge management elements. Of specific interest in this category of elements is element 515, Steel Protective Coating (AASHTO2019). This element is optional and is an additional descriptor to a corresponding NBE. Data for nonstandardized UWS elements, namely diaphragms, were also included in the review, when available. All NBE and bridge management element numbers referenced below refer to the numbering used in the MBEI (AASHTO 2019).

Element Condition States and Associated Statistics Compiled

The quantitative data associated with each NBE or CoRe element are expressed by condition states, which are intended to be as objective and repeatable as possible, making this dataset ideal for comparing performance between structures and/or over time (Ryan et al. 2012). The condition state data provide two types of information regarding deterioration: the severity and extent. The condition states represent severity using an integer scale to represent the severity of any deterioration, with a condition state of 1 representing the best condition, and increasing integers indicating worse conditions. A 1 to 4 rating scale was used for UWS components in the CoRe rating system. Subsequently, a 1 to 4 rating scale was adopted for all elements in the NBE rating system, where the descriptors for each condition state were as follows (AASHTO 2011):

1. Good—No or minor deterioration.
2. Fair—Minor to moderate deterioration.
3. Poor—Moderate to severe deterioration.
4. Severe—Perhaps warranting structural review.

Specifically, for unpainted steel, the first edition of the MBEI defined the condition states as follows (AASHTO 2011):

1. No defects.
2. Pitting.
3. Section loss without capacity reduction.
4. Reduction in operation capacity.

With the second edition of the MBEI, painted steel and unpainted steel were no longer distinguished from one another in different bridge element categories, and the concept of defect type for each NBE was introduced. Corrosion (coded as defect 1000) was one of these defects with the following condition states defined (AASHTO 2019):

1. None.
2. Freckled rust: Corrosion of the steel has initiated.
3. Section loss is evident, or pack rust is present but does not warrant structural review.
4. The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge, or a structural review has been completed and the defects impact strength or serviceability of the element or bridge.

For the steel protective coating, the condition states were defined as follows (AASHTO 2019):

1. Yellow-orange or light brown for early development; chocolate-brown to purple-brown for fully developed; tightly adhered, capable of withstanding hammering or vigorous wire brushing.
2. Granular texture.
3. Small flakes less than 1/2-inch diameter.
4. Dark black color with large flakes 1/2-inch diameter or greater, or laminar sheets or nodules.

The amount of each NBE or CoRe element in each condition state was provided to indicate the extent of the deterioration. For example, for girders, this amount was typically expressed as length of the girders in each condition state, while the condition of the diaphragms may be expressed as a count of the diaphragms in each condition state. In other words, the same element could be in more than one condition state.

The NBE or CoRe element condition state data from each structure were normalized using the percentage of each element type in each condition state (AASHTO 2019). For example, if 1,130 total linear feet (LF) of open unpainted steel girders (NBE element 107) were in four different condition states: 1,049, 56, 24, and 1 LF in condition states 1 through 4, respectively, and then the percentages in each condition state were readily computed as 93, 5, 2, and 0 percent in condition states 1 through 4, respectively. This normalization allowed for comparisons between structures of different sizes and configurations to be made with greater ease.

Qualitative Descriptions

For the bridge owner inspection reports reviewed in this study, the researchers frequently found that if the condition state of the element is greater than 1, qualitative or additional quantitative text descriptions accompanied the condition state data. For example, statements from bridge owners, such as “surface rust on superstructure steel,” provided a qualitative understanding of the reason why 5 percent of the girders of the structure to which this statement was referring were placed in condition state 3. Also, often quantitative statements such as “rust scale with up to 1/16-inch section loss on bottom flange (5 ft length each)” further explained the specific situation of a given element. All such statements were read, and lists of keywords associated with each CoRe element were noted when possible (although the presence, volume, and substance of such notes varied considerably among different structures). For example, keywords such as corrosion, pack rust, rust/scale, and section loss reflected UWS-related issues potentially affecting structural performance, whereas keywords such as impact or missing bolts were not considered UWS-related issues.

Photos

The qualitative descriptions discussed in the preceding section often referred to specific photos that were included elsewhere in the inspection report. These photos were valuable in further clarifying the condition of various elements. They were also useful in illustrating the surroundings of the bridges, which provided insight on planning field work in some cases.

Use of Inspection Reports

For all cluster bridges, the bridge owners' inspection report data were used to make a preliminary assessment of whether each bridge was experiencing overall corrosion. This single binary descriptor of corrosion was adopted after more quantitative approaches based on condition state data were found to produce dispersed results that prohibited a clear conclusion from being formed. These classifications were primarily based on the percentage of the girders in condition state 1 compared to condition states 2 or higher. Element 515 (steel protective coating) of the girders was the primary consideration when available, and element 107 (steel girder/beam) was the primary consideration when element 515 data were not provided (AASHTO 2019).

Oftentimes 100 percent of the girders were either classified into condition state 1, in which case the bridge was classified as not having overall corrosion, or into condition states 2 or higher, in which case the bridge was classified as having overall corrosion. For cases in which some percentage of the girders (as quantified by either element 515 when available or element 107 otherwise) were in both condition state 1 and condition states 2 or higher, the inspectors' notes were evaluated to classify the bridge. The presence of leaking joints and the overall size of the structure were also considered in making classifications in these cases.

The research team then compared these preliminary classifications to the classifications of the field bridges. In most cases, two classification systems were in agreement. However, in some cases, bridges were classified as not having overall corrosion based on the inspection reports but were classified as having overall corrosion based on the field results. Because the field results were more quantitative and standardized across all clusters, the field results were used in the final categorizations of field bridges.

In cases in which the field and inspection report classifications in a given cluster disagreed, the inspection reports for all bridges within that cluster were reassessed. This step was important, because disagreement between the field and inspection reports for any bridge indicates the possibility for systemic differences in what is classified as condition state 2 or higher within a given agency compared to what was considered overall corrosion in this study. The inspection report for the bridge(s) with disagreement between the field and inspection report conclusions was compared to the other inspection reports in that cluster. If the team found them to be similar to other inspection reports, then all bridges with similar inspection reports were not definitively classified.

DESK STUDY RESULTS

Table 16 summarizes the result of the desk study by indicating the number of bridges from each cluster (see chapter 4 for cluster details) that were categorized as having or not having overall corrosion and the number of bridges for which a definitive classification could not be made and were thus placed in the overall corrosion unknown category. Table 16 shows that for some clusters (those in Colorado, Iowa, North Carolina), all the bridges were in a single category, but typically more varied performance was observed.

Table 16. Summary of desk study results.

Cluster	Cluster Type	Overall Corrosion = No (no.)	Overall Corrosion = Yes (no.)	Overall Corrosion = Unknown (no.)
Colorado	Deicing	10	0	0
Iowa	Deicing	0	14	0
Maryland+ Virginia	Deicing	7	9	5
Minnesota	Deicing	0	9	11
New York	Deicing	15	2	3
Ohio	Deicing	0	10	6
Connecticut	Deicing+coastal	0	2	19
New Hampshire	Deicing+coastal	12	16	0
Louisiana+ Mississippi	Coastal	15	0	3
North Carolina	Coastal	10	0	0
Texas	Coastal	15	2	0

For some clusters (particularly those in Connecticut, Minnesota, and Ohio), a relatively large number of bridges were classified as overall corrosion unknown. This classification occurred because of a conflict between the field data from chapter 5 and one or more inspection reports. In all cases, the conflict was that a bridge that was classified as having overall corrosion in the field was classified as not having overall corrosion based on the inspection report. No occurrences of the opposite scenario occurred, which was logical, given the more thorough data collection efforts in this field work compared to the resources typically available for a routine inspection.

Specifically, in Connecticut and Ohio clusters, at least one field bridge had an estimated thickness loss (based on ultrasonic thickness measurements) that was categorized as "very high" per the corrosion rates given in National Cooperative Highway Research Program Report 314 and was indicated as not experiencing overall corrosion based on the owner's inspection report (Albrect et al. 1989). This category is the most severe, equating to greater than 0.0004 inches/yr per exposed surface, i.e., greater than 0.0008 inches/yr for the bottom flanges with top and bottom surfaces exposed. (There were also bridges meeting the criteria for a very high corrosion rate that were classified as having overall corrosion based on the owner's inspection report.) In Minnesota clusters, large rust flakes were observed on one field bridge that were not noted in the owner's inspection report.

Therefore, the researchers adopted a conservative approach for these three agencies. Because of the conflict that the field data sometimes indicated more severe corrosion than the inspection reports, all bridges in these agencies that were indicated as not having overall corrosion based on the initial review of the inspection reports were categorized in the overall corrosion unknown category. The consequence of this conservative approach was simply that these bridges (labeled as overall corrosion being unknown) were not used in the dataset used for making final recommendations for onsite conditions of caution for UWS in chapter 9. They were retained for all other purposes (e.g., the statistical analysis used in chapter 8). Furthermore, this situation does not necessarily suggest a systemic issue with the inspection process in these agencies, for UWS, or in general.

CHAPTER 7. DATA ON OWNERS' PRACTICES

INTRODUCTION

This introduction section contains two subsections. The first discusses the objectives and scope of the data on owners' practices that was collected in this study. The second describes the methods of analysis that were used.

Objective and Scope

LTBPP State coordinators in 52 agencies (one representing the highway agencies of each State, District of Columbia, and Puerto Rico) were queried regarding their maintenance practices in general, bridge washing in particular, and usage rates of specific deicing agents. To supplement these data on bridge maintenance, some additional State maintenance manuals (abbreviated as MM in subsequent tables) were available to the researchers from prior work, and bridge-washing data from an AASHTO Subcommittee on Bridges and Structures (SCOBS) survey was also obtained (AASHTO 2016, 2018a). In addition to the deicing agent data from the LTBPP State coordinator inquiries, data from Clear Roads was extracted (Clear Roads 2019). These data were also reviewed and synthesized as input data for the UWS database discussed in chapter 3, which was then used for statistical analyses to assess the influence of these variables, as described in chapter 8.

Methods of Analysis

The section describes the methods that were used to collect and synthesize data on owners' practices.

Querying the LTBPP Portal for Relevant Information

A first step in this task was to query the LTBPP portal for any information on owners' practices (FHWA 2022b). That query yielded no information on these factors because of the difficulty of getting structured data on these variables.

Owner Inquiries

Inquiries to State bridge owners were used to learn the maintenance actions typically performed on their bridges, including, in particular, if they wash their bridges, and the type and amounts of deicing agents they use for ice and snow removal. The team performed two quality control steps on the gathered information. First, responses to open-ended questions were sorted into a manageable number of discrete categories. Owners were asked to confirm these categorizations were accurate. Second, the deicing agent data were reviewed and found to be highly variable, even between agencies with relatively similar environments. Thus, the data received from each agency were compared to the average quantities. This information was then shared with the owners, and the owners were asked to confirm if this comparison was reasonable in their opinion or if the data should be updated. This process resulted in the team correcting some misunderstandings about the type of data that were being sought (e.g., cumulative annual totals versus application rates per pass of a plow truck) and other reporting errors. All final data were reviewed for reasonableness and found to be satisfactory. These results are presented as follows.

Gathering and Synthesizing Available State Maintenance Manuals

Another step to developing a better understanding of the current maintenance practices and their impact on the performance of UWS was to gather, review, and synthesize State maintenance manuals. State agencies were asked to provide their bridge maintenance manual or any other information related to current practices for maintenance of UWS bridges. The details of the manuals obtained and the results of the synthesis are presented as follows.

Gathering and Synthesizing Other Relevant Information

During the final stages of this research, two existing datasets relevant to this study were discovered. One was the annual "State Bridge Engineers Survey" conducted by AASHTO SCOBS (AASHTO 2016, 2018a). This survey contained four questions related to bridge washing. The data from these responses were analyzed as part of the bridge-washing data presented in the following subsections.

The other relevant dataset that was discovered was the "Annual Survey of State Winter Maintenance Data" conducted by Clear Roads (2019). This dataset contained winter maintenance data for each agency, including deicing agent usage in tons of salt applied, gallons of salt brine applied, and total lane miles. The data from this survey were incorporated in the deicing agent usage data presented in the following subsections.

FINDINGS RELATED TO BRIDGE MAINTENANCE AND DEICING AGENT USE

This section contains three subsections discussing the findings on maintenance manuals, bridge washing, and deicing agent use, respectively.

Findings from Review of Maintenance Manuals

This section discusses the response rates and findings from the review of maintenance manuals in separate subsections.

Response Rates

Each LTBPP State coordinator was asked to provide any bridge maintenance manuals used by their agency. A summary of the type of responses received (or lack thereof) from the 52 agencies in terms of maintenance manuals is shown in table 17. Overall, bridge maintenance manuals were available for review from a total of 34 agencies. Twenty-one agencies that responded to the inquiry supplied maintenance manuals pertaining to bridge maintenance practices, and manuals were available from an additional 13 agencies from prior work (Shenton, Mertz, and Weykamp 2016). Twelve agencies responded but were unable to provide a manual. Of these 12, 4 agencies responded that they were in the process of working on a manual, and 8 agencies responded that they did not have a bridge maintenance manual. Nineteen agencies did not respond to the inquiry, and therefore a manual was unavailable.

Table 17. Maintenance manual responses.

Agency	Manual Provided	Working on Manual	No Manual	No Response	Manual from Other Work[1]
Alabama	—	—	X	—	X
Alaska	—	—	—	X	—
Arizona	X	—	—	—	—
Arkansas	—	X	—	—	X
California	X	—	—	—	—
Colorado	X	—	—	—	—
Connecticut	X	—	—	—	—
Delaware	—	—	X	—	X
District of Columbia	—	—	X	—	—
Florida	X	—	—	—	—
Georgia	—	—	—	X	X
Hawaii	—	—	—	X	X
Idaho	—	—	—	X	—
Illinois	—	X	—	—	—
Indiana	X	—	—	—	—
Iowa	X	—	—	—	—
Kansas	—	—	—	X	—
Kentucky	—	—	—	X	—
Louisiana	—	—	—	X	—
Maine	X	—	—	—	—
Maryland	—	—	X	—	X
Massachusetts	—	—	—	X	—
Michigan	—	X	—	—	X
Minnesota	X	—	—	—	—
Mississippi	—	—	—	X	—
Missouri	X	—	—	—	—
Montana	—	—	—	X	X
Nebraska	—	—	X	—	X
Nevada	—	—	—	X	X
New Hampshire	X	—	—	—	—
New Jersey	—	—	—	X	X
New Mexico	X	—	—	—	—
New York	X	—	—	—	—
North Carolina	—	—	—	X	—
North Dakota	X	—	—	—	—
Ohio	X	—	—	—	—
Oklahoma	—	—	—	X	—
Oregon	—	X	—	—	—
Pennsylvania	X	—	—	—	—
Puerto Rico	—	—	—	X	—
Rhode Island	—	—	X	—	—
South Carolina	—	—	—	X	—
South Dakota	—	—	X	—	X

Agency	Manual Provided	Working on Manual	No Manual	No Response	Manual from Other Work[1]
Tennessee	—	—	—	X	—
Texas	X	—	—	—	—
Utah	—	—	—	X	X
Vermont	—	—	X	—	—
Virginia	X	—	—	—	—
Washington	X	—	—	—	—
West Virginia	—	—	—	X	—
Wisconsin	X	—	—	—	—
Wyoming	X	—	—	—	—
Total	21	4	8	19	13

[1] Shenton, Mertz, and Weykamp 2016.

—No relevant information.

X = Answer received from respondent.

Review of Maintenance Manuals Results

The bridge maintenance manuals that were available from the 34 agencies were each reviewed in terms of information relevant to UWS bridge performance. Common categories were found between most of the manuals. These categories included joint maintenance, bearing maintenance, bridge washing, girder maintenance, information specific to UWS bridges, and corrosion. Table 18 lists the specific categories of information that were established to organize the contents provided in various manuals.

To condense and quantify this information, an objective quantitative rating, ranging between 0 and 3, was given to each manual based on the number of the categories listed in table 18 that it contained. An objective rating of 3 corresponded to more than six categories, a rating of 2 corresponded to four or five categories, a rating of 1 corresponded to one to three categories, and a rating of 0 corresponded to zero categories. A subjective quantitative rating, ranging between 1 and 3, was also given based on the extent of information provided in the manual. For the subjective quantitative rating, a rating of 3 corresponded to extensive information, such as likely defects along with suggested repair and/or maintenance activities; a rating of 2 corresponded to a mention of repair and/or maintenance activities; and a rating of 1 corresponded to no repair and/or maintenance information.

Most of the manuals that were reviewed contained information on four or five of the categories listed in table 18. The scope of information provided in the manuals was generally rather detailed. Three manuals received both an objective and subjective rating of 3, meaning they included a majority of the maintenance categories and provided information about bridge defects, along with suggested repairs or maintenance practice protocols. These manuals were the overall highest rated. Three manuals received a quantitative rating of 0 and qualitative rating of 1, meaning they included none of the maintenance categories and had no maintenance or repair information. These manuals were the overall lowest rated.

Table 18. Review of maintenance manual results.

Agency	Joint Clean	Joint Repair/ Maintenance	Joint Elimination	Bearing Clean	Bearing Repair/ Maintenance	Girder Clean	Bridge Wash (General)	Beam End Wash (Only)	Girder Repair/ Maintenance	UWS Specific	Corrosion	Objective MM Rating	Subjective MM Rating
AL	X	X	—	X	—	—	—	—	X	—	—	2	2
AZ	—	—	—	—	—	—	—	—	—	—	—	0	1
AR	X	X	X	—	—	—	—	X	—	—	—	2	3
CA	—	X	—	—	—	—	—	—	X	—	—	1	2
CO	—	X	X	—	X	—	X	—	—	X	X	2	3
CT	—	X	—	—	X	—	X	—	—	—	X	2	2
DE	—	X	—	X	X	X	—	—	X	—	—	2	3
FL	—	X	—	X	X	—	—	—	X	—	X	2	3
GA	X	X	—	—	X	—	—	—	X	—	—	2	3
HI	—	X	—	—	X	—	—	—	X	—	—	1	2
IN	X	—	—	X	—	—	—	X	—	—	—	1	2
IA	X	X	—	—	X	X	—	—	X	—	—	2	3
MA	—	—	—	—	—	—	—	—	—	—	—	0	1
MD	X	X	—	X	X	—	—	—	—	—	—	2	2
MI	—	X	—	—	—	—	X	—	—	—	—	1	2
MN	X	X	—	X	X	—	—	—	X	X	—	2	2
MO	X	X	—	X	X	X	—	—	—	—	—	2	3
MT	X	X	—	X	—	X	—	—	—	—	—	2	2
NE	X	X	—	X	X	X	—	—	X	—	X	3	3
NV	—	X	—	—	X	—	—	—	X	—	X	2	3
NH	—	—	—	—	—	—	X	—	—	—	—	1	1
NJ	—	X	—	—	X	—	—	—	X	X	X	2	3
NM	—	X	—	—	—	—	—	—	X	—	—	1	2
NY	—	X	—	X	X	—	—	X	X	X	—	2	3
ND	X	X	—	X	X	X	—	—	—	—	—	2	3

Agency	Joint Clean	Joint Repair/ Maintenance	Joint Elimination	Bearing Clean	Bearing Repair/ Maintenance	Girder Clean	Bridge Wash (General)	Beam End Wash (Only)	Girder Repair/ Maintenance	UWS Specific	Corrosion	Objective MM Rating	Subjective MM Rating
OH	—	X	—	—	X	—	—	—	X	—	X	2	3
PA	X	X	X	X	X	X	—	—	X	—	X	3	3
TX	X	—	—	—	—	—	—	—	—	—	—	1	2
UT	—	—	—	—	—	—	—	—	—	—	—	0	1
VA	—	X	X	—	—	—	—	—	X	—	X	2	3
WA	X	X	—	—	—	—	—	—	—	—	—	1	2
WI	X	X	X	X	X	—	—	X	—	—	X	3	3
WY	X	X	—	X	X	—	—	—	—	—	—	2	2
Total	16	27	5	14	19	7	4	4	16	4	10		

—No relevant information.

X = answer received from respondent; MM = maintenance manual.

Findings from Washing Inquiry

This section first provides an introduction describing the specific type of washing information that was collected. Then response rates and findings from the washing inquiry are discussed in separate subsections. Introduction

An inquiry on washing practices aimed to:

- Determine whether agencies washed bridges.
- Quantify the approximate percentage of UWS bridges washed: None, less than 10 percent, 10–50 percent, or greater than 50 percent.
- Quantify washing frequency: More than once per year, annually, every 2 yr, or less frequently than every 2 yr.
- Determine when bridges were washed: Not washed in any particular time of year, typically washed in the spring, or typically washed during some other time of year.
- Determine if the washing practices for UWS bridges included the girders: Always, at least half of the time (i.e., mostly), less than half of the time (i.e., rarely), or never.
- Determine if different washing practices existed for UWS bridges and other bridges.

The focus of this subsection is to discuss the responses to the preceding questions. In addition to the inquiries conducted as part of the present research, AASHTO SCOBS conducts an annual “State Bridge Engineers Survey” (AASHTO 2016, 2018a). These surveys contained the following questions regarding bridge washing:

- Does your State have a maintenance policy that includes regularly scheduled washing of high-performance steel or weathering steel superstructures?
- Does your agency use bridge-washing contracts?
- Has your agency successfully included any of these preventative maintenance activities on a bridge-washing contract (followed by a listing of activities)?
- Has your agency conducted a comprehensive study of the cost-effectiveness of bridge cleaning and washing measures?
- Has your agency evaluated the effect of a periodic program of bridge cleaning and washing on the service life of bridge elements?

The comparison of the responses to these questions for the most recent surveying year is also discussed in the following subsection.

Response Rates

Responses to the washing practices inquiry were received from the 33 State highway agencies listed in table 19. Table 19 also shows that two-thirds (22) of the responding agencies performed bridge washing and 19 of these answered all the questions listed in the preceding subsection. The majority of the questions were not applicable for agencies that did not wash their bridges.

Washing Inquiry Results

Table 19 shows that, of the 33 respondents, 22 agencies reported performing bridge washing to some extent. This represented a majority of the agencies that responded to the inquiry (67 percent) but only 42 percent of all agencies. In comparison, 12 agencies out of 40 respondents reported in the 2018 AASHTO survey utilizing bridge-washing contracts. It is possible that the discrepancy in the present inquiry and the AASHTO surveys was related to the specificity of asking if bridges were washed by contracts in the AASHTO survey, given that some owners may use their own resources to perform bridge washing.

Even though the majority of the respondents in the present inquiry indicated that they do perform bridge washing, this should not be interpreted to mean that bridge washing is a common practice. This conclusion was based on the fact that table 19 indicates that only four agencies reported that they wash more than 50 percent of their bridges. This number was similar to the 2016 AASHTO survey, where five respondents reported having a policy of regularly washing high-performance steel.

Other information summarized by table 19 includes that 22 agencies provided information on the frequency of bridge washing. Regarding the time of year during which washing is performed, 16 agencies reported that washing was performed in the spring. No other regular time of year was reported, but one agency reported that the time of year varied based on contracts. Table 19 shows that agencies washed the girders of the bridge relatively rarely, with the washing typically limited to other components such as decks, bearings, and/or drainage systems. The majority of respondents indicated that they have equivalent washing practices for UWS and other bridge types. Five agencies reported that they have different practices, but no details on the differences were provided or could be discerned from the agencies' maintenance manuals.

Regarding the other aspects of bridge washing that were queried by the AASHTO surveys, no more than one agency indicated the successful use of any other preventative maintenance activity on a bridge-washing contract (AASHTO 2016, 2018a). These items represented fairly generic items. Those that were reported to be successful by a single agency were: joint sealing, spot painting, joint closures, bridge repairs, drainage repairs, bearing replacement, corrosion protection, and other. No agencies reported having conducted any analysis of cost-effectiveness or service life related to bridge washing.

Table 19. Bridge washing responses.

Agency	Washed (Yes/No)	Washed (percent)	Wash Frequency	Wash Period	Wash Girders[1]	Difference Between UWS and Other Bridges (Yes/No)
Alabama	No	0	—	—	—	—
Arizona	No	0	—	—	—	—
Arkansas	Yes	<10	Less frequently	Spring	No	No
California	No	0	—	—	—	—
Colorado	No	0	—	—	—	—
Connecticut	No	0	—	—	—	—
Delaware	No	0	—	—	—	—
District of Columbia	Yes	—	Less frequently	—	—	—
Florida	No	0	—	—	—	—
Illinois	Yes	<10	Annually	Other (by contract)	Rarely	No
Indiana	Yes	>50	Annually	Spring	No	No
Iowa	Yes	<10	Less frequently	Spring	Rarely	Yes
Maine	Yes	>50	Annually	Spring	No	No
Maryland	No	0	—	—	—	—
Michigan	Yes	<10	Annually	Spring	Rarely	No
Minnesota	Yes	>50	Annually	Spring	Typically	No
Missouri	Yes	10–50	Annually	Spring	Rarely	No
Montana	No	0	—	—	—	—
Nebraska	Yes	<10	Annually	—	Rarely	Yes
New Hampshire	Yes	10–50	Every 2 yr	Spring	Rarely	No
New Mexico	No	0	—	—	—	—
New York	Yes	10–50	Every 2 yr	Spring	No	Yes
North Dakota	Yes	10–50	Annually	Spring	Rarely	No
Ohio	Yes	10–50	Annually	Spring	No	No
Oregon	Yes	—	Every 2 yr	—	—	—
Pennsylvania	Yes	10–50	Less frequently	—	No	Yes
Rhode Island	Yes	10–50	Every 2 yr	Spring	Always	No
South Dakota	Yes	>50	Annually	Spring	No	No
Texas	Yes	—	Less frequently	—	—	—
Virginia	Yes	<10	Annually	Spring	No	No
Washington	Yes	<10	Annually	Spring	Always	Yes
Wisconsin	Yes	10–50	Every 2 yr	Spring	Rarely	No
Wyoming	No	0	—	—	—	—

—Data not provided.

[1] Typically = at least half of the time; Rarely = less than half of the time.

Findings from Deicing Agent Use Inquiry

This section discusses the response rates and findings from the deicing agent use inquiry in separate subsections.

Response Rates

The researchers received a total of 24 responses from the inquiry asking each LTBPP State coordinator to supply as much information as possible regarding salts or chemicals used for deicing and snow removal. Near the conclusion of the data collection period, one of the respondents forwarded State-level data on deicing agents collected by Clear Roads (2019). Clear Roads "is a national research consortium focused on rigorous testing of winter maintenance materials, equipment, and methods for use by highway maintenance crews." The Clear Roads quantities and lane miles were found to be in general agreement with the deicing agent data that had been previously collected. In 33 cases, the Clear Roads data contained information from agencies for which no data, or incomplete data, were received as part of the present study. In these situations, the Clear Roads data were extracted and added to the present dataset. In total, deicing agent data were available from 38 agencies.

The team received a wide range of types of responses in terms of the deicing chemicals that were used and the level of detail of the data. To refine this information, the chemicals that were reported by each agency were categorized into corrosive solids, corrosive brines, and other. Corrosive solids included the following Cl^- containing chemicals: sodium chloride (NaCl), magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$). Corrosive brines included those containing Cl^- chemicals, including NaCl, $MgCl_2$, and $CaCl_2$. In addition, the brine quantities were converted to an equivalent weight of solid deicing agents to estimate total equivalent solids used for deicing. This calculation allowed for a single value to represent the summative deicing agent use within each agency.

The brine quantities were converted to solid quantities, as shown in figure 16. This conversion assumed typical brine concentrations that result in equal deicing capability for each of the three compounds, 23-percent NaCl solution, 32-percent $CaCl_2$ solution, and 27-percent $MgCl_2$ solution (Blackburn and Associates 2014).

$$1\ gal\ \ 23\%\ NaCl\ solution\ x\ \left(\frac{23\ lbs\ NaCl}{100\ lbs\ NaCl\ solution}\right) x \left(\frac{9.79\ lbs\ NaCl\ solution}{gal.}\right) x\ \left(\frac{0.61\ lb\ Cl^-}{lb\ NaCl}\right) = \ 1.4\ lbs\ Cl^-$$

Figure 16. Equation. Brine to solid quantities conversion.

Similarly, 1 gal of 32-percent $CaCl_2$ solution equals 2.2 lb Cl^-, and 1 gal of 27-percent $MgCl_2$ solution equals 2.1 lb of Cl^-. It should be understood that the assumption of the brine concentrations is only an approximation but is useful for providing an estimate. The sum of performing this type of calculation for each compound and the total amount of solid deicing agents is termed the total equivalent solids.

Quantities of other (non- Cl^- containing) deicing agents were deemed too variable to be meaningfully synthesized. A total of 30 responses were received from the original inquiry. The data that were provided revealed that the most relevant data that were widely available were agency-wide averages of annual quantities per lane mile. Deicing agent quantities per lane mile provided more valuable information by normalizing the data between each agency.

Deicing Agent Usage Results

Table 20 shows amounts of corrosive solids (NaCl, $CaCl_2$, and $MgCl_2$) and corrosive brines (NaCl brine, $CaCl_2$ brine, and $MgCl_2$ brine) for the 38 agencies from which these data were available. The total number of lane miles that these deicing agents were applied to by each agency is also reported in table 20. Deicing agent usage was also recorded in terms of quantities per lane mile to normalize the data and be able to compare usage rates between each agency.

Table 21 shows summary statistics for the data in table 20. The median, mean, standard deviation, maximum, and minimum are reported for each corrosive solid and each corrosive solid per lane mile (NaCl, $CaCl_2$, and $MgCl_2$), as well as each corrosive brine and each corrosive brine per lane mile (NaCl brine, $CaCl_2$ brine, and $MgCl_2$ brine). These statistics allowed comparisons to be made between the deicing agent data for each agency relative to the total population. For instance, the individual data for each agency can be compared with the mean or median to see if that agency used a relatively high or low amount of deicing agents compared with the rest of the dataset.

Table 22 shows the State average compared to the local jurisdiction maximum and minimum deicing agent usage for the four agencies that supplied regional data. The data in table 22 are in terms of corrosive solids applied per lane mile, because only Wisconsin supplied information on corrosive brines at this level of detail. The data in table 22 show that the maximum was between two and nine times the minimum deicing agent use for these four agencies, and the maximum was, on average, twice the average deicing agent use for these four agencies. The region corresponding with the maximum and minimum application rates for each agency is also listed. In addition to the data in table 22, Wisconsin supplied information on corrosive brines at the county level. These data showed a variability between 0 gal/lane (in multiple counties) and 477 gal/lane mi in Florence County, WI (which is in a rural area), with an average of 76.8 gal/lane mi. This measurement indicated that the State average deicing agent use metrics may be poor representatives of actual deicing agent use at any specific site.

Table 20. Deicing agent usage responses.

Agency	NaCl (tons)	NaCl/Lane Mile (tons/lane mi)	$CaCl_2$ (tons)	$CaCl_2$/Lane Mile (tons/lane mi)	$MgCl_2$ (tons)	$MgCl_2$/Lane Mile (tons/lane mi)	NaCl Brine (gal)	NaCl Brine/Lane Mile (gal/lane mi)	$CaCl_2$ Brine (gal)	$CaCl_2$ Brine/Lane Mile (gal/lane mi)	$MgCl_2$ Brine (gal)	$MgCl_2$ Brine/Lane Mile (gal/lane mi)	Lane Miles
AL	8,050	0.27	18,210	0.62	0	0.00	310,000	10.59	47,000	1.61	0	0.00	29,273
AK	6,200	0.53	3	0.00	0	0.00	1,119,000	95.10	0	0.00	50,000	4.25	11,766
AZ	19,000	1.36	8	0.00	—	—	160,493	11.46	—	—	38,463	2.75	14,000
AR	—	—	—	—	—	—	—	—	—	—	—	—	—
CA	25,000	0.49	0	0.00	10,000	0.20	900,000	17.76	0	0.00	450,000	8.88	50,679
CO[1]	172,325	7.49	8	0.00	910	0.04	1,204,444	52.37	0	0.00	10,266,402	446.37	23,000
CT	221,450	20.37	0	0.00	0	0.00	302,400	27.82	0	0.00	1,231,650	113.31	10,870
DC	—	—	—	—	—	—	—	—	—	—	—	—	—
DE	108,000	8.02	—	—	—	—	2,539,000	188.46	—	—	—	—	13,472
FL[1]	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	—
GA	20,746	0.52	117	0.00	0	0.00	600,000	15.03	200,000	5.01	0	0.00	39,919
HI	—	—	—	—	—	—	—	—	—	—	—	—	—
ID	116,828	9.48	0	0.00	0	0.00	7,395,559	600.29	0	0.00	1,939,630	157.44	12,320
IL[1]	550,214	12.06	16	0.00	—	—	1,534,975	33.65	428,495	9.39	—	—	45,617
IN[2]	225,000	7.50	—	—	—	—	—	—	—	—	—	—	30,000
IA	175,368	7.16	1,881	0.08	0	0.00	32,386,191	1,322.86	32,791	1.34	0	0.00	24,482
KS	96,000	3.79	0	0.00	0	0.00	3,900,000	154.15	0	0.00	18,000	0.71	25,300
KY	241,000	3.80	0	0.00	0	0.00	686,300	10.81	808,500	12.73	0	0.00	63,500
LA	—	—	—	—	—	—	—	—	—	—	—	—	—
ME	164,360	19.80	24	0.00	—	—	521,828	62.87	—	—	724,675	87.31	8,300
MD	184,877	10.78	—	—	—	—	3,008,000	175.47	—	—	9,870	0.58	17,143
MA	455,800	29.53	85	0.01	—	—	100,000	6.48	—	—	1,672,200	108.33	15,436
MI	619,043	19.32	—	—	—	—	1,794,885	56.01	566,806	17.69	—	—	32,045
MN	251,418	8.22	148,463	4.85	41,727	1.36	4,103,496	134.17	148,463	4.85	41,727	1.36	30,585
MS	—	—	—	—	—	—	—	—	—	—	—	—	—
MO	145,000	1.87	0	0.00	0	0.00	3,371,000	43.46	525,000	6.77	0	0.00	77,570
MT	1,858	0.07	0	0.00	0	0.00	7,089,690	283.59	0	0.00	3,079,795	123.19	25,000
NE	104,729	4.52	0	0.00	0	0.00	—	—	0	0.00	1,040,104	44.89	23,168
NV	—	—	—	—	—	—	—	—	—	—	—	—	—
NH	231,257	24.69	0	0.00	0	0.00	315,760	33.71	7,099	0.76	63,152	6.74	9,366
NJ	—	—	—	—	—	—	—	—	—	—	—	—	—
NM[1]	741	—	—	—	—	—	—	—	—	—	—	—	—
NY	1,280,000	28.78	—	—	—	—	939,000	21.11	36,520	0.82	138,580	3.12	44,472
NC	—	—	—	—	—	—	—	—	—	—	—	—	—

Agency	NaCl (tons)	NaCl/Lane Mile (tons/lane mi)	$CaCl_2$ (tons)	$CaCl_2$/Lane Mile (tons/lane mi)	$MgCl_2$ (tons)	$MgCl_2$/Lane Mile (tons/lane mi)	NaCl Brine (gal)	NaCl Brine/Lane Mile (gal/lane mi)	$CaCl_2$ Brine (gal)	$CaCl_2$ Brine/Lane Mile (gal/lane mi)	$MgCl_2$ Brine (gal)	$MgCl_2$ Brine/Lane Mile (gal/lane mi)	Lane Miles
ND	43,865	2.54	0	0.00	0	0.00	2,562,457	148.50	0	0.00	0	0.00	17,256
OH	955,051	22.05	82	0.00	0	0.00	10,628,625	245.44	928,989	21.45	0	0.00	43,304
OK	—	—	—	—	—	—	—	—	—	—	—	—	—
OR	4,558	0.24	0	0.00	0	0.00	0	0.00	0	0.00	7,600,000	398.11	19,090
PA	1,000,000	10.42	0	0.00	0	0.00	11,800,000	122.92	0	0.00	0	0.00	96,000
Puerto Rico	—	—	—	—	—	—	—	—	—	—	—	—	—
RI	154,000	48.35	0	0.00	0	0.00	14,000	4.40	0	0.00	800	0.25	3,185
SC	—	—	—	—	—	—	—	—	—	—	—	—	—
SD	63,558	3.41	—	—	—	—	1,575,146	84.63	—	—	416,894	22.40	18,612
TN	—	—	—	—	—	—	—	—	—	—	—	—	—
TX	20,944	0.11	30	0.00	1,256	0.01	5,815,454	30.91	0	0.00	0	0.00	188,128
UT	260,105	10.62	0	0.00	0	0.00	0	0.00	4,971	0.20	268,451	10.96	24,500
VT	173,365	26.63	0	0.00	0	0.00	2,639,940	405.46	0	0.00	214,034	32.87	6,511
VA	—	—	—	—	—	—	—	—	—	—	—	—	—
WA	68,800	3.64	—	—	—	—	—	—	781,300	41.34	529,300	28.01	18,900
WV	281,118	3.75	169	0.00	55	0.00	982,730	13.10	110,421	1.47	0	0.00	75,000
WI	567,600	16.37	96	0.00	0	0.00	5,742,575	165.60	164,695	4.75	146,059	4.21	34,678
WY	—	—	—	—	—	—	—	—	—	—	—	—	—

—No data to report.

[1] Data from inquiry.

[2] Indiana provided a range for their NaCl usage (i.e., 200,000–250,000 tons), so the average of 225,000 tons was used in the dataset.

Table 21. Deicing agent use statistics.

Statistic	NaCl (tons)	NaCl/Lane Mile (tons/ lane mi)	$CaCl_2$ (tons)	$CaCl_2$/Lane Mile (tons/ lane mi)	$MgCl_2$ (tons)	$MgCl_2$/Lane Mile (tons/ lane mi)	NaCl Brine (gal)	NaCl Brine/ Lane Mile (gal/lane mi)	$CaCl_2$ Brine (gal)	$CaCl_2$ Brine/ Lane Mile (gal/ lane mi)	$MgCl_2$ Brine (gal)	$MgCl_2$ Brine/ Lane Mile (gal/ lane mi)
Mean	237,295	10.23	5,640	0.19	2,075	0.06	3,413,028	134.65	159,702	4.34	907,266	48.67
Standard Dev	298,753	11.04	27,179	0.89	8,323	0.27	5,939,233	246.49	278,452	8.89	2,207,856	105.54
Max	1,280,000	48.35	148,463	4.85	41,727	1.36	32,386,191	1,322.86	928,989	41.34	10,266,402	446.37
Min	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Median	159,180	7.49	0	0.00	0	0.00	1,369,710	47.91	2,486	0.10	50,000	3.12

Table 22. Regional deicing agent use statistics.

Agency	Average Corrosive Solids/Lane Mile (tons/lane mi)	Maximum Corrosive Solids/Lane Mile (tons/lane mi)	Region with Maximum Corrosive Solids/Lane Mile	Minimum Corrosive Solids/Lane Mile (tons/lane mi)	Region with Minimum Corrosive Solids/Lane Mile
Maryland	12.1	31.2	District 6 (mountainous and rural)	3.5	District 1 (rural)
New Hampshire	28.0	41.0	Interstates in northern half of New Hampshire	22.0	Primary and secondary highways in southern half of New Hampshire
Pennsylvania	7.7	14.1	Butler (suburban)	2.7	Juniata (rural)
Wisconsin	15.3	25.3	Vilas (rural)	5.4	Richland (urban)

INPUT DATA FOR THE UWS DATABASE

Following an introduction subsection, this section contains subsections describing the input into the UWS database related to maintenance manuals, bridge washing, and deicing agent use, respectively.

Introduction

The philosophy adopted for determining the data to be included in the UWS database was to first gather data from owners in a format where differences between agencies could be clearly represented and then include all information that may be potentially relevant. Chapter 8 assesses the statistical significance of each of the variables that have been included, and many of these variables were ultimately found to be insignificant. However, the goal at this stage was to be as comprehensive as possible. The other overarching concept that should be clarified is that all maintenance data were collected on a per-agency basis. Thus, the data items that were included relate to typical practices of each bridge's owner, and no data exist on the maintenance practices of any individual bridge.

Maintenance Manuals Input Data

Regarding maintenance manuals in particular, the researchers posited the possibility that simply by adopting a maintenance manual, an agency gives greater consideration to maintenance. Another possibility was that by having maintenance practices related to certain key features of the bridge, either specifically (e.g., a procedure for joint cleaning) or generally (e.g., any procedure related to joints or bearings), a correlation with bridge performance exists. The team also hypothesized that the level of detail of the maintenance manual may similarly be somewhat correlated to an agency's effort expended on, and prioritization of, maintenance activities. To evaluate these hypotheses, for each bridge in the database, the following information pertaining to its owner was reported:

- Whether a maintenance manual exists (yes or no).
- Whether a maintenance procedure exists for each of the 11 items previously listed in table 18 (yes or no for each item).
- The number of maintenance categories where procedures exist that relate to any aspect of joints (integer value from 0 to 3).
- The number of maintenance categories where procedures exist that relate to any aspect of bearings (integer value from 0 to 2).
- The objective maintenance manual rating given in table 18.
- The subjective maintenance manual rating given in table 18.

Note that, in addition to joints and bearings, the other primary group of data that exist in table 18 is items related to the girder. As the majority of these items are related to cleaning and washing, which is believed to be better represented by the washing data discussed in the following subsection, the maintenance data were not specifically aggregated for girders in the same way that they were for joints and bearings.

Bridge Washing Input Data

Regarding bridge washing, all data from table 19 were included in the UWS database, except for the wash period data because no clear differences between different agencies exist for this variable. Therefore, for each bridge in the database, the following information was reported:

- Whether the bridge exists in an agency that performs bridge washing (yes or no).
- The approximate percentage of UWS bridges washed by the owner (none, less than 10 percent, 10–50 percent, or greater than 50 percent).
- The agency's typical washing frequency (annually, every 2 yr, or less frequently than every 2 yr).
- The rate at which the agency's washing practices included the girders (always, at least half of the time, less than half of the time, or never).
- If the owner had different washing practices for UWS bridges and other bridges (yes or no).

Note that whether bridges were washed (the first item in the preceding bullet list) was also captured by a categorization of "none" for the second bullet point, representing percentage of bridges washed. However, both of these descriptors were initially retained to assess their relative statistical significance.

Deicing Agent Use Input Data

Regarding deicing agent usage, the following information was reported for each bridge in the database:

- The agency's tons used per lane mile of NaCl, $CaCl_2$, and $MgCl_2$ solids of each compound individually and in total.
- The agency's gallons used per lane mile of NaCl, $CaCl_2$, and $MgCl_2$ brines of each compound individually and in total.
- Total equivalent deicing agent use.

CONCLUSIONS

The research team reviewed maintenance manuals from 34 agencies for the topics and level of specificity they contained. The scope of these were found to have significant variation, ranging from general information about common maintenance issues to detailed information for specific structural elements (e.g., joints, bearings, and girders). Numerical and binary systems describing the depth and breadth of each manual were developed for future statistical analysis in chapter 8.

The inquiry on washing practices revealed that washing was a relatively rare practice, with only seven agencies (out of 30 respondents) indicating that they wash more than 50 percent of their bridges. Washing of the girders was even more rare, with only three agencies (out of 19 respondents) indicating that they generally or always included the girders when washing the bridges. Rather, bridge washing was more typically noted as being performed on decks, drainage systems, joints, and/or bearings. The washing practices inquiry originally resulted in a wide variation in responses. Thus, the team made a second round of inquiries with the owners to attempt to describe the washing practices of each agency by categorical responses to six washing variables (i.e., whether washing was performed, approximate percentage of bridges that were washed, frequency of washing, time of year of washing, whether the girders were washed, and whether different washing practices existed for UWS and other bridges), which were identified by the first inquiry. Five of these variables were recommended for further evaluation in future statistical analysis. The excluded variable was time of year of washing, due to lack of more than one category being clearly populated for this variable.

The various quantities of deicing agent use that were obtained were synthesized into terms of corrosive solids ($NaCl$, $CaCl_2$, and $MgCl_2$) applied per lane mile, corrosive brines (those containing $NaCl$, $CaCl_2$, and $MgCl_2$) that were applied per lane mile, and total equivalent deicing agent use per lane mile (which represented an approximate sum of all Cl^--containing deicing agents that were reported). This information was available as State averages for 38 agencies and was used in the statistical analysis in chapter 8 to assess the relationship between State average deicing agent use and UWS performance.

CHAPTER 8. STATISTICAL ANALYSIS

INTRODUCTION

This introduction section describes the scope, goals, and an overview of the approach used in the statistical analysis performed in this study.

Scope

The statistical analysis included in this study investigated the relationship between UWS bridge performance and three broad categories of independent variables: NBI data, environmental conditions, and owner's practices. These variables are subsequently referenced as "NEO" variables for conciseness and are further described in the subsections that follow. The methodology for the statistical analysis consisted of:

- Analysis of the field data from phase 3.
- Analysis of the owner data compiled in the UWS database.
- Use of the output of these analyses to quantify values of influential variables that may cause unsatisfactory performance of UWS bridges.

Thus, the team considered two primary and interrelated datasets. One was termed the field bridge database, which included the 21 bridges that were field inspected in phase 3 and all associated field data. These 21 bridges were evaluated using the more consistent and structured field methods. Details are provided in the Methodology and Results section of this chapter for the intended uses of the varying field data. The second dataset was the national database of over 10,000 UWS bridges, which is described in chapter 3.

Goals and Overview of Approach

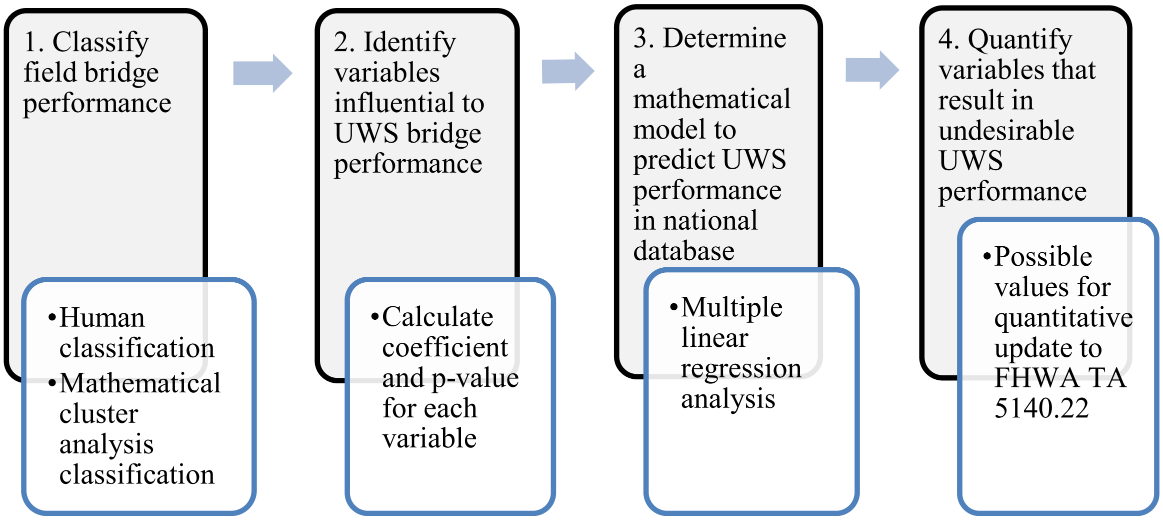
The overarching goal of the statistical analysis was to identify and understand the relationships between NEO variables and UWS performance. To this end, the statistical analysis involved three main parts: analysis of the field bridge database, analysis of the national database, and interpretation of these analyses. The specific goals were the following, which are illustrated in figure 17:

1. Categorize the performance of each of the bridges in the field bridge database. This categorization was based on two approaches: a mathematical cluster analysis considering quantitative performance measures at each sample location (i.e., tape test, UT, quantitative categorization of photos, and XRD) and a qualitative analysis based on subjective designations assigned by the research team. The mathematical and human performance designations were compared to assess if the mathematical results were reasonable.

2. Identify the NEO variables that show the highest correlations with performance of the bridges in the field bridge database, as quantified by field data collected in prior research tasks, and in the national database. This step was done through linear regression analysis and tests of statistical significance.

3. Identify a subset of the NEO variables influential to field performance that are most significant to the performance of the bridges in the national database, as quantified by owner data, and quantify their effects. One performance measure for bridges in the national database was bridge SCR. Additionally, the use of element level condition ratings was explored. Because the goals of this research program have always focused on overall performance that is not influenced by issues such as leaking joints, element level ratings of joints and the steel protective coating of girders were considered in this analysis. The quantification of performance took the form of two multivariate linear regression (MLR) equations: the performance of coastal bridges versus highway overpasses was quantified via separate equations, termed the performance prediction equations (PPE).

4. Use the PPE to determine specific values of influential values that result in desirable and undesirable UWS performance. These values serve to inform values for a quantitative update to FHWA TA 5140.22 (FHWA 1989).



Source: FHWA.

Figure 17. Illustration. Overview of statistical analysis methodology.

DATA DESCRIPTION

This section describes the data included in the statistical analysis. First, the variables and variable types that were considered are described. Because some of these variables are qualitative, the quantification of these variables is then described.

Variables and Variable Types Considered

Three broad categories of data were compiled in this research: NBI data, environmental data, and data on owner's practices. NBI data included information such as the geometric relationship between the bridge and the roadway, the ADT traveling under highway overpasses, and the SCR. Environmental data included climate variables such as humidity, snowfall, and atmospheric chemical concentrations. The environmental variables and the NBI variables, excluding the NBI variables that describe bridge condition, were also collectively referenced as site variables. Owner's practices included information such as formal maintenance procedures, bridge-washing practices, and deicing agent use. The specific types of data available in each of these categories are listed in the following subsections.

These subsections also indicate whether each of these variables was ultimately considered in the final data analysis and the reasons for excluding some variables. The most common reason for excluding a variable was the information for the variable was not available for a significant portion of the dataset. Because of the nature of the multilinear regression model, if information for a single variable was not available (out of the 55 variables considered), all the information for that bridge was deleted from consideration in the statistical analysis. Thus, including all 55 variables dramatically reduced the size of the dataset. So the variables were prioritized, and the value of the information of a specific variable was weighed against the value of the data that would be deleted by including the variable. The other common reason for excluding a variable was a lack of variability in its value. Additional discussion of this reason is provided in the following paragraphs.

Some variables were also not included because of a high level of correlation between two variables. This situation was the case for humidity and temperature variables, for which two different metrics existed for each of these variables. In the case of morning humidity and afternoon humidity, morning humidity was retained, and afternoon humidity was discarded because morning humidity was intuitively the more influential variable (because of dew formation). In the case of average and maximum temperature, average temperature was retained as representing more general conditions, and maximum temperature was discarded.

Lastly, the researchers originally planned to include refined information on each of six types of deicing agents. Because much of this data had values of zero (i.e., an agency used deicing agents, but not a wide variety of types such that data existed for all six types), only the total equivalent amount of deicing agents was used as described in the Owners' Practices subsection.

After excluding variables for these reasons, the team retained the remaining 25 out of the 55 variables for the highway crossing model, representing all major categories of variables (NBI, environmental, chemical concentration, general maintenance policies, bridge washing, and deicing agent use). For the coastal bridge model, 24 out of the 55 variables were retained. The difference in the variables considered for the highway crossing and coastal bridge models was that deicing agents were not included in the coastal bridge model. The reason for this exclusion was a large amount of deicing agent data were not available for coastal bridges (due to southern coastal States tracking this information with less frequency than more northern States). In both models, a large number of variables remained relative to the total number that is practical to consider in final recommendations for updating the UWS TA (FHWA 1989).

Most, but not all, of these data types were quantifiable. When quantities of given variables existed, they were used directly, and the units are listed in the subsections that follow. Other variables were categorical and are indicated by asterisks in the following tables. These variables were converted to quantities in order to be used in the statistical analysis as subsequently described in the Quantification of Qualitative Variables subsection.

National Bridge Inventory Data

The data from the NBI that were considered in the statistical analysis are shown in table 23 (FHWA 2022a). Quantification of the quantitative variables listed here that were not directly given in the NBI were calculated as discussed in chapter 3. The first column lists all the NBI variables considered. The second column shows whether the variable was ultimately included or not, and the third column indicates the reason some variables were excluded from the analyses, when applicable. Table 23 shows that 7 of the 11 original NBI variables were retained. The left lateral underclearance was excluded because 74 percent of the dataset did not have a value available for this variable.

Table 23. NBI variables considered in analyses.

NBI Variables	Included (Yes/No)	Reason for Excluding Variables
Crossing type (category)[1]	Yes	—
ADT under the structure (unitless)	Yes	—
ADTT under the structure (unitless)	Yes	—
Vertical underclearance (ft)	Yes	—
Left lateral underclearance (ft)	No	Large number of data not available
Right lateral underclearance (ft)	Yes	—
Age (yr)	Yes	—
SCR (unitless)	Yes	—
Weighted condition state of girders (number)	No	Low variability
Weighted condition state of steel protective coating of girders (number)	No	Low variability and large amount of data not available
Weighted condition state of joints (number)	No	Low variability

—Not applicable.

[1]Categorical variable.

The three condition state variables were also excluded. Using the weighted girder condition state as the dependent variable in the analysis resulted in very low correlation. This correlation was quantified by the standard coefficient of determination, R^2, where a R^2 of 1 represents a perfect correlation, and a R^2 of 0 represents no correlation. In this case, R^2=0.1. Furthermore, this analysis produced a much shorter list of influential variables with little overlap with the more intuitive list of influential variables that resulted from using SCR as the dependent variable. This result was attributed to the low variability of the weighted girder condition state values: 72 percent of the data had a value of 1.00 for this variable (despite any value from 1.00 to 4.00 being possible). For these reasons, and because the weighted condition state of the steel protective coating of the girders was not available for many (31 percent) of the bridges in the database, the other element-level metrics were also excluded.

Environmental Data

Three subcategories of environmental data existed: climate data, chemical concentration data, and distance to the coast. The specific variables considered in each of these subcategories are shown in table 24 and table 25.

Table 24. Chemical variables considered in analyses.

Chemical Variables	Included (Yes/No)[1]	Reason for Excluding Variables
Atmospheric Cl^- concentration	Yes	—
Atmospheric NO_3^- concentration	Yes	—
Atmospheric SO_4^{-2} concentration	Yes	—
Absorbed Cl^- concentration	Yes[1]	—
Absorbed NO_3^- concentration	Yes[1]	—
Absorbed SO_4^{-2} concentration	Yes[1]	—

—Not applicable.

[1] Included in field bridge database only; data not available for national database.

Table 25. Climate and geographic variables considered in analyses.

Climate and Geographic Variables	Included (Yes/No)	Reason for Excluding Variables
Mean total snowfall (inches)	Yes	—
Average annual morning humidity (percent)	Yes	—
Average annual afternoon humidity (percent)	No	Highly correlated with morning humidity; morning humidity is used instead due to generally being more severe
TOW (h/yr)	Yes	—
Mean number of days with temperatures ≤32 °F (unitless)	No	Large number of data not available
Average daily maximum temperature (°F)	No	Highly correlated with average temperature; average temperature is used instead to represent typical conditions
Average daily average temperature (°F)	Yes	—
Average number of days with heavy fog (unitless)	Yes	—
Average annual precipitation (inches)	Yes	—
Average number of days with measurable precipitation (unitless)	No	Large number of data not available
Average wind speed (mph)	Yes	—
Distance to the coast (miles)	Yes	—

—Not applicable.

Atmospheric chemical concentrations of the ions listed in table 24 were extracted from the NADP (2019), as described in chapter 3. Additionally, for all field bridges, IC was used to calculate the amount of each ion present in a given weight of rust sample removed from the bridge, which is termed herein as the absorbed chemical concentrations. Consequently, the atmospheric chemical concentrations can be thought of as describing the macroenvironment, while the absorbed chemical concentrations can be thought of as describing the microenvironment.

The UWS database described in chapter 3 also contained the climate data shown in table 25. These data were generally quantified by the 30-yr normal reported in the CAUS (further details are available in chapter 3) (NOAA 2002). Some highly correlated variables were excluded, as noted in table 25. Two variables were also excluded because of the large amount of data not available: mean number of days with temperature less than or equal to 32 °F contained 958 bridges with data not available, and average number of days with measurable precipitation contained 1,140 bridges with data not available. The remaining variables of average daily average temperature and average annual precipitation were used to represent similar concepts.

One geographic variable, distance to the coast, was included. This value was required to be separately calculated for groups of bridges by State (and separately for the District of Columbia and Puerto Rico). Because of this requirement, the distance-to-the-coast value was only calculated for bridges in States that form the Atlantic, Pacific, and Gulf coastlines. Only bridges in these States were included in the coastal bridge database (detailed in the subsections that follow), which was later limited to consideration of only bridges within 100 mi of the coastline.

For the highway crossing database (detailed in the subsections that follow), the value of distance to the coast was originally left blank for bridges in States that did not border a coastline, which was interpreted in the preliminary mathematical calculations as a zero. This action had the conceptual effect of the calculations assuming that a bridge in Kansas was on the coastline, for example. This action was later revised to change the distance to the coast to 1,000 mi for all bridges in States that do not border a coastline. This value was chosen as a round number exceeding the largest distance-to-the-coast value in the database, which was 602 mi. Review of the database also found that there were a small number of bridges in coastal States for which the GIS analyses did not return a value. These bridges were deleted for analyses where distance to the coast was a variable and included for analyses when distance to the coast was not a variable. This action caused a difference of four bridges (out of over 1,000 bridges) in various versions of highway crossing models that were investigated.

Owners' Practices

Chapter 7 identified three categories of data on owner's practices to be considered in the statistical analysis: data from maintenance manuals, data on washing practices, and data on deicing agent use. All three categories of data that were planned to be used are shown in table 26. Here it is shown that, while primary information on each of these data types was retained, the team deemed it necessary to exclude much of the more refined data that was planned to be included.

Table 26. Owners' practices variables considered in analyses.

Owners' Practices Variables	Included (Yes/No)	Reason for Excluding Variables
Whether a maintenance manual exists (category: yes or no)[1]	No	Low variability. More variability in ratings, which can capture the same concept
Whether a maintenance procedure exists for each of the 11 maintenance items found to be common to several agencies in chapter 7 (yes or no for each item)[1]	No	Large number of data not available
The number of maintenance categories where procedures exist that relate to any aspect of joints (unitless)	No	Large number of data not available
The number of maintenance categories where procedures exist that relate to any aspect of bearings (unitless)	No	Large number of data not available

Owners' Practices Variables	Included (Yes/No)	Reason for Excluding Variables
The objective MM rating given in chapter 7 (unitless)	Yes	—
The subjective MM rating given in chapter 7 (unitless)	Yes	—
Whether the bridge exists in an agency that performs bridge washing in any manner (category: yes or no)[1]	Yes	—
The approximate percentage of UWS bridges washed by the owner (category: none, <10 percent, 10–50 percent, or >50 percent)[1]	No	Large number of data not available
The agency's typical washing frequency (category: annually, every 2 yr, or less frequently than every 2 yr)[1]	No	Large number of data not available
The rate at which the agency's washing practices included the girders (category: always, at least half of the time, less than half of the time, or never)[2]	No	Large number of data not available
If the owner has different washing practices for UWS bridges compared to other bridges (category: yes or no)[1]	No	Large number of data not available
The agency's use of NaCl, $CaCl_2$, and $MgCl_2$ solids of each compound individually and in total (tons/lane mi)	No	Large number of data=0
The agency's use of NaCl, $CaCl_2$, and $MgCl_2$ brines of each compound individually and in total (tons/lane mi)	No	Large number of data=0
Total equivalent deicing agent use (tons Cl^-/lane mi)	Yes[2]	—

—Not applicable.

[1] Categorical variable.

[2] Included in highway crossing model only.

For example, only 2 of the 16 originally planned maintenance variables were retained. They were the objective and subjective ratings of each owner's maintenance manual that were compiled in chapter 7. These ratings represented an overall view of maintenance that is intermediate to the other variables that were discarded. Specifically, whether a maintenance manual exists was a relatively generic variable that was discarded because 7,593 (74 percent) of bridges in the national database had the same value of "yes." Because of the lack of variability of this variable, the objective and subjective ratings (which had greater variability) were used to capture the same concept; if a maintenance manual did not exist or was not available, these ratings were assigned values of zero for the manual ratings. On the other hand, variables describing whether a maintenance procedure existed for the 11 maintenance items documented in chapter 7 and the combinations of these items listed in table 26 were discarded because these were viewed as being overly specific, given that maintenance manuals were not received from many agencies.

Whether the bridge existed in an agency that performs bridge washing was the sole bridge-washing variable that was retained. While this information was available for most of the database, including the remaining washing variables limited the size of the database. Note that when this variable was set to yes, it did not necessarily mean that the bridge was subjected to washing, only that it existed in an agency that performed washing. However, the premise of this variable was that owners are adept at selecting the bridges most in need of washing when selective washing is applied within an agency. So, evaluating the influence of this variable provided a general assessment of the effectiveness of bridge washing as it is currently implemented.

Similarly, the only deicing agent metric that was considered was the total equivalent deicing agent use, which summed the quantities of liquid and solid deicing agents as detailed in chapter 7. This metric represented an aggregate view of deicing agent use, while including the more refined information for every deicing agent type resulted in including a high proportion of zero values into the dataset.

Quantification of Qualitative Variables

The categorical variables identified in the preceding subsections were generally binary variables. In these cases, the variables were quantified by 1 representing "yes" and 0 representing "no." The only remaining categorical variable that was included in the data analysis was crossing type. In the highway crossing model, the dataset was limited to bridges crossing highways, and no further consideration of crossing type was made. To represent crossing type in the coastal bridge model, three binary subcategories were used: highway crossing, water crossing, and railroad crossing, with 1 representing "yes" and a 0 representing "no" in each of these three subcategories.

METHODOLOGY AND RESULTS

This section describes the methodology and results of the field and national database analyses.

Field Bridge Database Analysis

The performance of the field bridges was assessed to determine relationships between field performance and variables that may affect this performance. To determine the relationship, an assessment of field performance must first be made. The researchers evaluated two approaches for the field performance assessment: a binary classification of performance as good or inferior based on the independent opinions of subject matter experts and a mathematical classification method. Then the researchers performed a statistical analysis to assess correlations between performance and possibly influential variables. The subsections that follow give the details of this work.

Subjective Analysis to Categorize Field Bridge Performance

The first step in analyzing the performance of the field bridges was to classify the performance of each field bridge as acceptable or unacceptable based on human opinion. This step was previously described by table 15 in chapter 5. This classification formed a baseline for evaluating the accuracy and reasonableness of the mathematical analysis that followed and provided context for others to interpret the results of this research.

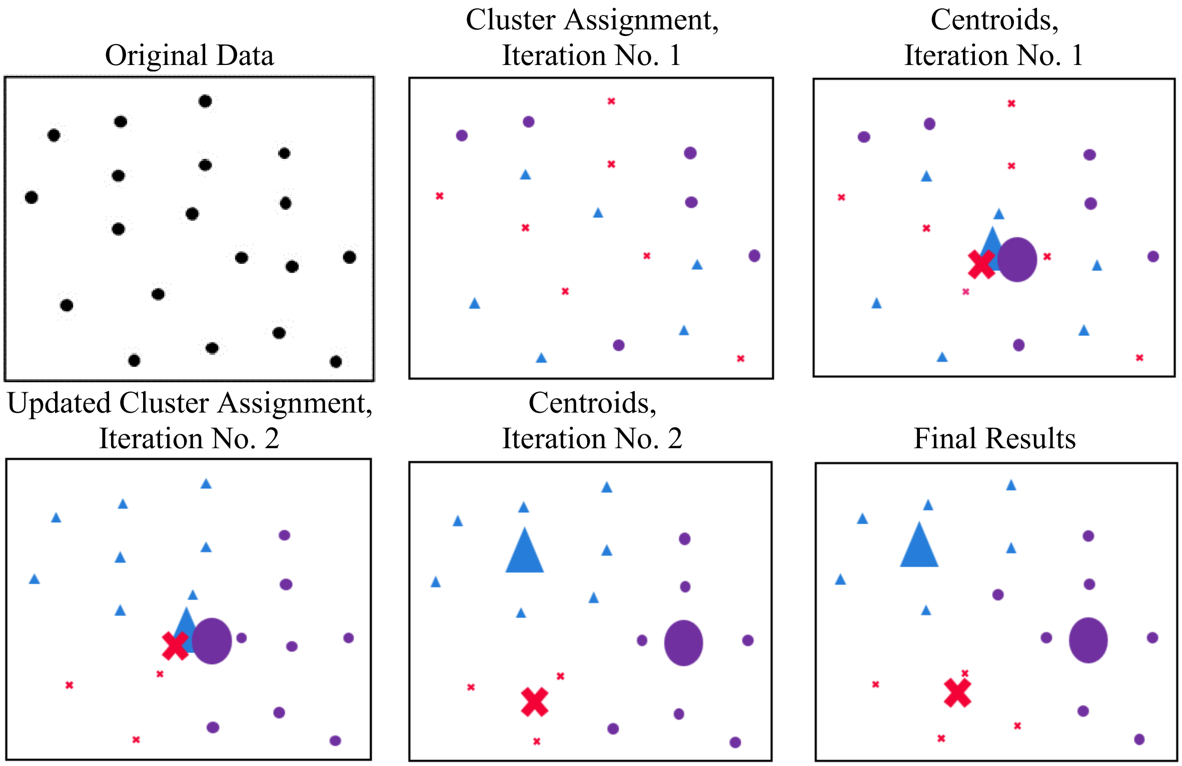
Cluster Analysis to Categorize Field Bridge Performance

This section first gives an overview of the specific type of cluster analysis used in this work. Then, how this method was applied in this study and the corresponding results are described.

Overview of k-Means Cluster Analysis Method

The second method of categorizing the field bridge performance was mathematically based. Specifically, k-means cluster analysis was used to systematically sort data into a predetermined number of groups. The concept of this method is that the data within each group are more similar to one another than to data in other groups. The basic objective is to group the data so that the variation of the data within each cluster is minimized and between clusters is maximized. Mathematically, this objective is achieved by minimizing the sum of the Euclidean distances between each data pair within a cluster, divided by the total amount of data in the cluster.

Figure 18 shows an example of the results of cluster analysis assuming three groups of data exist. In this simple two-dimensional example, each data point is described by two variables, which are plotted on x- and y-axes. The original data are shown in the top left of figure 18. Each datum is randomly assigned to a cluster in the top center plot, where different groups are represented by different symbols. In the top right, the cluster centroids are computed and shown as larger symbols. Then each data point is assigned to the nearest centroid, as shown in the bottom left. Next, the cluster centroids are calculated again according to the new assignment in the bottom center graph. This process is repeated until the assignments of each data point no longer changes (as depicted by the bottom right plot), which means the within-cluster variation is minimized and the optimal solution has been reached.



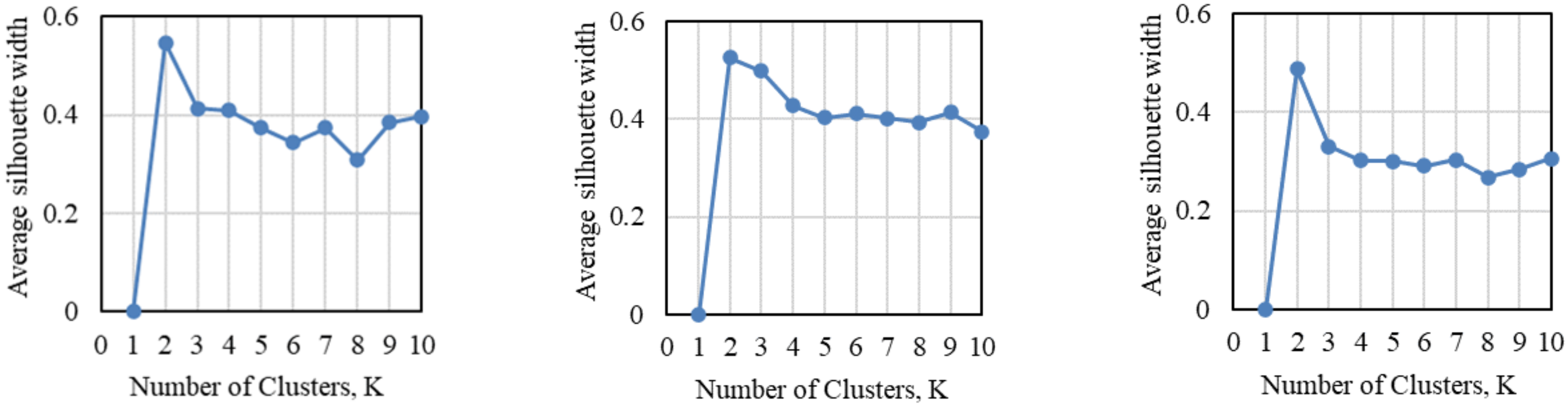
Source: FHWA.
Large X = the first group of data.
Large triangle = the second group of data.
Large circle = the third group of data.

Figure 18. Illustration. Example clustering analysis results.

Determination of Variables and Numbers of Clusters Considered

In this study, *k*-means cluster analysis was conducted to classify the performance of sampled locations of field bridges based on the following variables: thickness loss of steel as estimated from the UT testing, density, percentage of particles greater than 1/2 inch from the tape test results, and the ratio among different FeOOH isomers from the XRD analysis. The metric used to represent the XRD results was carefully considered, as discussed in the following paragraphs and considered in parallel with determining the optimum number of clusters to be used.

First, five ratios among different FeOOH isomers were evaluated to decide an XRD metric that can best represent XRD data in the *k*-means cluster analysis to categorize field bridge performance. The ratios were G:A, G:L, the sum of goethite and lepidocrocite to akageneite (GL:A), the sum of goethite and lepidocrocite to the sum of akageneite and magnetite and/or maghemite (GL:AM), and the sum of goethite to the sum of akageneite and magnetite and/or maghemite (G:AM), where the labels in parentheses introduce the labeling of these ratios that is used in figure 19 and figure 20. Before evaluating these metrics, the number of clusters to be used must be determined.



Source: FHWA.

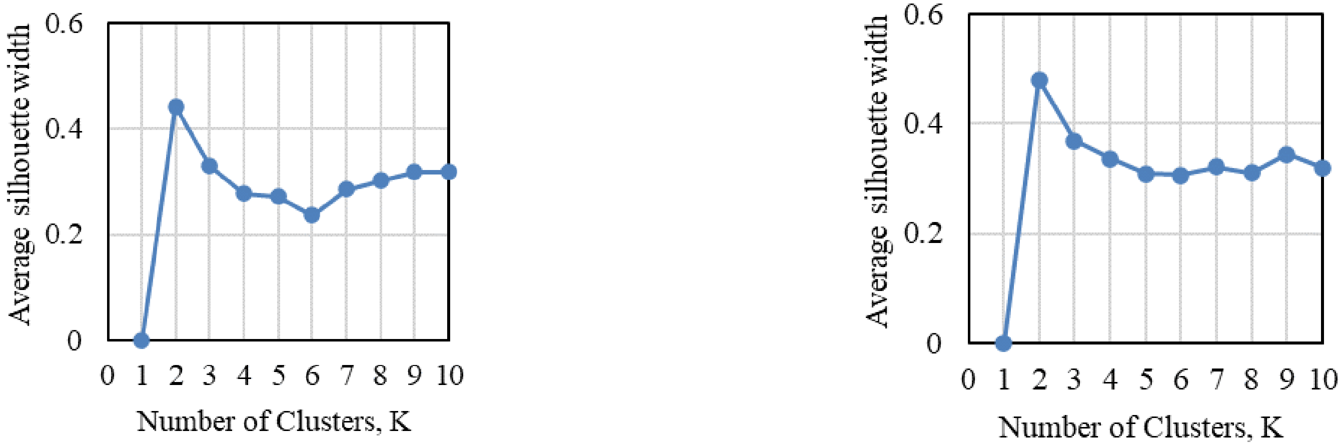
A. XRD ratio = G:A.

Source: FHWA.

B. XRD ratio = G:L.

Source: FHWA.

C. XRD ratio = GL:A.



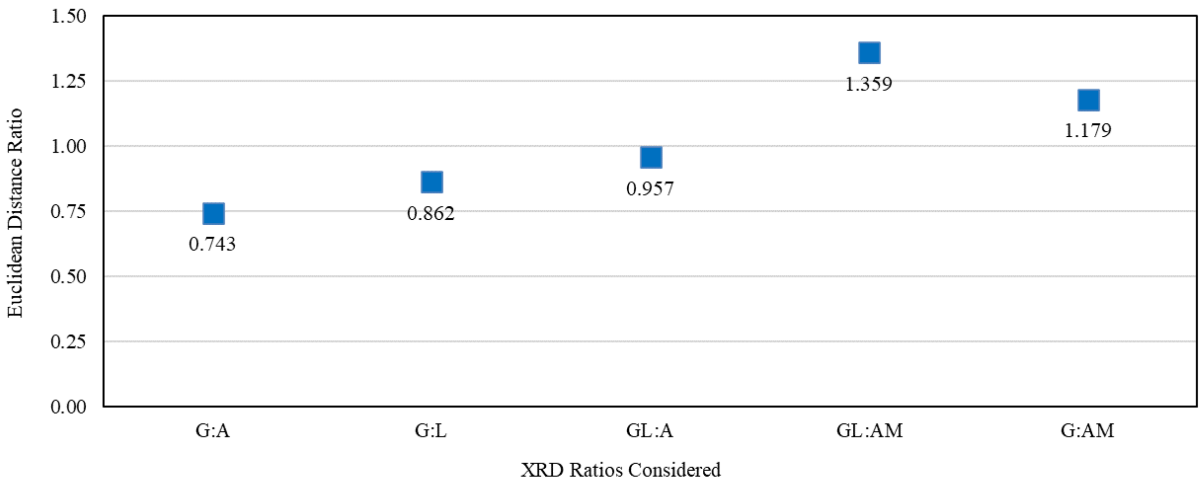
Source: FHWA.

D. XRD ratio = GL:AM.

Source: FHWA.

E. XRD ratio = G:AM.

Figure 19. Graphs. Average silhouette width versus K values for different XRD ratios..



Source: FHWA.

Figure 20. Graph. Ratio of distance within clusters to distance between clusters for five different ratios.

Silhouette coefficients determine how well each data point lies within its cluster as a way to measure the quality of the clustering, which can be used to determine the ideal number of clusters, *K*. This calculation compares distances between data points within the same cluster to data points in other clusters to achieve a result between −1 and 1. Positive 1 indicates distinctly clustered data. Silhouette coefficients were computed for different values of *K*, with a higher average silhouette width indicative of ideal clustering.

Figure 19 shows the average silhouette width of different values of *K* (based on the normalized scale described in the preceding paragraphs) for the five XRD ratios considered. The team concluded from these data that two clusters were ideal for all five ratios. Two clusters were also convenient for data interpretation, as they can be assigned to represent good and inferior field bridge performance. Because performance may vary for different locations within a bridge and the data organization discussed in the following subsection was designed to account for this possibility, four clusters were also evaluated for informational purposes.

According to the concept of *k*-means clustering analysis, a good cluster is represented by smaller Euclidean distances between data points within the same cluster and larger Euclidean distances between data points in other clusters. The ratio of the sum of these two Euclidean distances was calculated for the five different XRD metrics considered and is plotted on the *y*-axis in figure 20. The optimal ratio that can best represent XRD data is the one that has the smallest Euclidean distance ratio. This ratio was G:A, which is consistent with prior literature that often emphasizes the importance of these two isomers (Kamimura et al. 2006; Madani and Granata 2018; Díaz et al. 2018).

Data Formatting and Organization

Because *k*-means clustering uses Euclidean distances, accounting for the scale on which measurements are made is necessary. So, before running the analysis, the variables considered were standardized to have a standard deviation of 1 and mean of 0 so that they would have equivalent scales.

k-Means clustering also required that each data point be represented by the same number of independent variables. In this study, for each bridge, XRD data of four locations were available, UT of two locations were available, and density and percentage of particles greater than 1/2 inch of 12 locations were available. So, two options were considered to solve the issue of unequally sized data. One approach represented each bridge as one data point, using the average values for each metric. The other approach divided and averaged the data for each bridge into two groups, based on prior categorization of half of the sampled locations as "good" and half as "inferior" locations. Good locations were defined as web and exterior fascia surfaces of flange locations, and inferior locations were defined as all interior locations of flanges (including those on exterior girders).

Several different iterations of the *k*-means analysis were then performed as summarized by table 27 in the following subsection. These various analyses considered different numbers of datasets per bridge (as described in the previous paragraph), different numbers of clusters, different tape metrics, the inclusion or exclusion of UT thickness data, and the inclusion or exclusion of XRD data. While an optimum cluster number of two was previously determined, four clusters were also evaluated because the final dataset was more complex (contained more variables) than the dataset used to conclude that $K=2$ was optimum, and because there were four conceptual possibilities of data points: good locations within a good bridge, inferior locations with a good bridge, good locations within an inferior bridge, and inferior locations within an inferior bridge.

Cluster Analysis Results

The cluster analyses performed are summarized by table 27. The last three columns of table 27 indicate the success of the cluster analysis result based on how well the group assignments matched the subjective analysis results discussed in the previous subsection. To make this assessment, the cluster analysis results first needed to be interpreted, meaning that the two or four groups resulting from the cluster analysis were labeled as being good or inferior.

Table 27. Summary of cluster analyses performed and results.

Analysis No.	Datasets per Field Bridge	*K*	Tape Metric	UT Considered	XRD Metric	Average Individual Match (percent)	Best Individual Match (percent)	Consensus Match (percent)
1	2	2	Density	Yes	G:A	43	47	—
2	2	4	Density	Yes	G:A	61	68	63
3	2	4	Density	Yes	G:A	55	63	58
4	1	4	Density	Yes	G:A	82	95	84
5	1	2	Density	Yes	G:A	71	79	79
6	1	2	Density	Yes	—	71	79	74
7	1	2	Density	No	—	53	63	53
8	1	2	Percent > ½ inch	No	—	53	63	37

—Not applicable.

To make this determination, the researchers compiled the average value for each metric in each group. An example of this step is shown in table 28. In this example, the relative values of all three metrics were in agreement, i.e., the lowest tape spatial density, lowest UT, and highest G:A values were all in the same cluster. Thus, interpretation of these results was relatively straightforward. Cluster 1 was assigned the label "inferior," and cluster 2 was assigned the label "good." Table 29 shows a counter example where the interpretation was less straightforward because three metrics that were considered had an inconsistent relative ranking (the best two values in each metric are indicated by a superscript 1). In these cases, emphasis was placed on the UT results to determine the labels, as this metric was judged to be the most definitive indicator of performance.

Table 28. Average values of independent variables, by group, for analysis 1.

Cluster	Average Tape Spatial Density (percent)	Average UT (inches)	Average Percent Goethite/Percent Akageneite (unitless)	Label
1	16.0	0.040	0.691	Inferior
2	7.6	0.010	2.130	Good

Table 29. Average values of independent variables, by group, for analysis 4.

Label	Average Tape Spatial Density (percent)	Average UT (inches)	Average Percent Goethite/Percent Akageneite (unitless)
Worst	9.3[1]	0.043	0.461
Inferior	15.5	0.024	1.164[1]
Good	17.0	0.014[1]	4.207[1]
Best	5.0[1]	0.007[1]	0.673

[1] One of the best two values for the given metric.

Once the labels of the clusters were determined, the team evaluated the extent to which these labels matched the subjective labels using three metrics. The "average individual match" calculated how many of the cluster bridge labels matched the subjective bridge labels of each of the four researchers. Because the researchers did not unanimously agree on all bridges, a perfect match of this metric was not possible. Thus, the metric "best individual match" reported the percentage of the cluster bridge labels that matched the subjective bridge labels of the researcher who had the best match. Table 27 shows that analysis 4 provided the best match according to this metric, at 95-percent agreement. The final metric, "consensus match," compared the researchers' consensus summary label (table 27) to the cluster analysis results. Based on this metric, analysis 4 was also the superior model and the only model that produced a match percentage greater than 80 percent for all three metrics. Thus, analysis 4 was deemed the best clustering model.

However, on the evaluation of analysis 4 shown in table 29, the researchers found that the relative values of spatial density, UT, and XRD results were not logical. The table highlights the best two values in each metric to show that there was not a clear interpretation of the clusters, although ranking the clusters based on UT did provide good agreement with the subjective ratings. From this result, the team concluded that the subjective ratings of bridge performance were a more reliable data classification method than the mathematical classification, and the subjective ratings were directly used to categorize field bridge performance.

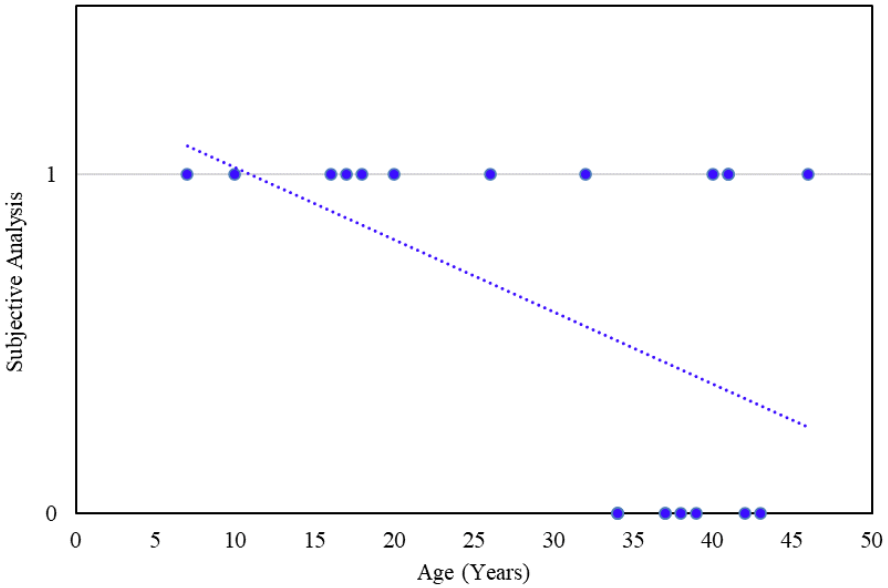
Identify Statistically Significant Variables Affecting Field Bridge Performance

The research team assessed the correlation between field bridge performance attained from the subjective analysis and each independent variable listed in the preceding subsection by calculating a coefficient and the *p*-value of each variable when incorporated in a linear regression. The *p*-value is a standard measure of statistical significance, having a value between 0 and 1. *p*-Values less than 0.05 are a common standard for defining that a variable is significant. Field bridge performance was quantified by subjective analysis (for reasons described at the conclusion of the previous section). Good performance was represented by a value of 0, and inferior performance was represented by a value of 1. A summary of results is shown in table 30. Using a *p*-value of 0.05 as an upper bound threshold, four variables were significant: performs bridge washing, average wind speed, NO_3^-, and age. However, the coefficients for performs bridge washing, average wind speed, and age were not reasonable. Specifically, the coefficients for performs bridge washing and wind were positive, indicating that higher values (i.e., performs washing and higher wind speeds) resulted in worse performance. This result is clearly counterintuitive in the case of bridge washing. Wind was assumed to have a beneficial drying effect, such that a negative coefficient on the wind variable was expected, although higher wind speeds could be responsible for greater amounts of salts deposited on the surface. The negative coefficient that was calculated for age indicates that higher age results in better performance. This result is clearly in opposition to all real-world experiences.

Table 30. Coefficients and *p*-values for field bridge dataset.

Variable	Coefficient	*p*-Value
Performs bridge washing	4.01	0.01
Average wind speed	1.56	0.03
Atmospheric NO_3^-	1.22	0.04
Age	−0.12	0.05
Atmospheric SO_4^{-2}	1.77	0.06
Average annual percent morning humidity	0.76	0.13
Absorbed NO_3^-	−15.89	0.13
ADTT under the structure	0.00	0.16
Average daily average temperature	−2.44	0.17
Atmospheric Cl^-	−0.68	0.18
Vertical underclearance	−0.38	0.21
Left lateral underclearance	−0.02	0.23
Mean total snowfall	0.56	0.25
Absorbed SO_4^{-2}	−1.58	0.26
TOW	−0.47	0.33
Distance to coast	−0.48	0.36
Total equivalent deicing agent use	0.05	0.53
Average annual precipitation	−0.29	0.53
ADT under the structure	0.00	0.73
Absorbed Cl^-	−0.15	0.75
Right lateral underclearance	0.00	0.90
Average number of days with heavy fog	−0.05	0.92

To evaluate this finding regarding the influence of age, figure 21 shows the correlation plot between the subjective analysis results and age of the 21 phase 3 field bridges. In figure 21, the vertical axis is the subjective result, represented by a value of 0 or 1, with 0 indicating a field bridge with good performance, and 1 indicating a field bridge with inferior performance. The horizontal axis is the age of each field bridge. Figure 21 shows that, in this small dataset, the older field bridges had better performance than the younger ones. This finding conflicted with the general expectation that younger bridges have better performance. Other variables also showed counterintuitive relationships (e.g., bridges with higher Cl^- concentrations had better performance). This result was attributed to the small number of field bridges for which data were available, particularly relative to the large number of potentially influential variables (i.e., the number of independent variables retained (24) exceeds the number of field bridges (21)) and the low (binary) variability of the dependent variable.



Source: FHWA.

Figure 21. Graph. Correlation between subjective analysis result and age of field bridges.

So, assessing the p-values between field bridge performance and each variable to obtain a more manageable number of variables for later analysis was not appropriate. Instead, in the national database analysis, all variables considered in the field bridge database were reevaluated for the national database analysis.

National Database Analysis

This section begins with describing the statistical modeling method used in this study. Then, an overview is provided of the two separate models created in this work—a highway crossing model and a coastal bridge model—and the rationale of developing these separate models. Lastly, details of these two models are provided.

Statistical Modeling Method

This section first describes the theory used in the statistical modeling using in the national database analysis. Then the specific decisions made in this study in applying this theoretical framework are discussed.

Theoretical Methodology

MLR analysis was conducted on the UWS database to assess the relationship between bridge performance and the NEO variables that were found to be statistically significant. The general format of an MLR equation is shown in figure 22.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_r X_r + \varepsilon$$

Figure 22. Equation. MLR equation format.

Where:

Y = the dependent variable.
β_i = the regression coefficients estimated by the least squares approach.
X_i = the significant NEO variables.
ε = the error.
r = the number of significant NEO variables.

In this work, the dependent variable is the SCR. MLR analysis was used on two subsets of the data—highway crossings and coastal bridges—based on intuition that the variables affecting performance in these two situations would be different, to create PPE for these two different situations.

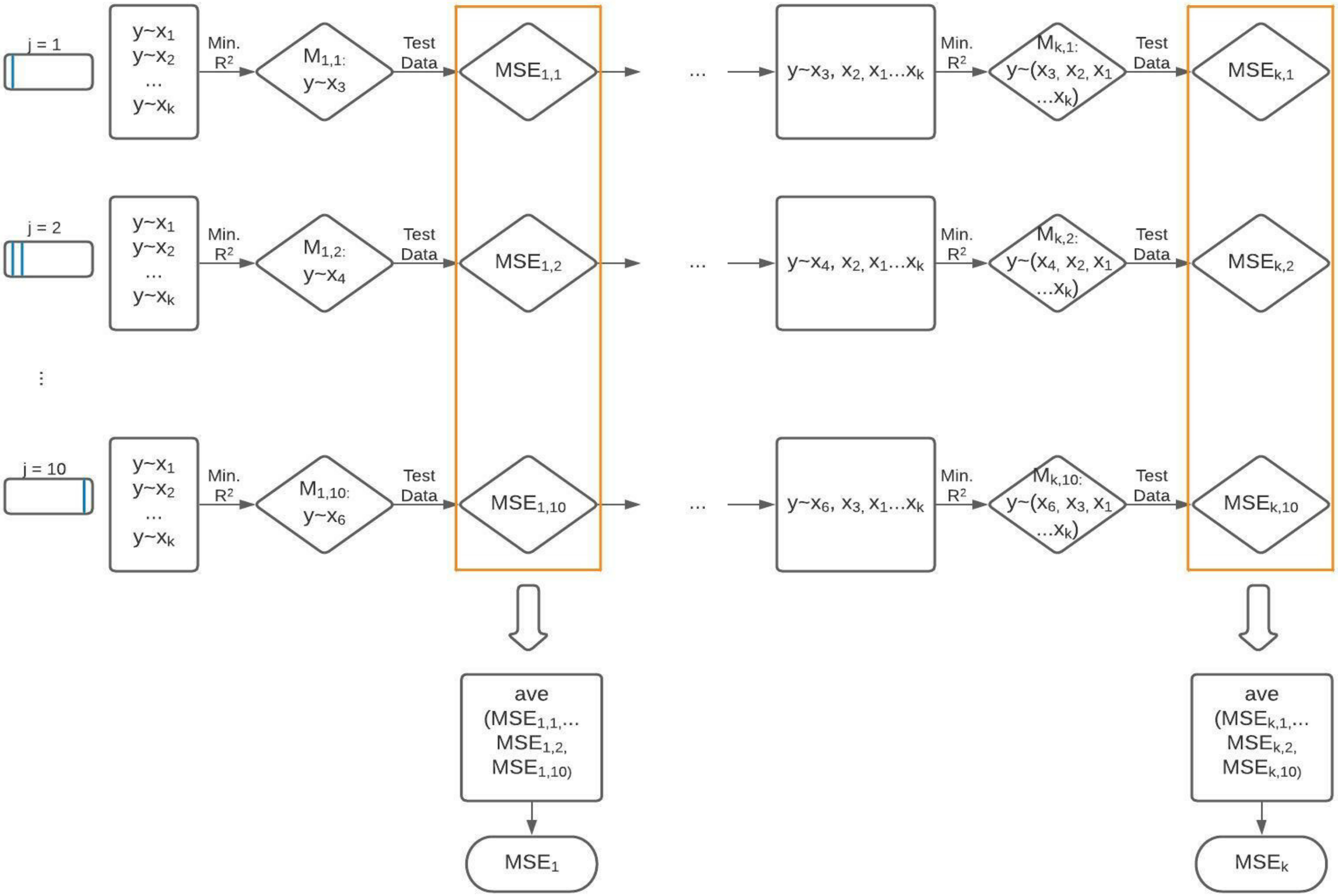
The PPE were defined by the number of variables included in the equations, the selection of these variables, and quantifying coefficients for each variable. Two primary techniques used to develop these equations include the forward stepwise selection of variables and the 10-fold cross-validation (CV) technique (as used in similar work by Ocel et al. 2017).

Two types of error exist in this type of modeling: training error and testing error. Training error is error when the equation is applied to the data used to fit the model. Testing error is error when the equation is applied to new data not used to fit the model. The 10-fold CV method is a resampling method used to select the optimal model that minimizes the testing error. In this method, the data are divided into 10 different training and testing sets. In the procedure outlined in the following paragraphs, the index j represents each of the 10 groups of training data.

Forward stepwise selection is used to select the best model for each number of variables (k) and each training dataset (j), as summarized by figure 23. This method begins with a model containing no variables, only an intercept, and then adds variables to the model one by one, until all the variables are in the model. At each step, the variable resulting in the greatest additional improvement to the fit is added to the model. The additional improvement is defined as having the highest R^2 value.

The details for the model development process using the forward stepwise selection of variables and the 10-fold CV technique are as follows (James et al. 2017):

1. Split the data into a training set and a test set. In the 10-fold CV technique, a set of n data is randomly split into 10 folds (represented by the rows in figure 23). One fold of data is called the test set (and is shown by the bounds on the boxes representing j on the left side of figure 23); the remaining nine folds of data are called the training set. Each row of figure 23 represents one forward stepwise selection (with the potential for different variables k to be added in each row). Hence, this process is repeated 10 times, each time with a different fold serving as the test set.



Source: FHWA.

Figure 23. Illustration. Overview of 10-fold CV modeling method.

2. Identify the best model (M_{kj}) for each number of variables (k) and each training dataset (j) by applying forward stepwise selection:

    a. Begin with the null model, which contains no predictors.

    b. Add the variable to the null model that results in the highest R^2 value of all the variables considered. This model is referenced as M_{1j}.

    c. Add a second variable to M_{1j} that results in the highest R^2 value. This model is referenced as M_{2j}.

    d. Add variables to M_{2j}, one at a time, until all the variables considered are in the model. These models are referenced as M_{kj}.

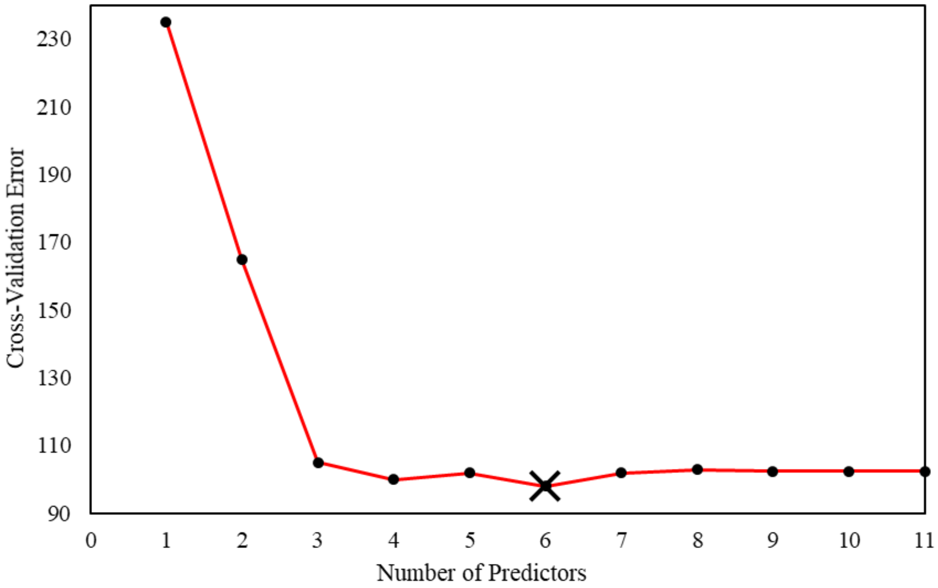
3. Select an optimal model by applying 10-fold CV:

    a. Compute the mean squared testing error (MSE) of each model M_{kj} and define this value as MSE_{kj}.

    b. Compute the average MSE, for each group of M_k models, based on the 10 datasets and quantify this value as MSE_k. For example, $MSE_{1,1}$, $MSE_{1,2}$, … $MSE_{1,10}$ are averaged and represented as MSE_1.

    c. Compare all MSE_k and select the k value resulting in the minimum MSE_k as the optimal k value. An example of results of this process is shown in figure 24. Here, the horizontal axis is the number of variables (k value), and the vertical axis is the CV error (i.e., MSE_k) on the testing dataset. In this example, the lowest value of MSE occurred when six variables were included in the model (indicated by the X). This example highlights that if a variable is added to a regression model, but it is not significant to the response, the training error for the new model is lower than the old regression model, but the testing error does not decrease because that variable is not significant to the response.

4. Obtain the optimal model on the full dataset using the forward stepwise process outlined in step 2 and the k value resulting from step 3 to obtain the final model. Report the *p*-values for each variable included in the final model to document the statistical significance of each variable.



Source: FHWA.

Figure 24. Graph. Example of the 10-fold CV result.

Application of Theoretical Methodology

The results of the 10-fold CV model indicated that a model with 14 and 20 variables was ideal for the highway crossing and coastal bridge models, respectively. However, these were not selected as the final models for several reasons. Instead, the results of the 10-fold CV method presented in the following paragraphs were limited to listing the most significant variables identified by these analyses. The reasons for not using the number of variables suggested by the 10-fold CV method were as follows:

- The number of variables included was too high for practical use.
- Measures of model fit (coefficient of determination and residual standard error (RSE)) had inconsequential improvements (as detailed for each specific model in the subsections that follow), after the addition of the first few variables.
- The *p*-values of additional variables exceeded 0.05, a standard value indicating that the variable was statistically significant to the model, after the addition of the first few variables.

So variables were added to the models using the forward stepwise approach until the *p*-values for a given variable exceeded 0.05. In general, only variables with *p*-values less than 0.05 were retained in the model. The exception to this criterion was that ADT under the structure had a *p*-value of 0.08 and was added to the highway crossing model for reasons detailed in the following subsection.

The coefficients of each model were then assessed for logic. Specifically, the positive and negative signs of coefficients were compared to known relationships between those variables and bridge performance. For example, higher snowfall is known to lead to greater deicing agent use, thus decreased bridge performance. Therefore, a negative coefficient was expected for the snowfall variable. When illogical coefficients were obtained, it required a more thorough assessment of the database to remedy such issues. Remedies to these problems included rational removal of some bridges and variables from the datasets and models, which is detailed in the following subsections for each model. Interaction terms that account for the correlation between some independent variables were also explored as a remedy to some illogical coefficients. These efforts are also detailed in the following subsections for each model.

Model Development Overview

Two MLR models were developed—one for highway crossings and one for coastal bridges—described separately in the following subsections. Before developing models, the researchers performed data cleaning of the national database. First, bridges built before 1964 were deleted, because this period was before the first weathering steel bridges in America were constructed.

Then, for many variables, the available data used numerical codes to represent conceptual information. These variables and the modifications made to their data are as follows: minimum vertical underclearance of 9999, minimum lateral underclearance on right of 999, and minimum lateral underclearance on left of 998, indicated that the clearance was greater than 100 ft. Thus, these values were coded as 100 ft, which maintained the concept of a large clearance (well exceeding typical values) and avoided coding the data as not available. When the minimum vertical underclearance was coded 000, it indicated and was coded as not available. Climate variables coded as –99999 meant missing or insufficient data; these were coded as not available. The consequence of coding any variables as not available was removing these bridges from the regression model.

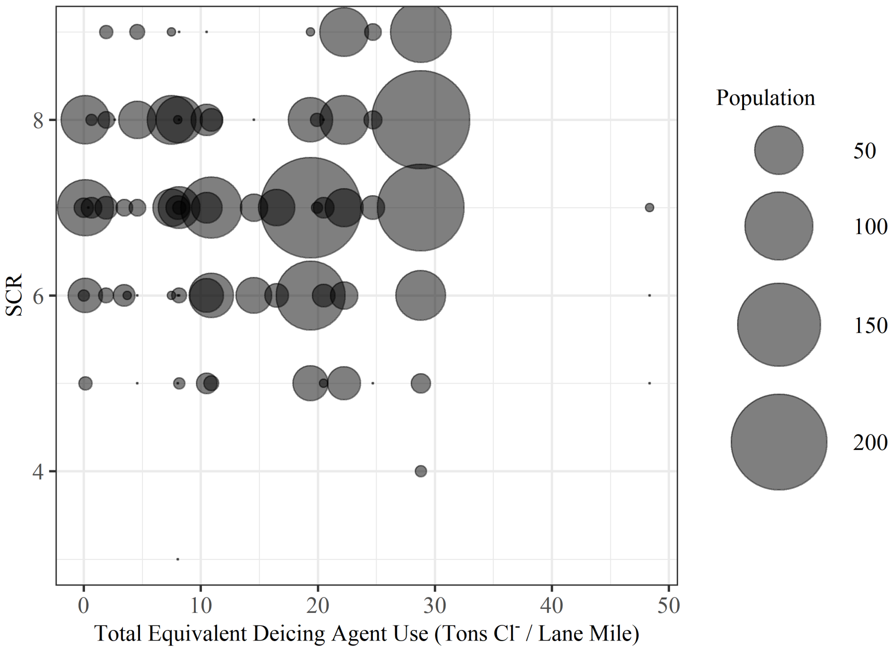
The final preliminary step of constructing the regression models was to account for the large differences between the ranges of different variables. For example, the range of age was between 1 and 54, but the range of ADT under the structure was between 0 and 771,518. Also, variables were measured in different measurement units (e.g., years, feet, mph). Therefore, before performing the multiple linear regression analysis, the researchers standardized the variables for both datasets to have a mean of 0 and a standard deviation of 1.

Highway Crossing Model

Crossing type was a categorical variable and was used to classify the type of service under the bridge and create the highway crossing dataset. All bridges with a service code of 1, 4, 6, or 8 were classified as a highway crossing and formed the highway crossing dataset: service code 1 indicated the type of service under the bridge was highway, with or without pedestrian; service code 4 indicated the type of service under the bridge was highway and railroad; service code 6 indicated the type of service under the bridge was highway and waterway; service code 8 indicated the type of service under the bridge was highway, waterway, and railroad.

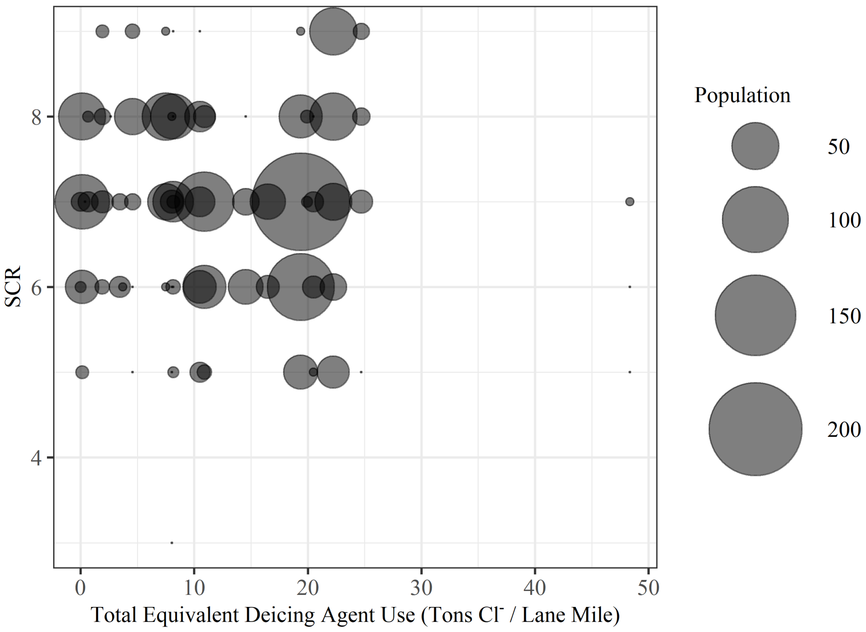
Data Cleaning

In a preliminary version of the highway crossing PPE, the team found that greater total equivalent deicing agent use resulted in better bridge performance in the mathematical model. Because this finding strongly conflicted with expectations and substantial volumes of anecdotal evidence, the reasons for this result were investigated. This investigation included analysis of the distribution plots of total equivalent deicing agent use and SCR shown in figure 25. Figure 25-A shows a large number of bridges had relatively high SCR values and the highest average total equivalent deicing agent use, as indicated by the larger circles in the top right corner. These bridges were all in New York, which represented 495 out of 1,845 bridges retained in the highway crossing dataset and reported the highest average total equivalent deicing use in this dataset. Figure 25-B shows the same data with New York excluded from the data.



Source: FHWA.

A. Original highway crossing dataset.



Source: FHWA.

B. Highway crossing dataset without New York.

Figure 25. Graphs. Correlation plot between SCR and total equivalent deicing agent use on original highway crossing dataset and on highway crossing dataset without New York.

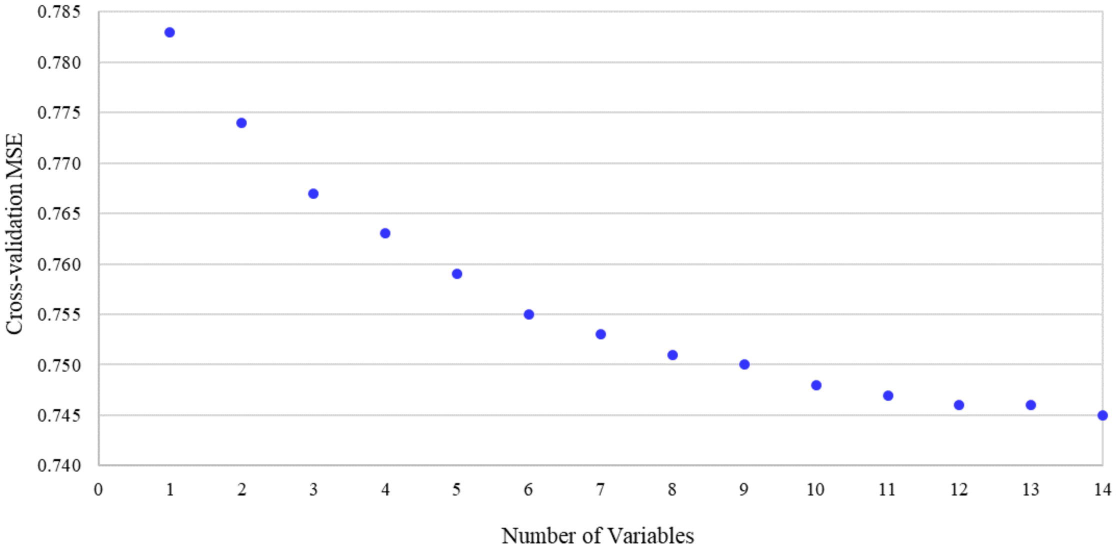
This large number of bridges with both high total equivalent deicing agent use and high SCR caused an MLR equation that predicted better performance with increasing use of deicing agents. One possible reason for this finding was the poor ability of an average deicing agent use value to adequately represent the wide variability across any State, perhaps particularly a State with as much geographic and population diversity as New York. Another possible reason is differences in SCR practices in New York that were observed during field work contributed to the counterintuitive result. Because of this superior performance with increased deicing agent use, New York bridges were excluded from the highway crossing dataset.

Model Development

The 10-fold CV analysis resulted in the 14 variables shown in table 31. Variables not included in this model were total equivalent deicing agent use, TOW, ADTT under the structure (although ADT under the structure is included), average annual precipitation, average annual percent morning humidity, and atmospheric SO_4^{-2} concentration. The results of this model (table 31) indicated that many of these variables were not statistically significant. This conclusion is indicated by the *p*-values, with *p*-values less than 0.05 being a typical threshold indicating statistical significance. Furthermore, figure 26 shows similar MSE values (a measure of model fit) with fewer than 14 variables compared to the 14-variable model.

Table 31. Summary of results of preliminary model based on 10-fold CV method—highway crossing model.

Variables	*p*-Value
Age	0.000
Performs bridge washing	0.000
Distance to the coast	0.000
Vertical underclearance	0.002
Atmospheric NO_3^-	0.008
Atmospheric Cl^- concentration	0.009
Average daily temperature	0.029
MM subjective rating	0.034
Right lateral underclearance	0.074
ADT under the structure	0.089
MM objective rating	0.166
Average number of days with heavy fog	0.168
Average total snowfall	0.182
Average wind speed	0.290



Source: FHWA.

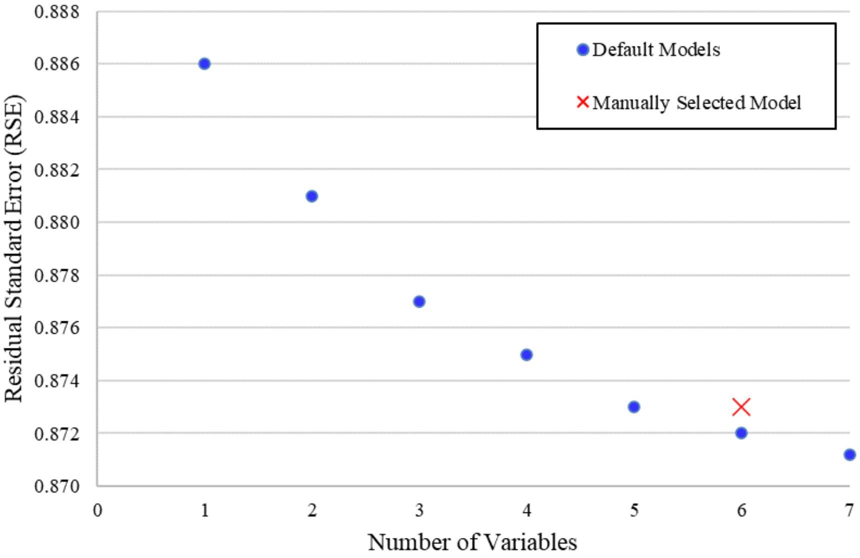
Figure 26. Graph. 10-fold CV method MSE versus number of variables—highway crossing model.

So the forward stepwise process was iteratively repeated, adding one variable at a time until the added variables were not significant. Results of this forward stepwise analysis are shown in table 32, figure 27, and figure 28. Table 32 shows that six variables were statistically significant (based on *p*-values less than 0.05, and with a dramatic increase in *p*-value due to adding the seventh variable). Then the results of this six-variable forward stepwise model were assessed for logic. The first five variables added to this model (age, performs bridge washing, maintenance manual subjective rating, vertical underclearance, and atmospheric Cl^- concentration) were all among variables previously considered to be important to UWS performance. The sign of the coefficients of each of these five variables was also logical, with variables that were expected to cause improved UWS performance with increasing values having positive coefficients and variables that were expected to cause decreased UWS performance with increasing values having negative coefficients.

Table 32. Summary of results from default incremental forward stepwise analyses—highway crossing model.

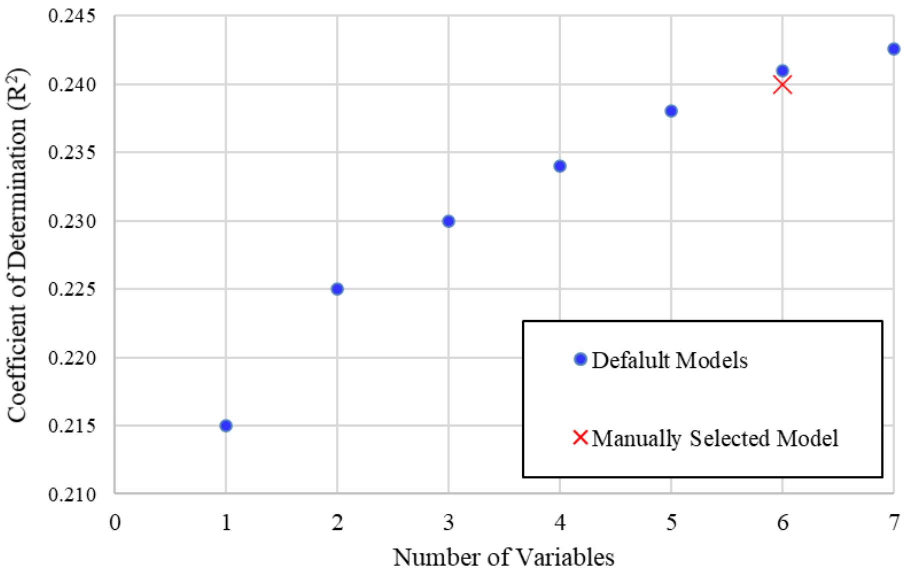
No. of Variables	Variable Added	*p*-Value	RSE	R^2	Coefficient Logical?[1]
1	Age	0.000	0.886	0.214	Yes
2	Performs bridge washing	0.000	0.881	0.224	Yes
3	MM subjective rating	0.000	0.877	0.230	Yes
4	Vertical underclearance	0.007	0.876	0.234	Yes
5	Atmospheric Cl^-	0.006	0.873	0.237	Yes
6	Distance to the coast	0.040	0.871	0.241	No
7	NO_3^-	0.326	0.870	0.243	No

[1] "Yes" indicates that the coefficient has a positive sign if increasing values are expected to improve UWS performance or a negative sign if decreasing values are expected to improve UWS performance; "No" indicates an opposite scenario.



Source: FHWA.

Figure 27. Graph. RSE versus number of variables—forward stepwise analyses for highway crossing model.



Source: FHWA.

Figure 28. Graph. Coefficient of determination versus number of variables—forward stepwise analyses for highway crossing model.

This finding was not the case for the sixth variable (distance to the coast). The distance-to-the-coast term had a negative coefficient, indicating worse performance with increasing distance to the coast, which was counterintuitive. This outcome was likely due to the data being biased by 72 percent of the dataset, which were not in a State along the Atlantic, Pacific, or gulf coastline and, therefore, had a large distance to the coast. Thus, distance to the coast was not included in the final highway crossing model.

The six-variable model was also assessed for what variables were not included. This assessment resulted in the conclusion that the six-variable model lacks the ability to represent the poor field performance observed of some highway overpasses subjected to high amounts of deicing agents. Deicing agent use is clearly the most significant issue causing poor performance of UWS based on the field work completed and the experiences of owners reported during this project. Considering that the amount of applied deicing agents is primarily a function of ADT under the structure and the amount of snowfall, the significance of these two variables, in addition to deicing agent use, was assessed (using the *p*-values in table 31 and other metrics).

These assessments showed that ADT under the structure was the most significant of these three variables. As a result, a manually supervised forward stepwise analysis was performed using the five most significant variables from the default analysis plus ADT and an additional analysis adding ADT and snowfall. Performing a similar manually supervised forward stepwise analysis with deicing agent use was also considered but not executed, given the highly course nature of these data (i.e., a single value representing all bridges within an agency).

The analysis using the five most significant variables from the default forward stepwise analysis in addition to ADT under the structure is labeled the manually selected model, and results of this model are shown in table 33, figure 27, and figure 28. Table 33 shows that the *p*-value of ADT under the structure was 0.080. This value was greater than the typical 0.05 value used as a threshold for assessing statistical significance, but it was a borderline value that is sometimes associated with variables included in regression models. Figure 27 and figure 28 also show the RSE and R^2 values resulting from the manually selected model, compared with those from the default models. These figures show that results of the manually selected model (containing six variables) were within 1 percent of the values for the default six-variable model and resulted in improvements relative to the five-variable model. Snowfall was not found to be statistically significant when added to the five most significant variables and ADT under the structure.

Table 33. *p*-Values for variables in final highway crossing model.

Term	Age	Performs Bridge Washing	MM Subjective Rating	Vertical Underclearance	Atmospheric Cl^-	ADT Under the Structure
p-Value	<2e-16	0.000	0.002	0.003	0.006	0.080

When correlated variables are included in statistical models, interaction terms that account for this correlation should be added to the model. Therefore, a final consideration was the correlations between the quantitative variables, which are shown in table 34. A value of +1 indicates that the values are perfectly correlated and that the increase or decrease is in proportion to one another; a value of −1 indicates that the values are perfectly correlated but that an increase in one variable correlates with a decrease in the other variable; and 0 indicates no correlation is present. Performs bridge washing and maintenance manual subjective rating are not included in table 34 because these were categorical variables; the integer-only values of these variables render an assessment of variable correlations irrelevant. Aside from these variables, table 34 shows no significant correlations between any of the variables included in the manually selected six-variable model (with the highest absolute value of any coefficient of determination being 0.19). Therefore, no interaction terms between variables were included in the highway crossing model.

Table 34. Variable coefficients of determination—highway crossing model.

Variable	Age	ADT Under the Structure	Vertical Underclearance	Atmospheric Cl^-
Age	—	−0.08	−0.19	−0.04
ADT under the structure	−0.08	—	0.02	0.01
Vertical underclearance	−0.19	0.01	—	0.14
Atmospheric Cl^-	−0.04	0.01	0.14	—

—Not applicable.

The manually supervised six-variable model was selected as the final highway crossing model because of the following features: similitude between the manually supervised six-variable model and the default six-variable model, the illogical nature of the representation of distance to the coast in the default model, and the ability of the manually supervised six-variable model to have greater applicability in assessing the influences of deicing agents, which are known to be a key concern.

Figure 29 shows the final model of the highway crossing dataset in terms of the standardized values of the variables, indicated by the “std” subscript. Figure 30 shows the equivalent form of figure 29 based on recalculating the coefficients so that the actual value of the variables can be used instead of the standardized values.

$$\begin{aligned} SCR_{P,std} = {} & -0.241 - 0.437 * \mathit{Age}_{std} + 0.283 * \mathit{PBW}_{std} + 0.074 * \mathit{MM\ Subjective\ Rating} + \\ & 0.073 * \mathit{Vertical\ Underclearance}_{std} - 0.066 * \mathit{Atmospheric\ Chloride}_{std} - \\ & 0.042 * \mathit{ADT\ Under\ the\ Structure}_{std} \end{aligned}$$

Figure 29. Equation. Final PPE for highway crossings in terms of standardized values of variables.

$$\begin{aligned} SCR_{P} = {} & 6.590 - 2.931 * 10^{-2} * \mathit{Age} + 2.665 * 10^{-1} * \mathit{PBW} + 1.141 * 10^{-1} * \mathit{MM\ Subjective\ Rating} + \\ & 1.597 * 10^{-1} * \mathit{Vertical\ Underclearance} - 2.522 * 10^{-1} * \mathit{Atmospheric\ Chloride} - \\ & 5.890 * 10^{-7} * \mathit{ADT\ Under\ the\ Structure} \end{aligned}$$

Figure 30. Equation. Final PPE for highway crossings in terms of actual values of variables.

All the variables included in this model and their coefficients were deemed reasonable. Because the dataset was standardized before the multiple regression analysis was performed, assessing the importance of variables was possible by comparing the standardized regression coefficients in figure 29, which are arranged in order of decreasing absolute value. The most important variable has the maximum absolute value of the standardized coefficient. For the highway crossing model, age was the most important variable, which was not surprising. This variable was followed by performs bridge washing , then maintenance manual subjective rating, the vertical underclearance, the concentration of atmospheric Cl^{-}, and the ADT under the structure, in that order.

The quantitative importance of bridge washing and maintenance were novel findings of this study, supporting anecdotal evidence and—in the case of bridge washing—informing a topic of significant debate in bridge management practices. The important influences of vertical clearance and ADT under the structure were also not surprising. The importance of atmospheric Cl^{-} concentration relative to other variables may be viewed as surprising. However, this variable was found to be influential in the more limited correlation of field performance that was performed at the conclusion of phase 2.

The adjusted R^2 value of this highway crossing model was 0.240, and the RSE was 0.873. While these values were not indicative of a particularly good fit to the data, the fit was deemed to be acceptable, given the tremendous amount of unavoidable scatter in the dataset.

Coastal Bridge Model

This section describes the development of the coastal bridge MLR model.

Filtered Variables

Including all the variables listed in the subsection, Variables and Variable Types Considered, at the beginning of this chapter resulted in exclusion of all data from Georgia, South Carolina, North Carolina, and Virginia from the dataset because of lack of availability of deicing agent (from South Carolina, North Carolina, and Virginia, although Virginia data were available from an external source) and bridge-washing information (from Georgia and South Carolina). Because this action represented the exclusion of a large region of the Atlantic coast, these issues were carefully considered.

In consideration of the lack of availability of deicing agent data, a model was created excluding the States for which these data were not available. Archival information on deicing agent in use in Virginia was manually added for this analysis (Balakumaran and Weyers 2019). The findings of this analysis were that deicing agent use was not a statistically significant variable. This same finding was obtained for the highway crossing model. Therefore, the research team decided to remove deicing agent use as a variable considered in the coastal bridge model so that data from North Carolina and South Carolina could be included in the dataset.

Because performs bridge washing data were not available for South Carolina and Georgia, alternative models were created assigning this variable to equal yes and no. In neither of these models was performs bridge washing determined to be an influential variable. So the results were independent of the performs bridge washing assignments.

Data Cleaning

A key consideration in developing the coastal bridge model was establishing the criteria for including the bridge in the dataset used to develop the model. Four different thresholds for a distance to the coast were evaluated: 10 mi (0 mi < distance to coast ≤ 10 mi), 50 mi (0 mi < distance to coast ≤ 50 mi), 100 mi (0 mi < distance to coast ≤ 100 mi), and all bridges in coastal States (defined as a State being on the Pacific, Atlantic, or gulf coasts).

At this stage of the analysis, two other decisions remained to be made regarding forming the dataset for the coastal bridge model. One of these was whether New York would be included in the dataset. This uncertainty was because a high number of the bridges (305 to 1,896 bridges, depending on the distance-to-the-coast threshold adopted) were from New York, and the team suspected that including these bridges may bias the dataset in ways similar to the bias this inclusion created in the highway crossing model. The other decision was whether Georgia and South Carolina would be included in the database and how performs bridge washing would be considered if so. So models were created for each of the four distance-to-the-coast thresholds listed in the previous paragraph while alternately including or excluding New York and alternately assuming performs bridge washing for South Carolina and Georgia was yes or no, as summarized by table 35.

Table 35. Results of data analysis to determine if distance to the coast is a significant variable for different distance-to-the-coast thresholds.

Groups	10 mi	50 mi	100 mi	All Coastal State Bridges
SC and GA: PBW = yes; include NY	No	No	Yes	No
SC and GA: PBW = yes; exclude NY	No	Yes	Yes	No
SC and GA: PBW = no; include NY	No	No	Yes	No
SC and GA: PBW = no; exclude NY	No	Yes	Yes	No

PBW = performs bridge washing.

For the 16 models summarized by table 35, MLR analyses were performed, and the significance of distance to the coast as a variable was evaluated. These analyses showed that distance to coast was a significant variable for all of the 100-mi datasets. So, a 100-mi threshold was used to create the coastal bridge dataset to assess the performance of coastal bridges. This threshold appeared to be optimum, resulting in a distance to the coast that was neither too small nor too large. When the smallest threshold of 10 mi was used, distance to the coast was not a significant variable, presumably because of insignificant variation over this distance. The 50-mi-to-the-coast threshold resulted in distance to the coast being a significant variable only if New York was excluded from the analysis. If all bridges in coastal States were included, distance to the coast was not a significant variable. This result was likely due to bridges farther from the coast biasing the dataset in this case.

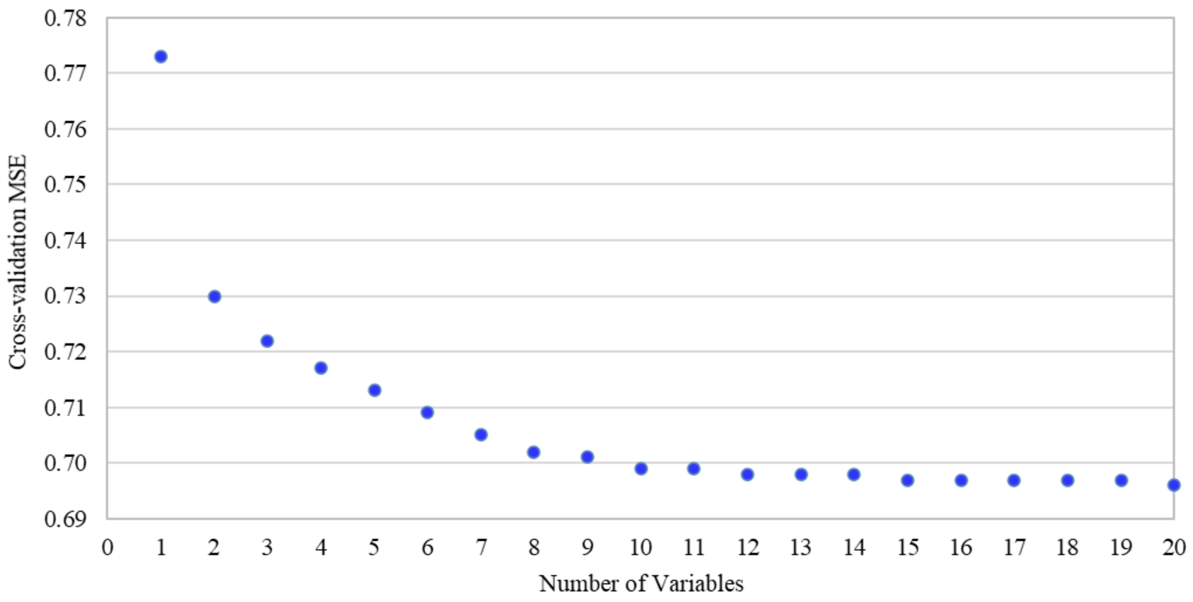
After choosing the distance-to-the-coast threshold, the models with and without New York were compared. The researchers found that the results for the models drastically differed. The model that included New York contained many more variables with little overlap between which variables were included in the models. This result suggested that the New York data were biasing the dataset. Therefore, the New York data were also excluded from the coastal bridge model.

Model Development

The 10-fold CV analysis resulted in the 20 variables shown in table 36. This result represented all the variables considered, except for ADT under the structure (although ADTT under the structure is included) and maintenance manual subjective rating. However, table 36 shows that many of these variables were not statistically significant (as indicated by *p*-values greater than 0.05). Furthermore, figure 31 shows the same MSE (0.70) results for all models between 8 and 20 variables when the MSE was rounded to two digits.

Table 36. Summary of results of preliminary model based on 10-fold CV method—coastal bridge model.

Variables	*p*-Value
Age	0.000
Right lateral underclearance	0.000
MM objective rating	0.003
Mean total snowfall	0.007
Waterway crossing	0.014
Average wind speed	0.036
Average number of days with heavy fog	0.051
Average annual percent morning humidity	0.066
Average annual precipitation	0.069
Atmospheric SO_4^{-2}	0.175
ADTT under the structure	0.175
Atmospheric NO_3^-	0.212
Vertical underclearance	0.393
Highway crossing	0.457
TOW	0.565
Atmospheric Cl^-	0.577
Performs bridge washing	0.641
Average daily temperature	0.692
Railroad crossing	0.718
Distance to the coast	0.993



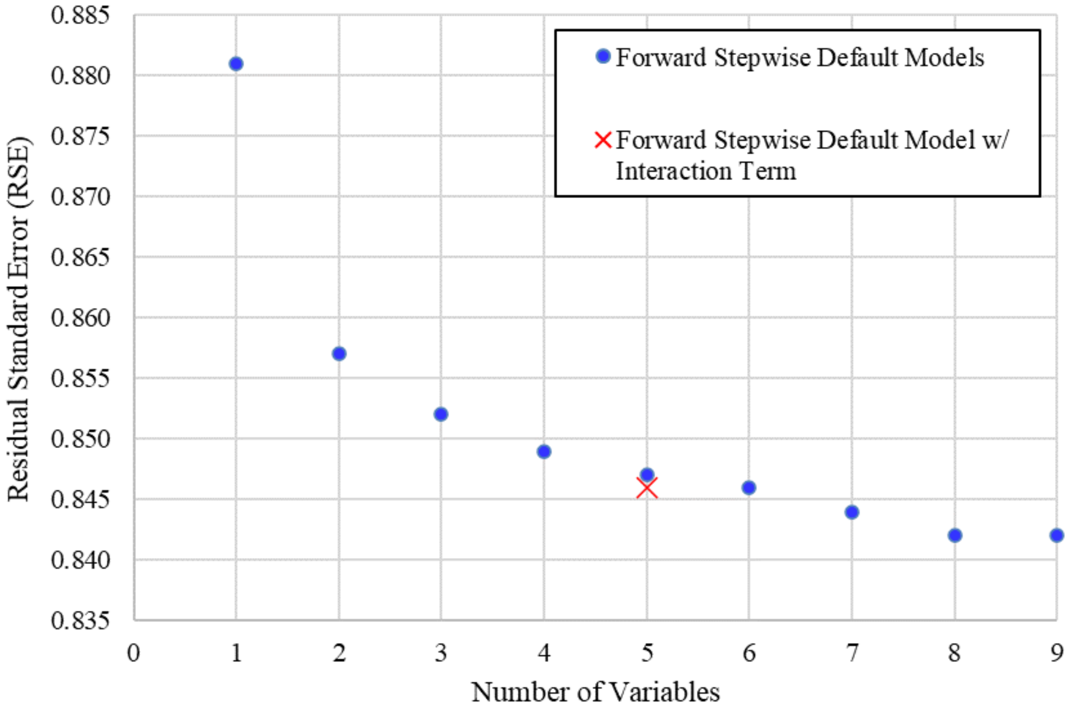
Source: FHWA.

Figure 31. Graph. CV MSE versus number of variables—coastal bridge model.

So, the forward stepwise process was iteratively repeated, adding variables one at a time in the order of their significance until the added variables were not significant. Results of this forward stepwise analysis are shown in table 37, figure 32, and figure 33. Table 37 shows that eight variables were statistically significant. However, when the sixth variable was added, the improvement in RSE and coefficient of determination was only 0.001 and 0.002, respectively.

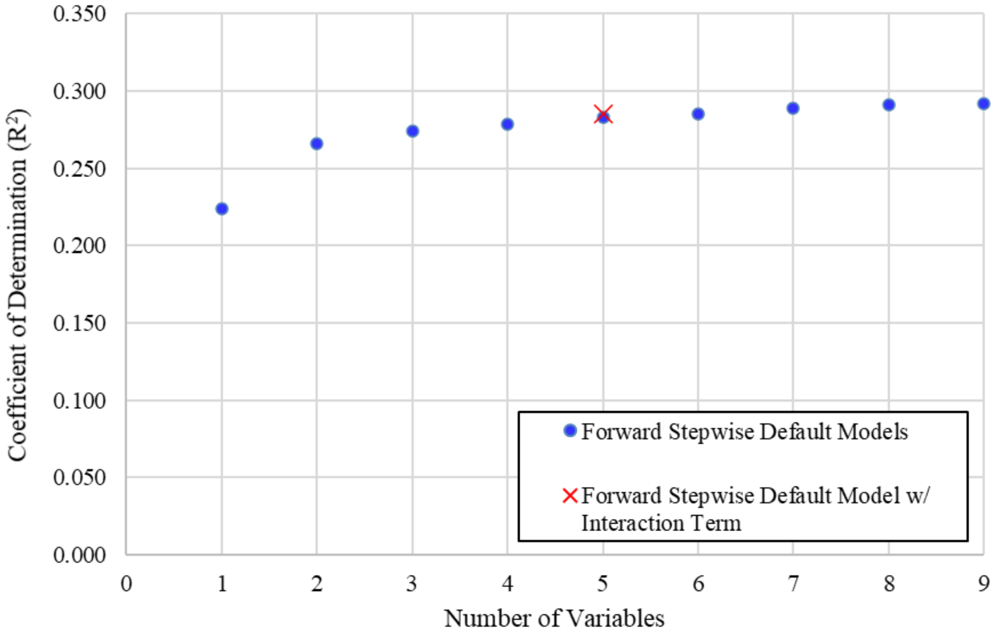
Table 37. Summary of results from default incremental forward stepwise analyses—coastal bridge model.

No. of Variables	Variable Added	*p*-Value	RSE	Adjusted R^2	Coefficient Logical?
1	Age	0.000	0.881	0.224	Yes
2	Average number of days with heavy fog	0.000	0.857	0.266	No
3	Right lateral underclearance	0.000	0.852	0.274	Yes
4	Distance to the coast	0.001	0.849	0.279	Yes
5	Waterway crossing	0.007	0.847	0.283	Yes
6	Mean total snowfall	0.016	0.846	0.285	No
7	Average annual percent morning humidity	0.009	0.844	0.289	No
8	MM objective rating	0.031	0.842	0.291	No
9	Average annual precipitation	0.072	0.842	0.292	Yes



Source: FHWA.

Figure 32. Graph. RSE versus number of variables—forward stepwise analyses for coastal bridge model.



Source: FHWA.

Figure 33. Graph. Coefficient of determination versus number of variables—forward stepwise analyses for coastal bridge model.

Then the results of the eight-variable forward stepwise model were assessed for logic. Of the first five variables added to this model, three of these—age, distance to the coast, and waterway crossing—were variables previously considered to be important to UWS performance. Furthermore, the sign of the coefficient on all three of these variables was logical. The other two of the five most influential variables—average number of days with heavy fog and right lateral underclearance—were somewhat surprising additions to this list of most influential variables. The average number of days with heavy fog was considered a possible indicator of humidity. However, the positive sign on this variable suggested improved performance with increased fog. A possible explanation for this finding was fog providing a mild rinsing effect that removes contaminants. With increased lateral underclearance, the team hypothesized that increased air circulation was present, providing a drying effect. Because the signs on the coefficients of the sixth, seventh, and eighth variables were not logical, and the team desired to limit the final number of variables included to a number that was reasonable for practical applications, only the five most significant variables were included.

A final consideration was to examine the possible correlations between the included quantitative variables, which are shown in table 38. This analysis shows a modest (0.34) positive correlation between distance to the coast and average number of days with heavy fog, and between the right lateral underclearance and the average number of days with heavy fog (0.36). Therefore, the influence of adding interaction terms for each of these pairs of variables was evaluated. This evaluation showed that the interaction term, including number of days with heavy fog and distance to the coast, was a statistically significant variable that resulted in the other five influential variables remaining significant. However, the interaction term between the lateral underclearance and distance to the coast was not statistically significant. Furthermore, a correlation between distance to the coast and fog was intuitively logical (as they are known to have a natural relationship), whereas a correlation between lateral underclearance (a feature of the built environment) and distance to the coast was more likely purely coincidental.

Table 38. Variable coefficients of determination—coastal bridge model.

Variable	Age	Right Lateral Underclearance	Distance to the Coast	Average No. of Days with Heavy Fog
Age	—	0.03	0.14	−0.04
Right lateral underclearance	0.03	—	0.09	0.36
Distance to the coast	0.14	0.09	—	0.34
Average number of days with heavy fog	−0.04	0.36	0.34	—

—Not applicable.

So the final coastal model included the five variables found to be most statistically significant and an interaction term between distance to the coast and heavy fog. All variables in this model were statistically significant (table 39) and had logical coefficients. Furthermore, figure 32 and figure 33 show that the RSE and R^2 values that resulted from this model—0.846 and 0.285, respectively—exactly matched those from the default six-variable model (when rounding to three digits; the fit of the final coastal model is slightly worse for both metrics if four digits of precision are used). Yet the coefficients on the variables were more logically intuitive in the five-variable model with the interaction term equation than in the default six-variable model.

Table 39. *p*-Values for variables in final coastal bridge model.

Term	Age	Right Lateral Underclearance	Average No. of Days with Heavy Fog	Distance to Coast	Average No. of Days with Heavy Fog × Distance to Coast	Waterway Crossing
p-Value	<2e-16	0.000	0.000	0.001	0.033	0.007

Figure 34 shows the final coastal bridge model in terms of the standardized values of the variables, indicated by the “std” subscript. Figure 35 shows the equivalent equation with coefficients corresponding to actual values of the variables. Because the dataset was standardized before the multiple regression analysis was run, assessing the importance of the variables was possible by comparing the standardized regression coefficients. The most important variable had the maximum absolute value of the standardized coefficient. For the coastal bridge model, age was the most important variable, followed by average number of days with heavy fog, whether the bridge was a waterway crossing, right lateral underclearance, distance to coast, and the interaction term between number of days with heavy fog and distance to the coast, in that order.

$$\begin{aligned}\text{SCR}_{\text{P,std}} = {} & 0.076 - 0.490*\textit{Age}_{std} + 0.161*\textit{Average Number of Days with Heavy Fog}_{std} - \\ & 0.145*\textit{Waterway Crossing}_{std} + 0.124*\textit{Right Lateral Underclearances}_{std} + \\ & 0.089*\textit{Distance to Coast}_{std} - \\ & 0.056*\textit{Average Number of Days with Heavy Fog*Distance to Coast}_{std}\end{aligned}$$

Figure 34. Equation. Final PPE for coastal bridges in terms of standardized values of variables.

$$\begin{aligned}\text{SCR}_{\text{P}} = {} & 7.458 - 3.799*10^{-2}*\textit{Age} + 1.412*10^{-2}*\textit{Average Number of Days with Heavy Fog} - \\ & 1.190*10^{-1}*\textit{Waterway Crossing} + 9.970*10^{-3}*\textit{Right Lateral Underclearance} + \\ & 5.807*10^{-3}*\textit{Distance to Coast} - \\ & 1.205*10^{-4}*\textit{Average Number of Days with Heavy Fog*Distance to Coast}\end{aligned}$$

Figure 35. Equation. Final PPE for coastal bridges in terms of actual values of variables.

As with the highway crossing model, the adjusted R^2 and RSE values of this model (0.846 and 0.285, respectively) were not indicative of a particularly good fit to the data. However, this result was deemed to be acceptable, given the tremendous amount of scatter in the dataset. Furthermore, these values for the coastal bridge model were slightly superior to those from the highway crossing model.

Sensitivity Analysis

A sensitivity analysis was performed to assess the effects of the variability of influential parameters on the SCR_{P} values predicted by the equations shown in figure 29, figure 30, figure 34, and figure 35. These sensitivity analyses provided general understanding of the influence of each variable and informed the selection of performance benchmarks discussed in the following subsection.

To perform the sensitivity analysis, first the minimum, maximum, and 10th, 25th, 50th, 75th, and 90th percentile values of each independent variable were compiled. These values were separately compiled for each independent variable in the equations shown in figure 29, figure 30, figure 34, and figure 35 using the databases used to create each PPE.

Once realistic ranges of the influential variables were compiled, they were varied independently and in combination to assess the influence on SCR_{P}. In most cases, a constant age of 50 yr was selected as a value that was relatively high to inform long-term performance, but within the bounds of the age range used to develop the PPE. A higher age of 75 yr was also considered and will be discussed in the subsection, Determination of Performance Benchmarks.

When variables were independently varied, the remaining variables were set to their median values. When variables were simultaneously varied, all variables were sorted based on relative severity to account for the fact that some variables had a positive effect on SCR_{P} (e.g., distance to the coast), whereas others had a negative effect (e.g., ADT under the bridge). So, for example, when variables were simultaneously varied, the 10th most severe variable combination used the 10th percentile values (i.e., lower numbers) for variables with negative coefficients in the regression model, and the 90th percentile values (i.e., higher numbers) were used for variables with positive coefficients.

Highway Crossing Model

Table 40 reports the minimum, maximum, average, and selected percentile values for each of the independent variables (except for age) used in the highway crossing model. To summarize this data, it shows a large—but not surprising—variability in ADT under the structure. The vertical underclearance was the quantitative variable with the least variability in terms of percent change. The variability was just over 3 ft between the 10th and 90th percentile values. Recalling that values of vertical underclearance that were considered outliers were excluded from the analysis, the team also considered the variability including outliers. This evaluation showed a similar amount of variability between the 10th and 75th percentile values, where the range between these percentiles was less than 3 ft. The variability of the atmospheric Cl^- concentrations showed much less variability between the 10th and 50th percentile values than the remainder of the dataset. From the 50th to 75th percentile values, the atmospheric Cl^- concentration more than doubled, and similar comparisons existed between the 75th and 90th percentile values and 90th percentile and maximum values. Most (85 percent) of the bridges contained in the highway crossing database were from agencies that perform bridge washing. Most of the bridges in the database were in agencies with maintenance manuals that received a subjective rating of either 2 or 3 (the two best ratings).

Table 40. Variability of influential parameters—highway crossing model.

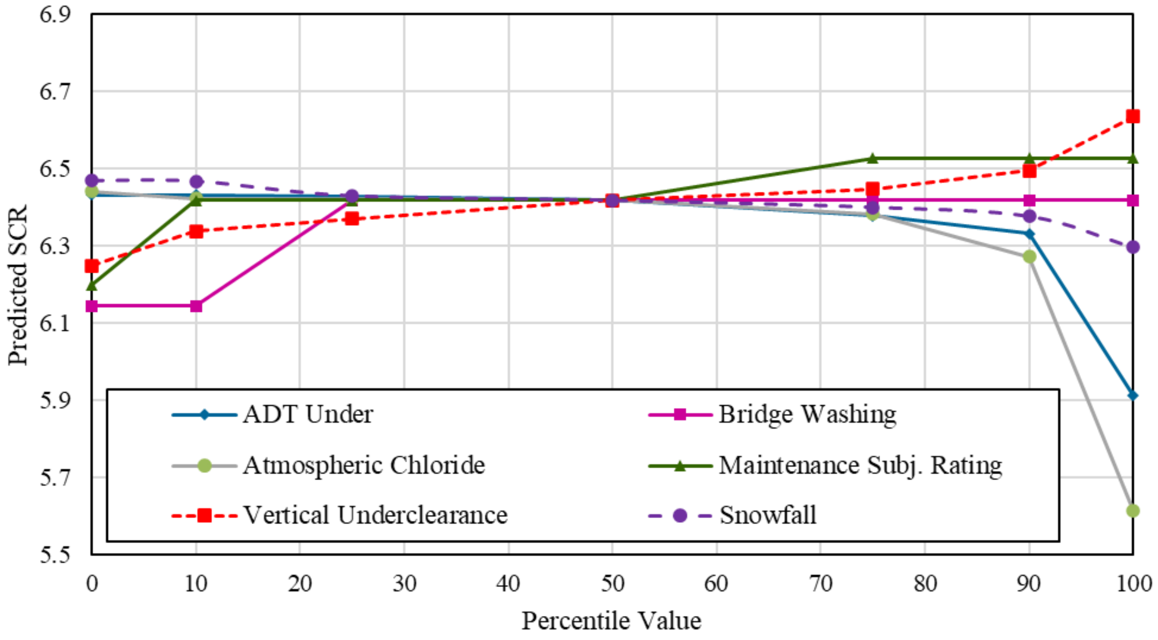
Quantity	ADT Under the Structure (count)	Vertical Underclearance (ft)	Atmospheric Cl^- (ppm)	Performs Bridge Washing (unitless)	MM Subjective Rating (unitless)
Minimum	0	12.8	0.000	0	0
10th percentile	1,035	14.8	0.062	0	2
25th percentile	5,943	15.5	0.066	1	2
50th percentile	21,170	16.5	0.080	1	2
75th percentile	78,994	17.2	0.196	1	3
90th percentile	145,900	18.2	0.565	1	3
Maximum	752,250	21.3	2.746	1	3
Average	51,504	16.5	0.175	0.852	2.25

Table 41 shows the SCR_P values that resulted when the values in table 40 were input into figure 30, the remaining variables were assigned to equal their median values, and the age was assumed to be a constant value of 50 yr. These results showed a relatively small amount of variability in SCR_P for most typical values. In particular, the difference in SCR_P when the 10th versus 90th percentile values were used was 0.17 or less for each of the three numerical variables. Bridge washing had a larger effect of 0.27. When the full range of numerical variables that were possible were considered, the difference in SCR_P was 0.4 to 0.7 for each of the three numerical variables. The larger differences were attributed to the data in table 40, which shows that the difference between the maximum and 90th percentile values for ADT under the structure and atmospheric Cl^- concentration were 500 percent. While the variation in vertical underclearance was less due to excluding outlier values of this variable, the coefficient on this term was the largest of the site variables. This outcome resulted in the variation in SCR_P due to variation in vertical underclearance to be of a similar magnitude as the results from the variation of ADT under the structure.

Table 41. SCR_P values (unitless) for variable influential parameters—highway crossing model, age = 50 yr.

Quantity	Vary ADT Under	Vary Vertical Underclearance	Vary Atmospheric Cl^-	Vary MM Subjective Rating	Vary Washing
Least severe	6.40	6.62	6.41	6.50	6.12
10th most severe	6.40	6.47	6.39	6.50	6.12
25th most severe	6.40	6.42	6.39	6.50	6.39
50th most severe	6.39	6.39	6.39	6.39	6.39
75th most severe	6.36	6.34	6.36	6.39	6.39
90th most severe	6.32	6.31	6.27	6.39	6.39
Most severe	5.96	6.21	5.72	6.16	6.39
Range, 10th–90th	0.09	0.17	0.13	0.11	0.27
Range, 0–100th	0.44	0.41	0.69	0.34	0.27

Figure 36 presents a graphical representation of these data. Here the main observations were again the relatively small variability in SCR_P for the 10th to 90th percentile value of each variable, the larger impact of bridge washing compared to typical values of the other variables, and the significant impact of the maximum values for each numerical variable. Figure 36 also plots the influence of variable snowfall, which was observed to be small relative to the other parameters. For this reason, snowfall was not included in the final highway crossing model.



Source: FHWA.

Figure 36. Graph. SCR$_P$ versus individual variation of influential parameters—highway crossing model.

Another observation from the data in table 41 was that the relative significance of the variables differed, depending on the metric considered. In the previous subsection, the relative ranking of the importance of the variables—when standardized—was age, then bridge washing, followed by maintenance manual subjective rating, vertical underclearance, atmospheric Cl^- concentration, and ADT under the structure, in that order. The data in table 41 show that when typical practical values of the variables were considered (i.e., the 10th to 90th percentile values), and age was excluded due to its clearly dominant effect, the ranking of the influence of the variables was the same as indicated by their standardized coefficients, except for the influence of the maintenance manual subjective rating. However, maintenance manual subjective rating had a larger influence than bridge washing when the full range of practical values was considered. Also, when the full range of practical values was considered, atmospheric Cl^- concentration was the most significant variable.

Table 42 shows the effect of simultaneously varying all parameters, all site variables (ADT under the structure, vertical underclearance, and atmospheric Cl^- concentration), and all maintenance variables (washing and maintenance manual subjective rating). Not surprisingly, these calculations resulted in a much larger range of SCR$_P$ values, between 4.61 and 6.77. Considering the median 80 percent of the values (between the 10th and 90th percentiles of most severe values), the effect of varying all variables simultaneously was 0.76. Comparing the effects of influence of site variables and owner variables showed these types of variables had the same effect for the median 80 percent of values (which corresponded to the variations in the values of the variables shown in table 40). Considering the full range of values, the site variables had more influence than the owner values. This effect was dominated by the influence of atmospheric Cl^- concentration, as shown in table 41.

Table 42. SCRP values (unitless) for combinations of variable influential parameters—highway crossing model, age = 50 yr.

Quantity	Vary All	Median Owner Variables, Vary Site Variables	Median Site Variables, Vary Owner Variables
Least severe	6.77	6.65	6.50
10th most severe	6.60	6.49	6.50
25th most severe	6.55	6.43	6.50
50th most severe	6.39	6.39	6.39
75th most severe	6.28	6.28	6.39
90th most severe	5.84	6.11	6.12
Most severe	4.61	5.11	5.89
Range, 10th–90th	0.76	0.38	0.38
Range, 0–100th	2.15	1.55	0.61

Coastal Bridge Model

Table 43 reports the minimum, maximum, average, and selected percentile values for each of the independent variables (except for age) used in the coastal bridge model. Table 43 shows a range of lateral clearance values between 0 and 100 ft (based on the coding of lateral underclearance explained in chapter 3), with half of the bridges having a lateral clearance less than 16.1 ft, and most of the bridges having a lateral clearance less than 30 ft. The average number of days with heavy fog is observed to be between 20 and 30 d for most bridges, with some bridges having much higher or lower values (between 5 and 66 d). The distance to coast varies between 0 and 100 mi, as this distance was the criteria used to define the database; table 43 shows that 25 percent of the bridges are within 3 mi of the coast, most of the bridges are within 15 mi of the coast, and 75 percent of the bridges are within 50 mi of the coast. Waterway crossings were represented by a categorical variable equal to 0 and 1, with most bridges having service types under the bridge other than waterways.

Table 43. Variability of influential parameters—coastal bridge model.

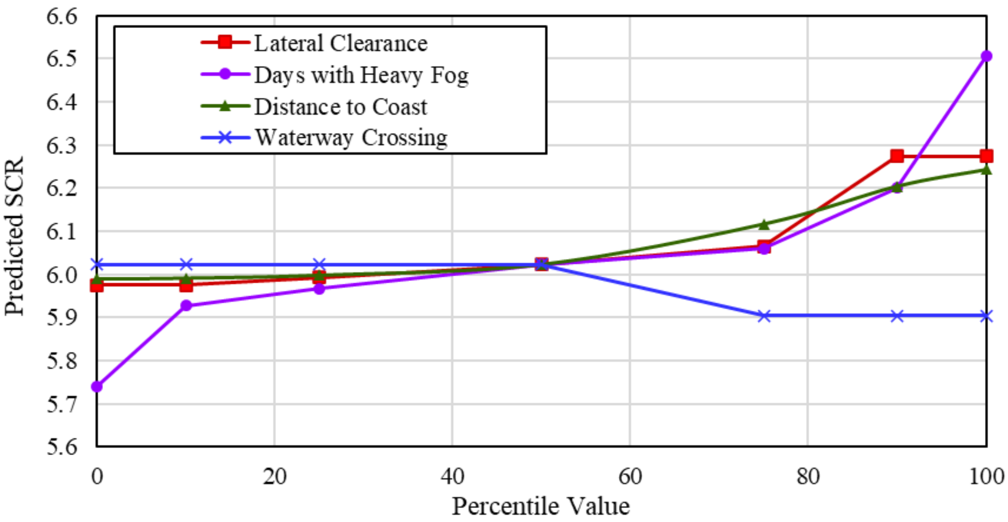
Quantity	Right Lateral Underclearance (ft)	Average No. of Days with Heavy Fog (d)	Distance to Coast (mi)	Waterway Crossing (unitless)
Minimum	0.0	5	0	0
10th percentile	0.0	19	1	0
25th percentile	5.9	23	3	0
50th percentile	16.1	27	13	0
75th percentile	29.9	30	50	1
90th percentile	98.4	41	84	1
Maximum	98.4	66	100	1
Average	27.9	28	28	0.39

Table 44 shows the SCRP values that result from various combinations of the values in table 43 when input into the equation shown in figure 35, and the age is assumed to be a constant value of 50 yr. The first four data columns of table 44 show the SCRP when the variable of interest is varied, and the remaining variables are set to their median values. These data again show a relatively small amount of variability in SCR_P for most typical values. In particular, the difference in SCR_P when using the 10th versus 90th percentile values is 0.30 or less for each variable. When the full range of numerical variables that are possible are considered, the difference in SCR_P does not appreciably change when lateral clearance, distance to the coast, or crossing type are considered, but does when number of days with heavy fog is considered. This result is because of the more uniform distribution of values of lateral clearance and distance to the coast, while the minimum and maximum values of number of days with heavy fog differs more dramatically from the 10th and 90th percentile values (table 43).

Table 44. SCR_P values (unitless) for variable influential parameters—coastal bridge model, age = 50 yr.

Quantity	Vary Lateral Clearance	Vary No. of Days with Heavy Fog	Vary Distance to Coast	Vary Waterway Crossing	Vary All
Least severe	6.27	6.51	6.24	6.02	6.46
10th most severe	6.27	6.20	6.20	6.02	6.39
25th most severe	6.07	6.06	6.12	6.02	6.06
50th most severe	6.02	6.02	6.02	6.02	6.02
75th most severe	5.99	5.97	6.00	5.90	5.91
90th most severe	5.97	5.93	5.99	5.90	5.84
Most severe	5.97	5.74	5.99	5.90	5.62
Range, 10th–90th	0.30	0.27	0.21	0.12	0.56
Range, 0–100th	0.30	0.77	0.25	0.12	0.83

Figure 37 presents a graphical representation of the table 44 data. A main observation here is the small variability for all variables other than fog, particularly for the 0 to 75th percentile values. Other primary observations are the relatively small variability when number of days with heavy fog values between the 10th to 90th percentile are considered and the more significant variation in SCR_P when the maximum and minimum values of number of days with heavy fog are considered.



Source: FHWA.

Figure 37. Graph. SCR$_P$ versus individual variation of influential parameters—coastal bridge model.

Comparing the data in the first three data columns of table 44 shows that the relative significance of the variables differs, depending on the metric considered. In the previous subsection, the relative ranking of the importance of the variables—when standardized—was age, then number of days with heavy fog, lateral clearance, distance to the coast, and crossing type, in that order. The summary data in the last two rows of table 44 show that when practical values of the variables are considered, and age is excluded due to its clearly dominant effect, number of days with heavy fog remains the most significant variable when the full range of practical values is considered. However, all the quantitative variables have similar effects for most typical values (e.g., when the 10th to 90th percentile values are considered). Yet, it is noteworthy that distance to the coast has the lowest effect (of the quantitative variables) based on the range of SCR$_P$ values resulting from comparing either the 10th to 90th or 0 to 100th percentile values. Crossing type has the overall lowest effect in terms of all metrics considered.

The last column of table 44 shows the effect of simultaneously varying all three values. These calculations result in a slightly greater range of SCR$_P$ values. When the median 80 percent of the values are considered (between the 10th and 90th percentiles of most severe values), the effect of varying all three numerical variables simultaneously is a difference in SCR$_P$ of 0.56. When the full range of values is considered, the difference in SCR$_P$ increases to 0.83, and this increase relative to the median 80-percent values is mostly due to variation in the number of days with heavy fog.

Application of Regression Models

In this subsection, the PPE are used to determine threshold values for the influential parameters that can be used to inform a quantitative update to the UWS TA (FHWA 1989). The first subsection below discusses the methodology for this exercise, and the second subsection discusses the results.

Determination of Performance Benchmarks

The PPE can be used to determine specific values of the influential parameters that result in desirable and undesirable UWS performance. The first step in doing so is to establish a performance target. Two potential performance targets were initially considered: an SCR_P greater than or equal to 5.0 after 75 yr, and an SCR_P greater than or equal to 6.0 after 50 yr. Because an SCR_P of 5 after 75 yr was a target easily met by even extreme combinations of variables in the highway crossing model, an SCR_P of 6 after 50 yr was selected.

Next, considering that both the highway crossing and coastal bridge models contain multiple variables, the approach taken was to determine a modestly severe value (MSV) for each variable. Three sets of MSVs were generally considered: the 90th percentile most severe values (either the 10th or 90th percentile values numerically, whichever had the most negative impact on SCR_P), the 75th percentile most severe values (either the 25th or 75th percentile values numerically, whichever had the most negative impact on SCR_P), and the median values, as a simple alternative to assess the variability in output based on selected MSV. Rounded versions of these values that may be of more practical use were also considered. Another definition of MSV that was considered but abandoned was the median values ±1 standard deviation (whichever operation causes this most severe situation). This option resulted in vertical underclearance values corresponding to the 0 percentile, which was viewed as overly severe and not a realistic representation of typical highway crossings.

The MSV was input for each variable into the PPE for $n-1$ variables. Next, the PPE was solved for the value of variable n that results in the performance target being met. This value was termed the variable threshold value. This step was iteratively repeated for each variable. The intent of these variable threshold values is to provide information for a quantitative update to the UWS TA (FHWA 1989).

The mathematical influences of the various choices of MSV were then considered. These data showed that a consistent definition of MSV for the two different models did not yield practical results. For the highway crossing model, the performance target of SCR_P of 6 at 50 yr was easily met when median values for the MSV were used, but very difficult to meet when the 90th percentiles of most severe values were used. The combinations of the parametric values that occur in the highway crossing and coastal bridge databases were then evaluated. This evaluation showed that there were no cases in the highway crossing model where the 90th percentile most severe values simultaneously occurred for all variables. In the coastal bridge model, this situation occurred for less than 1 percent of the bridges. This information led to computing an "average site percentile" that simply averaged the percentile values of each influential variable (again ranked based on severity of impact to SCR_P versus a consistent ascending or descending order) for each bridge. The 90th percentile of average site percentiles was then considered as a more nuanced definition of MSV. These values were 71 for the highway crossing model and 77 for the coastal bridge model (i.e., approximately 75 for both models). Thus, the 75th percentile most severe values for each variable were used in the highway crossing model to produce a realistically severe environment when all variables were considered in combination. This choice resulted in variable threshold values that were practically reasonable and generally consistent with field observations.

When the 75th percentile values were selected as the MSV for the coastal model, the result was high threshold values (falling between the 68th to 79th percentile values for each variable). In other words, this result would suggest unacceptable performance of most of the UWS coastal bridges, which is not consistent with real-world observations. Therefore, the median values were selected as the general concept for the MSV instead.

Threshold Values for Influential Parameters

The following subsections describe the threshold values for influential parameters for the highway crossing model and coastal bridge model, respectively.

Highway Crossing Model

Table 45 shows the specific values of each variable in the highway crossing PPE that result in achieving the performance threshold of an SCR_P of at least 6.00 at an age of 50 yr when the other quantitative variables are at their 75th percentile values and various combinations of washing and maintenance manual subjective ratings are assumed.

Table 46 is a modified version of these same data using rounded values for the quantitative variables. Specifically, the ADT is rounded down to the nearest 5,000 (equaling 75,000) and up to the nearest 100,000 (equaling 100,000) to explore the sensitivity of the results within this range of MSV. These values represent the 74th and 80th percentile of ADT for the bridges considered in the development of the highway crossing model. The effect of this range of ADT values was concluded to be relatively minor. The vertical underclearance is assigned a value of 16 ft in table 46, which represents rounding up the MSV of vertical underclearance to the nearest foot. The atmospheric Cl^- concentration was rounded to the nearest 0.1 ppm (which equated to rounding up) in the table 46 calculations.

Table 45. Calculation of threshold values for influential parameters using MSV—highway crossing model.

Solving For	Washing? (Yes/No)	MM Subjective Rating (unitless)	Age (yr)	ADT Under the Structure (unitless)	Vertical Underclearance (ft)	Atmospheric Cl⁻ (ppm)	SCR_P (unitless)
ADT under the structure	No	0	50	0	15.5	0.196	5.83
ADT under the structure	No	2	50	≤96,485	15.5	0.196	6.00
ADT under the structure	No	3	50	≤290,265	15.5	0.196	6.00
ADT under the structure	Yes	2	50	≤54,9033	15.5	0.196	6.00
ADT under the structure	Yes	3	50	≤742,812	15.5	0.196	6.00
Vertical underclearance	No	0	50	78,994	≥20.0	0.196	6.00
Vertical underclearance	No	2	50	78,994	≥15.3	0.196	6.00
Vertical underclearance	Yes	2	50	78,994	≥9.81	0.196	6.00
Atmospheric Cl⁻ concentration	No	0	50	78,994	15.5	0.000	5.83
Atmospheric Cl⁻ concentration	No	2	50	78,994	15.5	≤0.238	6.00
Atmospheric Cl⁻ concentration	Yes	2	50	78,994	15.5	≤1.294	6.00
Atmospheric Cl⁻ concentration	Yes	3	50	78,994	15.5	≤1.747	6.00

Table 46. Calculation of threshold values for influential parameters using rounded MSV—highway crossing model.

Solving For	Washing? (Yes/No)	MM Subjective Rating (unitless)	Age (yr)	ADT Under the Structure (unitless)	Vertical Underclearance (ft)	Atmospheric Cl$^-$ (ppm)	SCR$_P$ (unitless)
ADT under the structure	No	0	50	0	16.0	0.200	5.85
ADT under the structure	No	2	50	≤135,776	16.0	0.200	6.00
ADT under the structure	Yes	2	50	≤58,7982	16.0	0.200	6.00
ADT under the structure	Yes	3	50	≤781,762	16.0	0.200	6.00
Vertical underclearance	No	0	50	100,000	≥20.2	0.200	6.00
Vertical underclearance	No	2	50	100,000	≥15.6	0.200	6.00
Vertical underclearance	Yes	2	50	100,000	≥10.1	0.200	6.00
Vertical underclearance	No	0	50	100,000	≥20.2	0.200	6.00
Vertical underclearance	No	2	50	100,000	≥15.6	0.200	6.00
Vertical underclearance	Yes	2	50	100,000	≥10.1	0.200	6.00
Atmospheric Cl$^-$ concentration	No	0	50	100,000	16.0	0.000	5.84
Atmospheric Cl$^-$ concentration	No	2	50	100,000	16.0	≤0.284	6.00
Atmospheric Cl$^-$ concentration	Yes	2	50	100,000	16.0	≤1.340	6.00
Atmospheric Cl$^-$ concentration	Yes	3	50	100,000	16.0	≤1.793	6.00
Atmospheric Cl$^-$ concentration	No	0	50	75,000	16.0	0.000	5.86
Atmospheric Cl$^-$ concentration	No	2	50	75,000	16.0	≤0.342	6.00
Atmospheric Cl$^-$ concentration	Yes	2	50	75,000	16.0	≤1.399	6.00
Atmospheric Cl$^-$ concentration	Yes	3	50	75,000	4.87	≤1.851	6.00

The following are offered as potential conclusions from these calculations in table 45 and table 46:

- Without washing or maintenance (as indicated by the presence of an maintenance manual) when the other two quantitative variables are at or near their 75th percentile values, there are no practical values of ADT or atmospheric Cl^- concentration that achieve the performance benchmark. This finding is demonstrated by the values of zero for these variables when washing is assigned "no" and maintenance manual subjective rating is assigned zero in table 46. A vertical clearance of 20 ft is required in this situation. These observations indicate the importance of owners' actions in affecting bridge performance.

- An ADT up to approximately 100,000 is expected to result in satisfactory performance in most cases, regardless of whether bridge washing is performed, assuming a typical level of maintenance (as reflected by documentation received of owners' maintenance practices). When a greater ADT exists and deicing agents are used, bridge washing or high attention to maintenance is recommended for consideration.

- Most practical values of vertical underclearance are expected to result in satisfactory performance in most cases. In agencies that perform bridge washing and have typical maintenance practices, the performance benchmarks can be achieved with a relatively small vertical underclearance of 10 ft (which is less than the AASHTO (2018b) requirements, and thus this vertical underclearance will be achieved automatically for most situations). In agencies that do not perform bridge washing, this value increases to 15 ft. Also, in agencies with neither bridge washing nor formally documented maintenance programs, this value increases to 20 ft.

- The majority of atmospheric Cl^- concentrations are expected to result in satisfactory performance in most cases (regardless of whether bridge washing is performed). When the atmospheric Cl^- concentration exceeds approximately 0.24 ppm and deicing agents are applied, bridge washing and/or high attention to maintenance is recommended for consideration. This atmospheric Cl^- concentration is the 81st percentile value. With washing, a maximum atmospheric Cl^- threshold of 1.29 ppm was calculated. Cl^- concentrations exceed this value at only one weather station (in New Jersey) in the UWS database. Locations where 0.24 ppm are exceeded can be viewed in maps provided by the National Atmospheric Deposition Program (NADP 2019).

Note that while speed limit has been suggested as a variable that may be influential to the performance of UWS highway overpasses (because higher travel speeds may increase the amount of deicing agents that accumulate on highway overpasses), it was not part of the present scope of work to include speed limit data.

Coastal Bridge Model

Table 47 shows the specific values of each variable in the coastal bridge PPE that result in achieving the performance threshold of an SCR_P of at least 6.00 at an age of 50 yr when the other quantitative variables are at various values. Before the specific values that result from these calculations are discussed, the impact of choosing various values for the MSV should be understood.

Table 47 shows that when selecting the 75th percentile values as the MSV, the result is high threshold values (falling between the 68th to 79th percentile values for each variable). In other words, this situation would suggest unacceptable performance of most of the UWS coastal bridges, which is not consistent with real-world observations. Therefore, the median values were selected as the general concept for the MSV instead. Then (as previously done for the highway crossing model) rounded values of these MSV that may be more convenient for practical application were considered. These values were rounded as follows:

- The median value of lateral underclearance was 16.4 ft when rounded to the nearest integer in meters. This value was used.
- The median value of number of days with heavy fog was 27 d. Due to the significant influence of this variable, alternative calculations were performed by rounding this number up and down to the nearest 5 d.
- Distance to the coast was rounded down to the nearest 5 mi, equaling 10 mi.

The researchers also considered the results of the calculations in table 47 relative to the sensitivity results shown in figure 37, which shows that the more severe values of distance to the coast and lateral underclearance result in very little difference in SCR_P. The following are offered as potential conclusions from these calculations:

- The last data rows for lateral clearance and distance to the coast in table 47 show that when neither of the other two quantitative variables is particularly severe, any practical value of lateral clearance and distance to the coast will result in achieving the performance benchmark (as indicated by the negative signs on the values resulting from these calculations). These calculations and the relative insensitivity of SCR_P to extremely small values of these variables are reasons to consider whether a quantitative benchmark for these variables is needed.
- The table 47 data corresponding to median MSV show values of 10 ft for lateral underclearance and 4 mi for distance to the coast as threshold values. If a benchmark on these variables is desired, these values are in the closest general agreement with prior field observations from this study and other research.

- A minimum of 25 d of heavy fog is required to achieve an SCR_P of at least 6.00 in typical coastal conditions, according to the PPE. This value represents the 41st percentile for fog. A high percentage of the bridges that have a lower number of days with heavy fog are located in Virginia and Maryland. Additional consideration of this finding relative to the prior field work conducted in Maryland and Virginia is discussed in chapter 9.

These calculations are performed using the median value for the waterway crossing value, which assumes that the bridge does not cross a waterway. For bridges that do and do not cross waterways, the same performance occurs but with a 3-yr offset according to the coastal bridge PPE. This finding means that the same threshold values could be used for all crossing types, but with the expectation of these performance benchmarks being reached for these combinations of variables at 47 yr for bridges that cross waterways and 50 yr for other bridges, on average. The results in this subsection represent preliminary values for informing a quantitative update to the UWS TA (FHWA 1989). In chapter 9, these results are assessed relative to the field performance that has been discussed in chapter 5 and chapter 6 to form final conclusions of this study. These conclusions are based on the fact the PPE equations represent highly generalized trends, while the field work has focused on more exceptional situations.

Table 47. Calculation of threshold values for influential parameters using alternative MSV—coastal bridge model.

Solving For	MSV	Age (yr)	Lateral Underclearance (ft)	Fog (No. of Days with Heavy Fog)	Distance to Coast (mi)	Interaction Term (mi)	Waterway Crossing (unitless)	SCR_P (unitless)
Lateral clearance	75th percentile	50	36	23	3	77	0	6.00
Lateral clearance	Median rounded down	50	20	25	10	250	0	6.00
Lateral clearance	Median rounded down	50	10	27	13	359	0	6.00
Lateral clearance	Median round fog up, round distance down	50	−1	30	10	300	0	6.00
Fog	75th percentile	50	7	30	3	89	0	6.00
Fog	Median rounded down	50	16	26	10	258	0	6.00
Fog	Median rounded down	50	16	25	13	82	0	6.00
Fog	Median round fog up, round distance down	50	16	26	10	258	0	6.00
Distance to coast	75th percentile	50	7	23	34	765	0	6.00
Distance to coast	Median rounded down	50	16	25	14	345	0	6.00
Distance to coast	Median rounded down	50	16	27	4	106	0	6.00
Distance to coast	Median round fog up, round distance down	50	16	30	−15	−438	0	6.00

CHAPTER 9. ANALYSIS OF RESULTS

METHODOLOGY

The research summarized in this report has culminated in two primary types of available data: statistical models describing UWS performance and field data on the performance of UWS. In chapter 8, the statistical models were applied directly to suggest possible threshold values for various parameters that affect UWS performance. The purpose of chapter 9 is to compare and contrast these values with observed field performance and, consequently, refine the recommended threshold values for updating the UWS TA (FHWA 1989).

Summary of Statistical Model Data

The statistical models are described in chapter 8. These models are based on data extracted from the NBI (based on owners self-identifying UWS bridges, as described in chapter 3), environmental data (described in chapter 3), and data on maintenance and deicing practices (described in chapter 7). These data were used to fit multilinear regression models to two datasets: highway crossings and coastal bridges. The output of this model is an SCR_P value as a function of the performance variables that were found to be most influential. While there are limitations to using SCR (and, therefore, SCR_P) to represent the performance of UWS (e.g., subjectivity, generalized measure of performance that may not be related to corrosion), corrosion effects are by far the most common reason for decreasing SCR. Therefore, the use of SCR allows for a large database of UWS performance data.

Summary of Cluster Bridge Data

To assess the validity of the possible threshold values for various parameters that affect UWS performance that were output from the statistical model (table 45 through table 47), these values were compared to the corresponding values and associated performance of the cluster bridges (chapter 6). To facilitate this analysis, the researchers attempted to classify the field performance of all cluster bridges as either having or not having overall corrosion, with overall corrosion being defined as corrosion away from leaking joints or details known to trap moisture. This classification was generally possible in most cases, but not enough information was available to definitively classify all cluster bridges. These classifications were largely based on the owner inspection reports (with additional context provided by the field work discussed in chapter 5).

Comparison and Discussion of Available Data

The largest advantage of the statistical models is the large number of bridges included in the analyses (1,200–1,400, depending on the specific model being considered). By comparison, just under 200 cluster bridges are within the scope of this study. The largest disadvantage of the statistical model is that the model quantifies performance by a single metric (SCR_P), and this metric imperfectly describes the performance of UWS and is represented by a small range of integers (from 0 to 9), resulting in a course description of performance. Therefore, the fit of the models to the datasets is unavoidably lower than ideal. The classification of the corrosion performance of the cluster bridges offers a more thorough and, therefore, accurate description of UWS performance. Therefore, the advantages and disadvantages of the two primary types of available data can be balanced by one another. By using the cluster bridge classifications along with the statistical model results, confidence in the validity of the resulting recommendations can be gained.

The general agreement between the two data types was assessed by computing the SCR_P value for each cluster bridge using the relevant statistical model(s) (i.e., the highway crossing PPE and/or the coastal PPE). An ideal scenario is that the SCR_P values for the bridges with overall corrosion are, on average, less than those from bridges without overall corrosion. Table 48 shows that this expectation was not realized. Both the deicing and coastal PPE resulted in slightly higher SCR_P for bridges with overall corrosion than those without overall corrosion, when all cluster bridges that were relevant to each model were considered. When the researchers considered only cluster bridges from the coastal clusters and not those from the deicing+coastal clusters, equal SCR_P were obtained for both groups of cluster bridges (when rounding to the nearest tenth). When the SCR_P results were normalized by age, a higher normalized SCR_P for the bridges without overall corrosion was only achieved for the bridges in the coastal-only clusters.

Table 48. SCR_P and SCR_P/age (yr) for cluster bridges.

Model	SCR_P Overall Corrosion = Yes	SCR_P Overall Corrosion = No	SCR_P/Age Overall Corrosion = Yes	SCR_P/Age Overall Corrosion = No
Deicing model average: deicing and coastal+deicing clusters	6.9	6.8	0.30	0.24
Coastal model average: coastal and coastal+deicing clusters	6.9	6.8	0.24	0.24
Coastal model average: coastal-only clusters	6.9	6.9	0.21	0.24

The primary conclusion drawn from these findings is that, while the statistical models predict general trends, they lack the refinement to definitively identify the conditions resulting in overall corrosion. This conclusion is a logical limitation of the statistical models, given that they are fits to thousands of data points, while the bridges experiencing overall corrosion are arguably outliers in this dataset. Therefore, the team concluded that the primary advantage of the statistical models is identifying which parameters may be important for describing UWS performance and which parameters have a negligible effect. However, the researchers decided that recommendations for specific values of the influential parameters associated with inferior performance of UWS should generally be based on field observations rather than the statistical model values. The following two sections review these results for the coastal and highway crossing environments, respectively.

COASTAL RESULTS

This section summarizes the findings related to coastal environments to provide final recommendations and commentary on those findings.

Variables and Values Considered

A total of seven variables were identified as being of potential importance for defining a coastal environment based on prior tasks of this research, as summarized by table 49. Four of these were identified by the coastal bridge statistical model: number of days with heavy fog, lateral underclearance, distance to the coast, and whether the bridge was a waterway crossing. Considering the distinguishing features of the cluster bridges that did and did not experience overall corrosion revealed three additional variables of potential interest: humidity, atmospheric Cl^- concentration, and vegetation. Humidity and atmospheric Cl^- concentration were revealed as correlating with good and inferior performance of UWS at the conclusion of phase 2 of this research, and these same trends continue with the inclusion of the larger phase 3 dataset. Vegetation was revealed to be an additional variable correlating with bridges that did and did not experience overall corrosion during the present phase of work. At the conclusion of phase 2, distance to the coast and crossing type were also indicated as being of potential importance, agreeing with the statistical model results.

Table 49. Variables considered in defining coastal environment.

Variable	Included in PPE	Included in Phase 2 Conclusions	Included in Final Recommendations
Fog	Yes	No	No
Lateral underclearance	Yes	No	No
Distance to coast	Yes	Yes	Yes
Crossing type	Yes	Yes	Yes
Humidity	No	Yes	Yes
Atmospheric Cl^- concentration	No	Yes	Yes
Vegetation	No	No	Yes

As summarized by table 49, the following five variables are recommended for consideration in the final definition of a coastal environment for UWS: distance to the coast, crossing type, humidity, atmospheric Cl^- concentration, and presence of significant vegetation. The rationale for the inclusion of these variables, the exclusion of the remaining variables in table 49, and the specific values of each of the included variables are discussed in the following subsections.

Fog

The coastal bridge PPE revealed a counterintuitive relationship between fog and SCR_P, with more days with heavy fog correlating with high SCR. The team evaluated this trend further by examining the correlation between fog and other parameters considered in the statistical model for the complete dataset as well as subsets of the dataset that had high and low numbers of days with heavy fog. This evaluation revealed that the subset of bridges with a low number of days with heavy fog had a negative correlation between fog and SCR; this finding matches the intuition that more fog corresponds to worse performance.

However, the subset of the data that had a high number of days with heavy fog had a positive correlation with SCR, meaning that more fog resulted in better performance. Furthermore, the sensitivity analysis in chapter 8, as summarized by figure 37, found that the influence of number of days with heavy fog was also greatest for the bridges with the 90th to 99th percentile values for number of days with heavy fog. These two facts suggest that the bridges with a high number of days with heavy fog having better performance than their counterparts is the reason for the counterintuitive relationship between fog and SCR_P in the coastal bridge PPE.

Therefore, the subset of bridges with a high number of days with heavy fog was more carefully evaluated. This evaluation demonstrated that 80 percent of these bridges are located in Maine and New Hampshire, and that these bridges generally have low atmospheric Cl^- concentrations. The following facts were then considered:

- The influence of fog appears to be most significant for bridges in the extreme northeast.
- Coastal bridges in the northeast were found to generally be governed by the deicing agent effects rather than the coastal environment effects.
- The apparent influence of fog may be related to atmospheric Cl^- concentration, which was ultimately directly included in the coastal environment definition.

Therefore, fog was excluded from being a variable used to define a coastal environment for UWS bridges.

Lateral Clearance

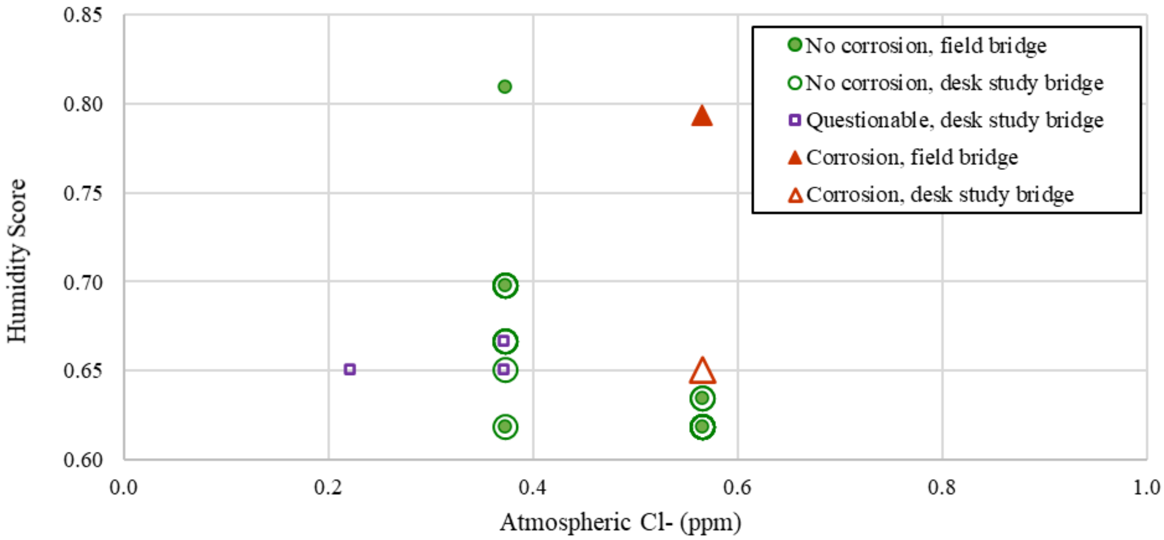
The coastal bridge PPE was used to suggest a possible threshold value of lateral underclearance of 10 ft in chapter 8, with greater clearances resulting in better performance. This recommendation was evaluated relative to the observed field performance, which revealed:

- The two coastal bridges with overall corrosion had lateral underclearances of 100 ft, the largest value recorded per NBI procedures.
- Many bridges had lateral underclearances less than 10 ft, and these bridges did not have overall corrosion.

Therefore, because of the lack of a correlation between field performance and later underclearance, lateral underclearance was excluded from being a variable used to define a coastal environment for UWS bridges.

Humidity and Atmospheric Cl^- Concentration

From the evaluation of two coastal clusters in phase 2, the researchers observed that the two bridges with inferior performance were in an environment that contained both high humidity and high atmospheric Cl^- concentration, whereas none of the bridges with good performance was located in these environments. These findings are summarized by figure 38 and are supported by the phase 3 cluster results as well as a review of additional bridges in the UWS database. Therefore, the prior preliminary threshold values of a humidity score of at least 0.65 and an atmospheric Cl⁻ concentration of at least 0.565 are recommended for partially defining a coastal environment for UWS bridges. In the UWS bridges that exhibit inferior performance, these factors are present in combination with a small distance to the coast while also serving as a waterway crossing.



Source: FHWA.

Figure 38. Graph. Relationship between humidity, atmospheric Cl⁻ concentration, and UWS performance.

Distance to the Coast

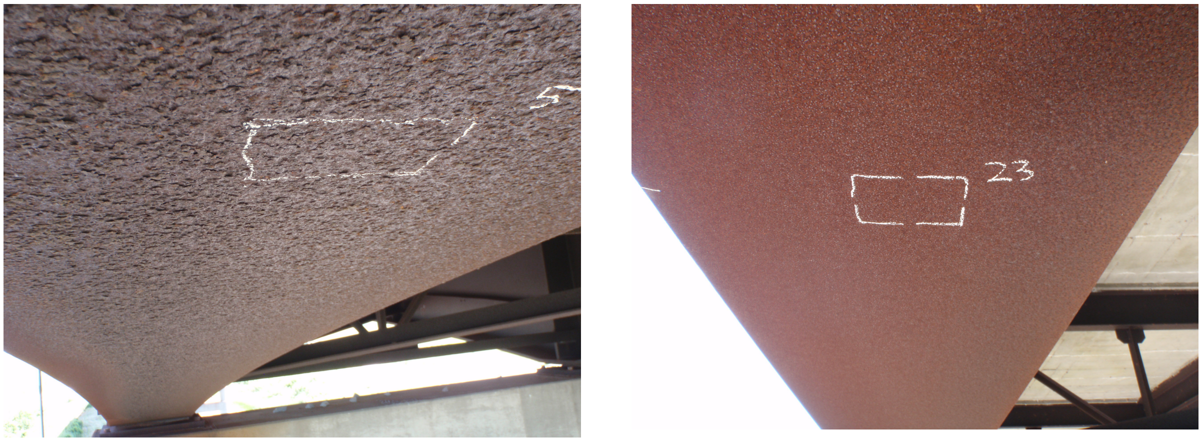
Three different distance-to-the-coast thresholds for defining a coastal environment for UWS bridges were considered. These thresholds, organized from least to most restrictive, and their rationale are described as follows.

1. No distance from the coast is excluded from the recommended use of UWS. This option is the most lax of those considered. The rationale behind this suggestion is that the coastal UWS bridges with inferior performance did not display widespread problematic levels of corrosion. Figure 39 shows the range of the visual appearance of the bottom surface of the bottom flange of the sole coastal field bridge with inferior performance to illustrate this point. If this concept were implemented, detailing and maintenance recommendations should be emphasized.

2. A coastal environment for UWS is defined by a variable distance to the coast, depending on whether significant vegetation is in close proximity to the structure. Specifically, a distance to the coast of 0.1 mi was found to correlate to field performance (when combined with the critical values of other parameters), and no significant vegetation was in close proximity to the structure. Whereas a distance to the coast of 1 mi was found to

correlate to field performance (when combined with the critical values of other parameters), and significant vegetation was in close proximity to the structure.

3. A coastal environment for UWS is defined by distance to the coast of 1 mi when combined with the critical values of other influential environmental parameters (i.e., the humidity, atmospheric Cl^- concentration, and crossing type discussed in the preceding and following subsections). This definition represents a simplification of the option described in option 2 of this list by eliminating the need to distinguish between sites with different vegetation characteristics and the subjectivity associated with such determinations.



Source: FHWA.

A. Worst performance.

Source: FHWA.

B. Best performance.

Figure 39. Photos. Condition of bottom flange of sole UWS coastal field bridge with inferior performance—worst and best performance.

Of these three options, a preliminary recommendation is made for option 2 and option 3 in the preceding list. Both of these options are deemed to be reasonably conservative. Option 3 offers greater simplicity in terms of describing the environment and in terms of its implementation by avoiding the need to classify the level of vegetation at the site, which is inherently subjective and would be based on limited field data at this time.

Crossing Type

In the coastal bridge PPE, whether the bridge was a waterway crossing was found to be a statistically significant variable, with worse performance indicated for bridges that served as waterway crossings. In the desk study, both of the coastal bridges with inferior performance were waterway crossings. Therefore, waterway crossings are used as a criterial for defining a coastal environment for UWS bridges.

Vegetation

As mentioned in the subsection Distance to the Coast, differences in UWS performance for coastal bridges were observed to be correlated with the presence or absence of significant vegetation sheltering the superstructure. This point was most apparent for a group of four bridges within 6 mi of one another, three of which were within 1 mi of one another. These four bridges had no significant differences in their environments based on the numerous site features quantified or otherwise described in the UWS database. Therefore, Google Street View was used to further assess the sites, which revealed the images shown in figure 40. These photos revealed that the most striking difference in the sites of these bridges, which correlated with UWS performance, was the site vegetation characteristics of the four bridges. The two bridges shown in figure 40-A and figure 40-C do not contain overall corrosion and no significant vegetation, whereas the opposite is true for the two bridges in figure 40-B and figure 40-D. Therefore, the influence of site vegetation is recommended for consideration in defining a coastal environment for UWS bridges. This consideration can be done either directly (i.e., option 2 in the Distance to the Coast subsection) or indirectly (i.e., option in the Distance to the Coast subsection).

© 2022 Google®. © 2022 Google®.

A. Without overall corrosion. B. With overall corrosion.

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C. Without overall corrosion. D. With overall corrosion.

Figure 40. Photos. Comparison of site conditions for bridges without and with overall corrosion.

Final Recommendations

Combining the recommendations for each variable that were outlined in the preceding section results in two options for defining a coastal environment for UWS bridges, as described by table 50 and table 51. These two options are based on option 2 and option 3 of the distance-to-the-coast recommendations, with option 2 accounting for the effects of vegetation and option 3 being a simpler definition. A critical feature of these options is that all the listed criteria for a given environment must be met for the environment to demonstrate accelerated corrosion (i.e., high humidity, high atmospheric Cl^- concentration, and low distance to the coast must be simultaneously present while the bridge also serves as a waterway crossing).

Table 50. Recommended definition of coastal environment for UWS bridges—vegetation option.

Parameter	Inferior Environment 1	Inferior Environment 2
Distance to coast (mi) *and*	≤0.1 *and*	≤1 *and*
Vegetation (category) *and*	NA *and*	Yes *and*
Humidity score (unitless) *and*	≥0.65 *and*	≥0.65 *and*
Atmospheric Cl^- (ppm) *and*	≥0.565 *and*	≥0.565 *and*
Crossing type	Waterway	Waterway

Table 51. Recommended definition of coastal environment for UWS bridges–simplified option.

Parameter	Inferior Environment
Distance to coast (mi) *and*	≤1 *and*
Humidity score (unitless) *and*	≥0.65 *and*
Atmospheric Cl^- (ppm) *and*	≥0.565 *and*
Crossing type	Waterway

Commentary on Final Recommendations

This section contains subsections discussing the final recommendations for coastal environments in relationship to field performance and the current UWS inventory.

Relationship to Field Performance

The recommended definitions of a coastal environment for UWS bridges match the observed field performance well, as follows:

- Two coastal cluster bridges have inferior performance; both of them are described by the recommended definitions.
- Forty coastal cluster bridges have good performance; none of them are described by these categories.
- Five coastal and deicing cluster bridges have inferior performance that are not classified by the deicing highway crossing criteria discussed in the Heavy Deicing Use Results section; four of them are described by these categories.
- Thirty-one coastal and deicing cluster bridges have good performance; none of them are described by these categories.

Therefore, in summary, the recommended definitions are applicable to 78 cluster bridges and match the observed performance of 77 (99 percent) of them. Given the highly variable variations in sites and owner practices, this definition is deemed an excellent fit to observed performance.

Relationship to Current UWS Inventory

This section contains subsections describing the extent of the UWS inventory that is represented by the recommended definition of a coastal UWS bridge and the performance of the bridges in the current inventory that meet this definition.

Scope

The current UWS bridge inventory was compared to the two quantifiable environments recommended in the Final Recommendations subsection: inferior environment 1 in table 50 and the sole inferior environment in table 51. This comparison demonstrated that less than 0.1 percent and 0.1 percent of the current population of UWS bridges are described by these two environments, respectively (table 52). These findings speak to both the severe nature of these environments and that owners have often avoided using UWS in coastal environments based on the prior caution on this topic. Therefore, implementation of the proposed recommendations could increase the use of UWS in the many coastal locations that do not meet the stringent requirements proposed herein.

Table 52. Comparison of current UWS inventory to recommended definition of coastal environment for UWS bridges.

Metric	Vegetation Option: Inferior Environment 1	Simplified Option: Inferior Environment	All Other
Current inventory (percent)	<0.1	0.1	99.9
Average SCR/age (yr)	0.30	0.27	0.45

Performance

Table 52 also compares the performance of the bridges in the current UWS inventory that meet the recommended definition of a coastal environment to the remainder of the bridges used in the coastal bridge dataset in chapter 8. This dataset is small, with only 8 and 12 bridges falling into each of the two proposed inferior environments. However, when SCR is normalized by age, the bridges in the two proposed inferior environments have lower SCR/age values than the other bridges in this dataset. This finding serves to support that the proposed environments are reasonable.

HEAVY DEICING USE RESULTS

This section summarizes the findings related to highway overpasses in heavy deicing environments to provide final recommendations and commentary on those findings.

Variables and Values Considered

A total of seven variables were identified as being of potential importance for defining a heavy deicing use environment based on prior tasks of this research, as summarized by table 53. In general, the results of the statistical model and conclusions from the phase 2 review of field performance were well aligned with one another. Four of the variables were common to the results of both approaches: crossing type, vertical underclearance, ADT under the structure, and atmospheric Cl^{-} concentration. The statistical model also revealed the importance of bridge-washing and maintenance practices. On the other hand, considering the distinguishing features of the cluster bridges that did and did not experience overall corrosion suggested the importance of snowfall, as quantified here by average annual snowfall.

Table 53. Variables considered in defining heavy deicing use environment.

Variable	Included in PPE	Included in Phase 2 Conclusions	Included in Final Recommendations
Crossing type	Yes (by definition)	Yes	Yes (by definition)
Vertical underclearance	Yes	Yes	Yes
ADT under the structure	Yes	Yes	Yes
Atmospheric Cl^{-} concentration	Yes	Yes	Yes
Snowfall (average annual)	No	Yes	Yes
Bridge washing	Yes	No	Indirectly
Maintenance practices	Yes	No	Indirectly

As summarized by table 53, all of these variables are recommended for consideration in the final definition of a heavy deicing agent use environment for UWS, but with varying approaches. Four variables have specific quantities recommended, as detailed in the following subsections: vertical underclearance, ADT under the structure, crossing type, and atmospheric Cl^{-} concentration. The definition is also limited to crossing types that include highway crossings. Lastly, bridge washing and maintenance practices are clearly important in the performance of UWS bridges; however, insufficient information exists to quantify this effect at the present time. Therefore, best practices on these owner practices are recommended to be implemented for all UWS bridges, but these are not directly used in defining a heavy deicing use environment. Additional rationale for the inclusion of these variables and the specific values of each of the included variables are discussed in the following subsections.

Crossing Type

All known cases of overall corrosion of UWS bridges in environments where deicing agents are used are a result of road spray from vehicles passing under bridges serving as highway overpasses. While deicing agents applied on a bridge can also cause accelerated corrosion, these issues can be mitigated by proper detailing, drainage system design, and joint maintenance. When bridges are designed properly, detailed, and maintained, deicing agents applied to the driving surface of a bridge are not a concern for UWS. Therefore, the definition of heavy deicing use environment is limited to bridges that serve (fully or in part) as highway overpasses.

Vertical Underclearance

Both the statistical model and review of field performance of the cluster bridges suggested that vertical underclearance is an important variable affecting UWS performance in highway overpasses over roadways treated with deicing agents. These findings are logical, considering that road spray from traffic beneath the bridge can reach the superstructure with greater probability and volume with reduced vertical underclearance.

A vertical underclearance less than or equal to 18 ft is recommended as one criterion for defining a heavy deicing use environment. This value correlates well with observed performance of the cluster bridges. Specifically, 50 out of the 60 highway crossings with inferior performance, based on the field and desk studies, have a vertical underclearance in this range (typically in combination with high values of the other influential parameters discussed in this subsection). Thirty-eight of these bridges have a vertical clearance between 16 and 18 ft. Lower vertical clearance limits suggested by the statistical model (i.e., 10 ft for agencies with washing practices and typical maintenance practices and 15 ft for agencies without washing practices) were found to be too lax compared to field performance.

ADT Under the Structure

Both the statistical model and review of field performance of the cluster bridges suggested that ADT under the structure is an important variable affecting UWS performance in highway overpasses over roadways treated with deicing agents. These findings are logical because roadways with higher ADT generally are exposed to greater amounts of deicing agents.

From the statistical model results, an ADT under the structure of 100,000 was suggested as a value where inferior performance of UWS may occur (when combined with other severe site characteristics). This value was found to correlate with observed field performance in some cases; most bridges with this value of ADT under the structure do experience inferior performance of UWS. Therefore, this value is recommended as one criterion for defining a heavy deicing environment. A snowfall of at least 18 inches/yr is observed as occurring simultaneously with this volume of ADT under the structure when inferior performance of UWS is observed, i.e., traffic alone does not cause accelerated corrosion: deicing use must also be present.

The review of the cluster bridges indicates there are also several cases of inferior performing UWS in deicing environments with lower ADT values. The precise values of ADT under the structure that are correlated with inferior performance vary based on other site conditions, namely, average annual snowfall and atmospheric Cl^- concentration. When the atmospheric Cl^-

concentration is elevated (as defined in the next subsection to be greater than or equal to 0.1 ppm) and snowfall is moderate (as defined in the Snowfall subsection to be 22 inches/yr, on average), an ADT under the structure of 4,000 is recommended as a criterion for defining a heavy deicing use environment. When the atmospheric Cl^- concentration is low (less than 0.1 ppm) and snowfall is moderate (as defined to be 22 inches/yr on average), an ADT under the structure of 10,000 is recommended as a criterion for defining a heavy deicing use environment.

Atmospheric Cl^- Concentration

Both the statistical model and review of field performance of the cluster bridges suggested that atmospheric Cl^- concentration is an important variable affecting UWS performance in highway overpasses over roadways treated with deicing agents. These findings are logical because Cl^- are known to accelerate corrosion. However, in most situations, the effect of Cl^- in deicing agents dominates the corrosion compared to the effect of atmospheric Cl^-. This conclusion is based on the considerably worse performance of bridges in heavy deicing environments compared to those in coastal environments and that chloride concentration only appears to be an influential variable in the lowest ADT situations.

An atmospheric Cl^- concentration greater than or equal to 0.1 ppm is considered elevated and recommended as a criterion for defining a heavy deicing use environment. This value correlates well with observed performance of the cluster bridges. Higher atmospheric Cl^- concentrations suggested by the statistical model (i.e., 0.24 ppm for agencies without washing practices and 1.29 ppm for agencies with washing practices) were found to be too lax compared to field performance.

Snowfall

Snowfall was found to be an important factor, combined with variables discussed in the preceding subsections, in distinguishing the performance of UWS in the cluster bridges. This finding is logical because without snow or the freeze–thaw conditions associated with snowfall, deicing agents are not applied. Snowfall was also suggested as being moderately important in the development of the statistical model but was not included in the final version of the PPE given in chapter 8. For these reasons, the researchers recommend including snowfall as a criterion in the definition of a heavy deicing environment for UWS bridges.

An average annual snowfall of 22 inches (when combined with the other severe values discussed in the previous subsections) was observed to be a distinguishing feature between bridges with and without overall corrosion, in most cases. For very high ADT under the structure of 100,000 or more, a lower average annual snowfall of 18 inches (when combined with the other severe values discussed in the previous subsections) was observed to be a distinguishing feature between bridges with and without overall corrosion. These two snowfall values are, therefore, recommended as criteria for defining a heavy deicing use environment.

Bridge Washing and Maintenance Practices

The statistical model revealed the importance of bridge washing and maintenance practices, with bridge washing being second only to age of the structure as the parameter most strongly correlated to SCR. Therefore, the research team recommends emphasizing the benefit of bridge washing and maintenance when providing guidance on the use of UWS.

Final Recommendations

Combining the recommendations for each variable that were outlined in the previous subsections results in three combinations of criteria for defining a heavy deicing use environment for UWS bridges, as described by table 54. All of the listed criteria for a given environment must be met in order for the environment to demonstrate accelerated corrosion. Inferior environment 1 describes a high ADT environment. When this level of ADT is present under the bridge, a wider range of vertical underclearances and snowfall values is associated with inferior performance (compared to the other two inferior environments defined in table 54); atmospheric Cl^- concentration is not demonstrated to be a factor in these situations. Inferior environment 2 represents a moderately high combination of ADT and snowfall. Specifically, inferior environment 2 represents a 90th percentile combination of the most severe values of vertical underclearance, ADT under the structure, and average annual snowfall. Inferior environment 3 describes an environment with both elevated exposure to deicing agents and atmospheric Cl^-.

Table 54. Recommended definitions of heavy deicing use environment for UWS bridges.

Label	Inferior Environment 1	Inferior Environment 2	Inferior Environment 3
Crossing type	Highway	Highway	Highway
Vertical Underclearance (ft)	Any	≤18	≤18
ADT under (count)	≥100,000	≥10,000	≥4,000
Average annual snowfall (inches)	≥18	≥22	≥22
Atmospheric Cl^- (ppm)	NA	NA	≥0.1

Commentary on Final Recommendations

Relationship to Field Performance

The recommended definitions of a heaving deicing use environment for UWS bridges match the observed field performance well. Given the more widespread geographic areas and associated ranges of performance, matching the criteria for defining a heavy deicing environment to field performance was more challenging (compared to the coastal environment). In general, the recommended definitions are applicable to 92 cluster bridges (that were defined as being in either a deicing cluster or coastal and deicing cluster). Seven of these were box girders, all of which had good performance that was partially attributed to the lack of an exterior bottom flange surface where water and Cl^- could collect. Therefore, the researchers suggest that the proposed definitions should be applied to I-girder bridges only (with caution given that keeping the interior of boxes dry is essential). With this limitation:

- Sixty deicing or deicing and coastal cluster I-girder bridges have inferior performance; 49 (82 percent) of them are described by the recommended definitions.
- Twenty-five deicing or deicing and coastal cluster I-girder bridges have good performance; 21 (84 percent) of them are not described by these categories.

Therefore, in summary, the recommended definitions are applicable to 85 cluster bridges and match the observed performance of 70 (82 percent) of them. Given the highly variable variations in sites and owner practices, these definitions are deemed to be a good fit to observed performance based on the information available for these structures.

Relationship to Current UWS Inventory

This section contains subsections describing the extent of the UWS inventory that is represented by the recommended definition of a heavy deicing environment for UWS bridges and the performance of the bridges in the current inventory that meet this definition.

Scope

The current UWS bridge inventory was compared to the three heavy deicing use environments defined in table 55. This comparison demonstrated that 2, 10, and 5 percent of the current population of UWS bridges are described by these three environments (table 55). Some bridges fall into multiple categories, resulting in the total percentage of the current population of UWS bridges being described by any of these categories being 11 percent. While this number may seem somewhat high, it is aligned with intuition based on extensive reviews of field performance of UWS bridges throughout the United States that has occurred throughout this research effort. Accelerated corrosion of bridges over heavily salted roadways is not uncommon and has been observed at a rate consistent with these percentages.

Table 55. Comparison of current UWS inventory to recommended definition of heavy deicing use environment for UWS bridges.

Metric	Inferior Environment 1	Inferior Environment 2	Inferior Environment 3	All Inferior	All Other
Current inventory (percent)	2	10	5	11	89
Average SCR/age (yr)	0.27	0.32	0.34	0.31	0.36

Performance

In table 55, the performance of the bridges in the current UWS inventory that meet the recommended definition of a heavy deicing environment is also compared to the remainder of the bridges used in the highway crossing dataset in chapter 8. This comparison shows that when SCR is normalized by age, the bridges in the three proposed inferior environments have slightly lower SCR/age values than the other bridges in this dataset. This finding serves to partially support that the proposed environments are reasonable.

RECOMMENDATIONS ON OTHER ENVIRONMENTS

Based on the owner information identifying the environments where inferior overall performance of UWS was observed (as described in chapter 2), the focus of this research was coastal bridges and highway overpasses over roadways in environments where deicing agents are used. Again, the reader is reminded the inferior overall performance describes performance that cannot be directly attributed to poor detailing or joint maintenance practices. The previous sections of this chapter have discussed recommendations on these environments. Three other environments are mentioned in the current UWS TA where recommendations are also offered based on the knowledge gained on UWS performance during the course of this research (FHWA 1989). These are high TOW environments, bridges with low clearance over water, and bridges in industrial environments. Specifics of these recommendations are given in the following subsections.

High Time of Wetness

The current UWS TA cautions against the use of UWS in areas with high rainfall, high humidity, and persistent fog (FHWA 1989). The rationale of this guidance is that these situations increase moisture and, therefore, corrosion rates. A more quantitative recommendation on this topic appears elsewhere in the UWS TA, which states "if the yearly average TOW exceeds 60 percent, caution should be used in the use of bare weathering steel." The 60-percent TOW threshold is generally agreed upon by subject matter experts as a condition for caution or additional evaluation. Therefore, the researchers recommend removing the general caution regarding rainfall, humidity, and fog to focus on the more quantitative metric of TOW.

Some UWS bridges have performed well in these high TOW environments, and some have not. In the United States, these high TOW environments are limited to coastal regions in the Pacific Northwest. Those bridges that have not performed well are in a high TOW macroenvironment, as well as a microenvironment that causes local increases in humidity. Specifically, the bridges that have not performed well are waterway crossings (at least sometimes with limited vertical clearance), are in areas of dense vegetation, and are located in areas of high TOW. Thus, the combined severity of the TOW, vertical clearance, and vegetation could be recommended as a consideration.

Low Water Clearance

The UWS TA currently recommends that weathering steel bridges should be used cautiously when 10 ft or less of vertical clearance is present over stagnant, sheltered water, or when 8 ft or less is present over moving water (FHWA 1989). Decades of applying these recommendations suggest that these limits are at least adequate, and possibly conservative, for providing good-performing UWS. The alternative criteria for moving and stagnant water in the FHWA guidelines can also be thought of in terms of the size of the body of water. Coastal plains, wetlands, and other bodies of stagnant water are also generally relatively large bodies of water. Providing larger vertical clearance in these situations is logical, due to the greater likelihood for a larger body of water to cause a change in humidity than a smaller body of water. Conversely, small bodies of water (either based on metrics such as their flow rate, absolute width, or width relative to the size of the structure) likely have little impact on the TOW. In environments with low potential for flooding and lacking in excessive humidity, UWS bridges with as little as 6 ft of vertical clearance above water have demonstrated satisfactory performance (CHA 2021). Therefore, reduction or removal of the low water clearance recommendation for moving water (at a minimum) is recommended.

A recommended additional (or alternative) consideration is not only the vertical clearance in the typical flow state but the propensity for flooding at the bridge site. Repeated or long-term flooding causes excessively wet environments. However, more significantly, flood events also frequently lead to trapped debris—and, therefore, moisture—on the superstructure. The moisture trapped in this debris can cause a long-term, continuously wet environment that greatly accelerates corrosion. Therefore, guidelines that consider the frequency of flooding that may occur at different elevations and that factor this consideration into site design and/or maintenance planning (i.e., clean-up efforts after flood events) may be beneficial.

Industrial Areas

The current UWS TA cautions against the use of UWS in industrial environments (FHWA 1989). This concern is viewed as outdated due to the adoption of clean air standards. The current maximum sulfur dioxide emissions limit by the U.S. Environmental Protection Agency is 0.003 oz/in^3 (Environmental Protection Agency 2022). In contrast, a SO_4^{-2} concentration greater than or equal to 0.004 oz/ in^3 has been previously used as a criterion for defining sulfur dioxide levels that may cause performance issues with UWS. For these reasons, and because UWS bridge owners in the United States have not reported any problems with UWS bridges that are attributed to proximity to industrial sites, the researchers argue that previous considerations of "industrial environments" are not presently relevant to the United States.

CHAPTER 10. CONCLUSIONS

SUMMARY OF KEY FINDINGS

Based on the information received from owners (chapter 2), the research team identified two primary situations of concern for the overall performance of UWS: coastal environments and highway overpasses over roadways with large amounts of deicing agent use. Therefore, these two environments were the focus of this research. Overall performance was defined as performance away from known problematic details (meaning those that trap moisture) and leaking joints. Owners also reported numerous instances of leaking joints causing corrosion, and these issues are best mitigated through improved joint designs and maintenance. In particular, the adoption of jointless bridges is recommended wherever feasible.

The data reviewed in chapter 2 indicate that the performance of the national inventory of UWS bridges is generally good. This conclusion is based on owners' perceptions (figure 2), an analysis of SCR (table 1), a temporal analysis of SCR of UWS bridges (figure 3), and comparison of the temporal distributions of SCR for UWS and OS bridges (figure 3).

However, the field work completed in this study focused on UWS bridges in extreme environments, and inferior performance of UWS was observed in some of these situations. While good performance was generally observed in coastal environments, several instances of inferior performance were observed for highway overpasses over roadways heavily treated with deicing agents. This finding is most clearly illustrated by figure 15, which shows several bridges falling into a "very high" corrosivity category with estimated section loss amounts exceeding that recommended for capitalizing on the lifecycle cost savings of UWS. Specific deicing agent amounts were not available, but these bridges generally exist in areas with high combinations of ADT and snowfall. Conversations with local personnel suggest that the roadways beneath the worst performing of these bridges are subjected to near daily applications of brines for nearly half of the year.

The environments most often corresponding to these observations of inferior performance were quantified and are reported in table 50 and table 51 for coastal environments and in table 54 for highway overpasses. The quantitative recommendations for coastal environments that were discussed in chapter 9 (table 50 and table 51) are not particularly stringent and are expected to result in the use of UWS in environments where its use is currently avoided. For coastal environments, the threshold where inferior performance was observed was less than 1 mi from the coastline, in combination with high humidity for the geographic area, high atmospheric Cl^- concentration for the geographic area, and localized increases in humidity due to the bridge being a waterway crossing. This distance to the coastline is consistent with recent research specific to Florida (Granata et al. 2017). Vegetation was also observed as being influential, likely due to its effect of increasing local humidity and inhibiting drying actions.

Conversely, the quantitative recommendations for highway overpasses over roadways treated with large amounts of deicing agents identify three sets of circumstances where UWS is presently used and where caution is recommended in the future (table 54). These three sets of circumstances relate to different combinations of ADT under the bridge and snowfall, which together serve as a proxy for deicing agent application rates and atmospheric Cl^- concentrations. These three variables together represent the combined Cl^- exposure at a bridge site. The vertical underclearance was also revealed to be important as this affects the Cl^- exposure based on proximity to the underpassing roadway treated with deicing agents.

The researchers determined these quantified environments for coastal bridges and highway overpasses based on a thorough evaluation of the national UWS inventory, which was used to select representative bridges for field and desk studies based on a statistically driven process. Therefore, these recommendations are both more comprehensive and, through the use of quantified metrics, less subjective to apply than previous recommendations for defining environments of concern for UWS.

The environments described by table 54 are severe environments for UWS—and likely for other materials as well. Therefore, in these situations, an alternative material is not guaranteed to provide improved performance. For this reason, a sacrificial thickness (or corrosion allowance) for the horizontal surfaces of UWS on which water may collect is recommended as a prudent choice. The section loss measured on the bottom flanges of I-girders of bridges in these environments of caution suggests that adding 1/8 inch to these plate thicknesses would provide sufficient structural capacity over the intended lifespan of a typical UWS structure. This conclusion is based on reviewing the data in figure 15, where a maximum thickness loss of 0.07 inch was estimated for the group of field bridges considered herein (with ages up to 46 yr at the time of the field work; there is not a strong relationship between age and thickness loss in these limited data).

In addition to these key conclusions related to the primary goal of providing a quantitative update to the UWS TA, other key contributions of this study include (FHWA 1989):

- Developing the UWS database (chapter 3). This database can be found as a “special project” in the data section of the LTBPP InfoBridge portal (FHWA 2022b). In addition to its necessity for completing the present work in a statistically driven and comprehensive manner, this database may be useful for future data analysis or for serving as a template for future data collection efforts.

- Implementing a statistically driven method for selecting bridges for further evaluation (chapter 4), which was found to result in provision of a comprehensive evaluation of the situations of greatest interest relative to the time and financial resources available.

- Developing, implementing, and refining field work protocols for UWS inspection (chapter 5). These protocols involve a wide range of data types, from quite simple methods requiring no sophisticated training to highly sophisticated methods requiring expensive laboratory equipment. All or some of these can be used in future research as appropriate for the scope.

- Compiling and synthesizing data on owners’ maintenance, washing, and deicing agent practices (chapter 7). As a result, bridge washing was found to be a highly influential variable affecting UWS performance for highway overpasses (chapter 8). In this study, the available information was whether a bridge existed in an agency that performs bridge washing. Whether a specific bridge was washed was not information generally available or possible to include within the available scope of work. Because the statistical analysis (chapter 8) indicated that bridge washing was second only to bridge age in influencing the SCR of UWS highway overpasses, this outcome suggests that bridge washing is effective, and that owners are adept at selecting the bridges most in need of washing when selective washing is applied within an agency.

- Piloting a large-scale statistical analysis of the UWS database (chapter 8). This effort revealed that user intervention and high familiarity with the data is needed in the default statistical analysis approaches for meaningful results to be obtained.

- Establishing that the most significant variable affecting UWS performance is age. While this result is somewhat intuitive, this study has quantitatively validated this knowledge. Specifically, the PPE for highway crossings shown in figure 29 reports a standardized coefficient for age that is 1.5 times the absolute value of the next highest variable (performs bridge washing) and at least six times the absolute value of all other variables. The relative differences in these coefficients are directly related to their relative influence on SCR_P. Similarly, in the PPE for coastal bridges shown in figure 34, the standardized coefficient for age is at least three times the absolute value of the other variables in this equation.

RECOMMENDATIONS FOR FUTURE WORK

Recommendations for future work are organized into four topics:

- Research on appropriate environments for alternative materials.
- Inspection methods for UWS.
- Owner site-specific data.
- Data analysis methods.

Suggestions on these topics are given in the following paragraphs.

This project and others with similar goals have resulted in a large body of work that informs ideal environments for UWS. No other common structural material has been as extensively evaluated in this regard. This evaluation results in a situation in which environments of caution for UWS are known, but the performance of alternative materials—all of which also deteriorate over time—in these environments is unknown. Therefore, research on other structural materials in the environments of caution for UWS is highly recommended. This research would allow the ideal material in severely corrosive environments to be determined and improve the lifecycle cost of the NBI.

As described in chapter 6, the AASHTO documentation process for the inspection of UWS has evolved throughout the course of this research to include three slightly different criteria. All three of these procedures contain the concept of condition states, where the transition from condition state 1 (the best) to condition state 2 indicates a potential concern for the corrosion rate of UWS. Therefore, accurate categorization of condition state 1 versus condition state 2 is highly valuable as a bridge management metric and a research tool to capitalize on the effort involved in recording these data. However, while the description of condition state 2 has improved over time, the definitions relevant to UWS remain qualitative and subjective (i.e., "freckled rust," "corrosion … has initiated," and "granular texture"). In reviewing the inspection reports from 13 different agencies, rational variability in the interpretation of these descriptors is apparent. Therefore, less subjective—and perhaps quantitative—descriptors for the categorization of UWS condition states are recommended.

Beyond the typical owner inspection processes and the scope of work for the inspection processes used in this research (reported in chapter 5), the team collected field data for two additional data types. These data were collected because the opportunity existed to do so without adding undue effort. One of these two data types was a dry film thickness measurement at multiple locations on each of the phase 3 field bridges. While this measurement is typically used to assess the thickness of painted coatings, the electromagnetic principles used by this gauge could have applicability to UWS corrosion mechanisms. If so, this measurement would be a highly efficient means for future inspections conducted by either owners or researchers. While these data have been collected, it was beyond the scope of the present work to analyze or draw conclusions from it. Because the data exist and their interpretation would not require excessive effort relative to their potential value, future effort on this topic is recommended.

The second of these two inspection data types was standardized photos that contained a color standard, consisting of a magnetic bar wrapped with different colors of tape (as can be seen in figure 6 and figure 7). The purpose of this bar was to provide a means for standardizing the color in different lighting conditions in potential future image recognition analysis. This use could have value in providing the quantitative guidance needed for the UWS inspection process that has been described in the Summary of Key Findings section.

In this study, owner data on deicing agent use, general maintenance practices, and bridge washing were aggregated per agency. Despite the coarseness of these data, the statistical analysis (chapter 8) showed an influence of bridge-washing and typical maintenance practices. Given the importance of these two variables that was indicated by the statistical analysis (where their importance was second only to age as a predictor for SCR_P), more site-specific data on washing and maintenance would be valuable information for further understanding of minimizing the lifecycle cost of the NBI. Such information is recommended for inclusion in any future bridge clusters or similar research efforts.

However, in the same statistical analysis (chapter 8), the deicing agent data were not shown to be influential. Yet ADT under the structure was a statistically significant variable. Field performance was also found to correlate with snowfall amounts. Therefore, the researchers concluded that ADT under the structure and snowfall are the primary variables affecting site-specific amounts of deicing agent use. Furthermore, these site-specific variables represent the effect of deicing agents better than the agency-wide averages presently available. Because of potential variability of owners' practices, even for the same traffic volumes and snowfall amounts, more site-specific data on deicing agent use would be valuable information for potentially refining the recommendations made herein. Therefore, this information is also recommended for inclusion in any future bridge clusters or similar research efforts.

An additional type of owner data that may be of interest to further evaluate in future work is the speed limit on the underfeatures of highway overpasses. Higher travel speeds may increase the amount of deicing agents that accumulate on highway overpasses. This variable was not included in the present study.

Lastly, the primarily statistical analysis method used for forming conclusions in this study was based on a multilinear regression model (chapter 8). Since the initiation of this project, significant advancements have been made in machine-learning methods and in their use. Artificial neural networks could be readily applied to the current dataset to perhaps provide greater understanding of the significant volume of numerical and visual data that have been collected.

APPENDIX A. DATA COLLECTION PROTOCOLS

This appendix describes both the process used for collecting UWS field data in this study and the recommended protocols to be used in future UWS data collection efforts. In most situations, the actual and recommended future protocols are the same. The most significant difference is that these protocols were developed based on revisions to a preexisting draft protocol for evaluation of coated steel structures. Therefore, some mention of processes for coated steel data collection is made as recommendations for future protocols; these processes are specific to coated steel and were not used in the field data collection effects described in this report. When other differences between the protocols used in this study and those proposed for future data collection occur, these situations are denoted by footnotes.

DATA COLLECTED

These data include the description and location of corrosion on a steel superstructure.

ONSITE EQUIPMENT

The following is a list of the onsite equipment needed to execute this protocol:

- Ladder, access platform, snooper, bucket truck, man lift, and/or high-reach equipment (if necessary).
- Tape measure.
- Folding ruler (6 ft).
- Carpenter's square.
- Stainless steel chisel, preferably with wide blade.
- Stainless steel wire brush or hand broom.
- Stainless steel scoopula.
- Digital scale with tolerance of at least 0.004 oz.
- Sounding hammer.
- Firm rubber "J" roller, 3-inch width minimum.
- Lever pit gauge.
- Dry film thickness gauge.
- Ultrasonic measuring device and associated coupling agent.

- Electrically powered disk grinder.
- Laser measuring device (for convenience, optional).
- Temporary marker.
- Permanent marker.
- White chalk/soap stone.
- Tape sample chalk marking template (4 inches by 6 inches; for convenience, optional).
- Clear, plastic packing tape with a minimum width of 1.89 inches and minimum adhesive strength to steel of 55 oz/inch width, according to ASTM D3330 (ASTM 2004).
- Letter-size white paper.
- Data entry sheets (physical or digital).
- Pencil, sketch pad, and clipboard.
- Clear, plastic sealable bags.
- Color standard (further described in the following Methodology section).
- Digital camera.
- Lighting for work performed at night or other low-light conditions (e.g., lamps with magnetic bases, headlamps, lighting towers as needed).
- Equipment for transporting and organizing the supplies (e.g., toolboxes, trays, and/or belts; folders; laptops; tablets).

METHODOLOGY

General

Use the segmentation and numbering system for the superstructure (FLD-OP-SC-002, Structure Segmentation and Element Identification System) so defects and sampling locations can be located and noted by the unique element identifier (Hooks and Weidner 2016).

Use FLD-OP-SC-003, Determination of Local Origins for Elements, to establish a local origin on each element to be sampled or used to locate defects.

Visual Documentation of Structure

Overall photos are to be taken, with every site visit, that depict broad views of the bridge and specific areas of defects using FLD-DC-PH-002, Photographing for Documentation Purposes, to create a photo log (Hooks and Weidner 2016). A hand sketch should be provided with each picture at the first inspection depicting the observer's location and viewing angle relative to the bridge and kept consistent for all subsequent inspections. The mandatory photos include:

- Wide view of bridge viewing fascia girders/beams, capturing girder segments *1A* through *NA* and girder segments *1n* through *Nn* (i.e., both entering and exiting fascias). This photo should be taken from a distance of approximately 100 ft back from the bridge, but within the limits of site traffic control, or on the shoulder of the road if necessary. An example is shown in figure 41.

Source: FHWA.

Figure 41. Photo. Example of wide view of bridge.

- Girders at all bearing locations (bearing lines *AA* and *AB* minimum, and all *Px* locations). An example is shown in figure 42.

Source: FHWA.

Figure 42. Photo. Example of view of bearing location.

- A wide view of interior girders for each span (girder *B* through *n-1*). An example is shown in figure 43.

Source: FHWA.

Figure 43. Photo. Example of wide view of bridge interior.

- One closeup photo of each splice plate on fascia girders (if applicable). An example is shown in figure 44.

Source: FHWA.

Figure 44. Photo. Example of view of girder splice plate.

- One closeup photo of a lateral bracing-to-girder connection (if applicable). An example is shown in figure 45. This photo should focus on bolted connections, such as between cross-frame members and transverse stiffeners serving as lateral bracing connection plates, in areas where any pack rust is developing, if applicable.

Source: FHWA.

Figure 45. Photo. Example of closeup view of lateral bracing to girder connection.

- At least one photo depicting the general environmental exposure of the structure (e.g., over water) should be included if not captured in the wide view of the fascia girder. An example is shown in figure 46.

Source: FHWA.

Figure 46. Photo. Overall view of general bridge environment.

Sample Collection Locations

For UWS, four types of samples (photos, dry film thickness measurements, tape tests, and rust samples) should be collected before cleaning. Each of these samples should be collected at 12 locations per bridge. These locations include two different cross sections of the bridge. If the bridge is a highway crossing, one of these locations should be over the shoulder of the roadway, and the other should be over a travel lane of the roadway. If the bridge crosses a multilane highway, the location over a travel lane should be over the right travel lane. If the bridge is a water crossing, one of these locations should be over the visually estimated center of the waterway, and the other should be over vegetation (if possible) or soil, if no vegetation exists at the site; otherwise, it should be near the abutment. Within each bridge cross section, one exterior girder and one interior girder should be sampled. If the bridge is a highway crossing, these girders should be on the side of the bridge facing oncoming traffic in the lanes over which the sampled cross section is located. On each of these (two) girders at each (of the two) longitudinal positions sampled, samples should be taken in three locations (for a total of 12 specimens per bridge). The three locations to be sampled on each girder cross section are the top surface of the bottom flange on both sides of the web, and the side of the web facing traffic (if applicable) at approximately one-third of the height of the web above the bottom flange.

Photos of Sample Locations

Before photos are taken photos of specimen locations, a photo identifying the bridge should be taken. This photo can be a sign on or near the bridge that identifies the bridge, or a photo of a sheet of paper on which the bridge location and/or number is written. For UWS, take a minimum of two photos per specimen location: an overview photo and a closeup photo. All photos should be taken with a white balance setting appropriate to the lighting conditions.

Figure 47 and figure 48 show examples of the specimen overview photo. A primary purpose of the overview photo is to provide a label for the closeup photo, which is framed such that the specimen label is not visible. Consequently, the overview photo should always be the first photo taken at each specimen location. This photo should be taken with the camera parallel to the surface of the specimen location and include the specimen label.

Source: FHWA.

Figure 47. Photo. Example of flange specimen overview photo.

Source: FHWA.

Figure 48. Photo. Example of web specimen overview photo.

It is also advantageous to take a perspective photo (figure 49 and figure 50) that is framed such that information on the specimen location can be determined (e.g., flange or web, proximity to connecting elements) when unique information can be conveyed by this photo and it is convenient to do so.

Source: FHWA.

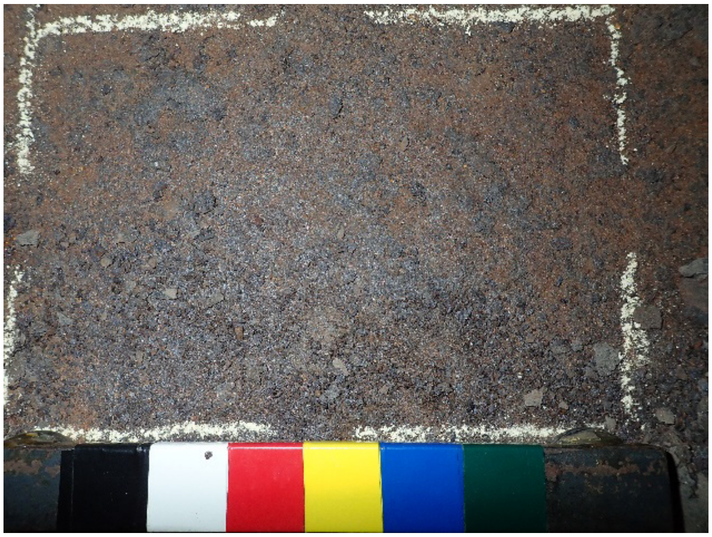
Figure 49. Photo. Example of flange perspective photo.

Source: FHWA.

Figure 50. Photo. Example of web specimen perspective photo.

The primary purpose of the closeup photo is to assess corrosion and color conditions of the specimen. These photos should be taken to facilitate convenient postprocessing using image recognition software, which dictates that all photos be taken as consistently as possible, with the image framed adhering to the following criteria:

- All photos should include a standard color reference, an example of which is a magnet wrapped with black, white, red, yellow, blue, and green tape, as shown in figure 51 and figure 52. In the specific instance of this color standard, the standard should be placed so that the black standard is at the bottom left of the frame.
- All photos should be taken with the camera held parallel to the photographed surface, such that there is no perspective in the photos (i.e., parallel lines should appear as parallel lines).
- All photos of flange locations should be framed in landscape orientation (figure 51).
- All photos of web locations should be framed in portrait orientation (figure 52).
- All photos should be taken with a zoom level such that the color standard and specimen area fill the vertical space of the frame (figure 51 and figure 52).



Source: FHWA.

Figure 51. Photo. Example of specimen closeup of flange specimen.

Source: FHWA.

Figure 52. Photo. Example of specimen closeup of web specimen.

Dry Film Thickness Measurements[1]

Collect measurements using a commercial dry film thickness gauge. Each sample area should be sampled at nine points in a three-by-three grid covering the full sampled area. Report the average and standard deviation of the nine readings as the dry film thickness measurement for the sample area.

Tape Samples

Collect tape samples using the following procedure:

- Mark a 4-inch by 6-inch rectangular area with white chalk and a number for reference. The longer dimension of the rectangle should be oriented vertically for web locations and longitudinally for flange locations. Sample locations on the bridge are numbered sequentially starting with 1 and ending with the maximum number of samples taken from the bridge. Record the center of the sample *x*,*y*,*z* location in field notes per FLD-OP-SC-002 (Hooks and Weidner 2016).

- Measure the vertical distance of the sample area from the roadway, ground, or water, and the horizontal distance from the nearest joint, pier, or abutment.

- Take two photos (FLD-DC-PH-002, Photographing for Documentation Purposes) of the sample area: one showing the complete sampled area, and one a closer perspective where the entire 4-inch by 6-inch area fills the entire field of view.

- Cut a piece of clear tape approximately 4 to 5 inches long. Place it on the surface of the steel. Roll over the tape using a firm rubber "J" roller, making 10 passes with firm pressure (e.g., approximately 2 lb of normal force through the roller).

- Remove the tape slowly with a shallow angle between the tape and the surface, taking approximately 5 s to remove.

- Adhere the tape to a clean sheet of white paper. Note the element, location, and sample reference number on the sheet, above or next to the sample. Multiple samples can be placed on a single sheet.

- Use the image processing methods given in appendix B to determine the overall percentage of rust particles and size distribution of rust particles.

Rust Sample Collection

For UWS, collect rust samples for later laboratory analysis. In the field, collect approximately 0.18 oz of rust by scraping the surface with a stainless steel chisel and letting it fall into a clear, plastic bag. If not enough rust can be collected from within the marked area, collect it from the

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[1] Dry film thickness measurements for the evaluation of UWS were piloted in this study. At the present time, there is insufficient understanding of the relationship between the dry film thickness measurements and UWS performance to recommend collecting these data in future studies.

surrounding area. Mark the bag with the bridge, element, location, and sample reference number. Seal the bag. After the completion of field work:

- Perform IC to determine soluble concentrations of Cl^-, SO_4^{-2}, and NO_3^- at each sample location identified in the preceding Sample Collection Locations section in accordance with the sample preparation and chemical analysis stated in appendix C.

- Perform XRD to determine the relative percentages of goethite, lepidocrocite, akaganeite, iron oxides, and other compounds present in the corrosion byproducts removed from the girder sampling locations identified in the preceding Sample Collection Locations section in accordance with the procedures given in appendix D. If resources do not allow processing all 12 of these samples, processing a minimum of 4 samples is recommended, with the sample locations being selected to represent the expected extremes in performance.

Pitting Depth Measurement

For both coated and uncoated steel, record the depth and note the spatial extent of any pitting using a lever pit gauge.

Ultrasonic Thickness Measurements

For UWS, determine the thickness of the steel. The thickness should be measured at a minimum of two locations: one representing a typical situation and one representing a girder location judged to be in the most corroded location. Note the location of all measurements. The procedure for determining the thickness using a UT gauge is as follows:

- Grind the oxide off a 0.75-inch-diameter area on one side of the plate until the bare metal is exposed only on the highest points of the corroded surface, leaving any depressions filled with oxide. Approximately one-third of the ground surface should have a metallic appearance.

- Apply coupling agent to the surface of the steel.

- Move the probe of a UT gauge around the ground area and retain the smallest reading.

- Record this reading as a reasonable estimate of the plate thickness.

STORING DATA, DOCUMENTS, AND IMAGES

The following protocols describe the procedures for storing data, images, and any other documents collected using this protocol (Hooks and Weidner 2016):

- FLD-DS-LS-001, Data, Document, and Image Storage—Local, for local storage.
- FLD-DS-RS-001, Data, Document, and Image Storage—Remote, for remote storage.

REPORTING

Transfer all metadata, data, documents, and images to FHWA, and/or upload all metadata, data, documents, and images into the LTBPP bridge portal (FHWA 2022b).

DATA COLLECTION TABLE

The data to be collected in the field evaluation of UWS structures are described in the following tables. Table 57 and table 58 elaborate on table 56 by describing the data types and color codes used, which are consistent with existing LTBPP protocols.

Table 56. Data collection table for UWS field data.

No.	Field Name	Data Type	Accuracy	Field Description	Row Color
1	NBI structure number	Text	Not applicable	Item 8, structure number; from NBI coding guide (FHWA 1995)	Green
2	Structure name	Text	Not applicable	Descriptive name for the bridge, e.g., Route 15 southbound over I–66	Green
3	State	Text	Not applicable	State code, e.g., Virginia = VA	Green
4	Protocol name	Text	Not applicable	Title of the protocol	Green
5	Data type	Text	Not applicable	e.g., raw or other	Green
6	First name of lead inspector	Text	Not applicable	First name of lead inspector	Green
7	Last name of lead inspector	Text	Not applicable	Last name of lead inspector	Green
8	Company affiliation of lead inspector	Text	Not applicable	Company affiliation of lead inspector	Green
9	Test date	Text	Not applicable	MM/DD/YYYY	Green
10	Test site	Text	Not applicable	Areas of bridge sampled, e.g., fascia girder and adjacent interior girder	Green
11	Test execution	Text	Not applicable	e.g., manual, robotic	Green
12	*x*-Location unit	Text	Not applicable	Units used for reporting value in item 42	Green
13	*y*-Location unit	Text	Not applicable	Units used for reporting value in item 43	Green
14	*z*-Location unit	Text	Not applicable	Units used for reporting value in item 44	Green
15	Vertical distance unit	Text	Not applicable	Units used for reporting value in item 45	Green

No.	Field Name	Data Type	Accuracy	Field Description	Row Color
16	Horizontal distance unit	Text	Not applicable	Units used for reporting value in item 46	Green
17	Reference point	Text	Not applicable	Origin of bridge as determined using FLD-OP-SC-002 reported using compass directions (e.g., SW corner of bridge) (Hooks and Weidner 2016)	Green
18	Rust percentage unit	Text	Not applicable	Units used for reporting value in item 47	Green
19	Area 0.03125 unit	Text	Not applicable	Units used for reporting value in item 48	Green
20	Area 0.0625 unit	Text	Not applicable	Units used for reporting value in item 49	Green
21	Area 0.125 unit	Text	Not applicable	Units used for reporting value in item 50	Green
22	Area 0.25 unit	Text	Not applicable	Units used for reporting value in item 51	Green
23	Area 0.5 unit	Text	Not applicable	Units used for reporting value in item 52	Green
24	Area 1 unit	Text	Not applicable	Units used for reporting value in item 53	Green
25	Area 2 unit	Text	Not applicable	Units used for reporting value item 54	Green
26	Area 4 unit	Text	Not applicable	Units used for reporting value in item 55	Green
27	Cl^- unit	Text	Not applicable	Units used for reporting value in item 56	Green
28	NO_3^- unit	Text	Not applicable	Units used for reporting value in item 57	Green
29	SO_4^{-2} unit	Text	Not applicable	Units used for reporting value in item 58	Green
30	DryFilmAvg unit	Text	Not applicable	Units used for reporting value in item 59	Green
31	DryFilmStndDev unit	Text	Not applicable	Units used for reporting value in item 60	Green
32	TypUT unit	Text	Not applicable	Units used for reporting value in item 61	Green
33	CorrosiveUT unit	Text	Not applicable	Units used for reporting value in item 62	Green

No.	Field Name	Data Type	Accuracy	Field Description	Row Color
34	Percent goethite unit	Text	Not applicable	Units used for reporting value in item 63	Green
35	Percent akaganeite unit	Text	Not applicable	Units used for reporting value in item 64	Green
36	Percent lepidocrocite unit	Text	Not applicable	Units used for reporting value in item 65	Green
37	Percent iron oxide unit	Text	Not applicable	Units used for reporting value in item 66	Green
38	Percent other unit	Text	Not applicable	Units used for reporting value in item 67	Green
39	Test notes	Text	Not applicable	Enter any noteworthy visual observations or unusual circumstances	Green
40	Element ID	Text	Not applicable	Element label per FLD-OP-SC-002 (e.g., girder, 1A) (Hooks and Weidner 2016)	Blue
41	Location	Text	Not applicable	Qualitative location of sampled area on the element, e.g., web of girder 1A	Blue
42	x-Location	Number	Not applicable	x-coordinate of the center of the sampled area	Yellow
43	y-Location	Number	Not applicable	y-coordinate of the center of the sampled area	Yellow
44	z-Location	Number	Not applicable	z-coordinate of the center of the sampled area	Yellow
45	Vertical distance	Number	Not applicable	Vertical distance between sampled area and roadway, ground, or water	Yellow
46	Horizontal distance	Number	Not applicable	Horizontal distance between sampled area and the nearest joint, pier, or abutment	Yellow
47	Rust percentage	Number	0.01 percent	Tape test result (see appendix B)	Yellow
48	Area with rust particles $\geq$ 0.03125 inches	Number	0.1 percent	Tape test result (see appendix B)	Yellow
49	Area with rust particles > 0.0625 inches	Number	0.1 percent	Tape test result (see appendix B)	Yellow
50	Area with rust particles > 0.125 inches	Number	0.1 percent	Tape test result (see appendix B)	Yellow

No.	Field Name	Data Type	Accuracy	Field Description	Row Color
51	Area with rust particles > 0.25 inches	Number	0.1 percent	Tape test result (see appendix B)	Yellow
52	Area with rust particles > 0.5 inches	Number	0.1 percent	Tape test result (see appendix B)	Yellow
53	Area with rust particles > 1 inches	Number	0.1 percent	Tape test result (see appendix B)	Yellow
54	Area with rust particles > 2 inches	Number	0.1 percent	Tape test result (see appendix B)	Yellow
55	Area with rust particles > 4 inches	Number	0.1 percent	Tape test result (see appendix B)	Yellow
56	Cl^-	Number	1 ppm	IC test result (see appendix C)	Yellow
57	NO_3^-	Number	1 ppm	IC test result (see appendix C)	Yellow
58	SO_4^{-2}	Number	1 ppm	IC test result (see appendix C)	Yellow
59	DryFilmAvg	Number	0.00001 inch	Dry film test result	Yellow
60	DryFilmStndDev	Number	0.00001 inch	Dry film test result	Yellow
61	TypUT	Number	0.001 inch	UT test result	Yellow
62	CorrosiveUT	Number	0.001 inch	UT test result	Yellow
63	Percent goethite	Number	1 percent	XRD result (see appendix D)	Yellow
64	Percent akaganeite	Number	1 percent	XRD result (see appendix D)	Yellow
65	Percent lepidocrocite	Number	1 percent	XRD result (see appendix D)	Yellow
66	Percent iron oxide	Number	1 percent	XRD result (see appendix D)	Yellow
67	Percent other	Number	1 percent	XRD result (see appendix D)	Yellow

StndDev = standard deviation; Typ = typical.

Table 57. Description of data types listed in table 56.

Column Heading	Column Description
No.	Sequential number of data item
Field name	Data field name
Data type	Type of data, such as text, number, binary large object, or PDF file
Accuracy	Accuracy to which the data are recorded
Unit	Unit in which a measurement is taken and recorded
Field description	Commentary on the data

Table 58. Description of color codes listed in table 56.

Color	Color Description
Green	Data items only entered once for each protocol for each day the protocol is applied
Pink	Logical breakdown of data by elements or defect types (not always used)
Blue	Data identifying the element being evaluated or the type of defect being identified
Yellow	LTBPP data reported individually for each element or defect identified
Orange	Comments on the data collection or data entered (not always used)

CRITERIA FOR DATA VALIDATION

Compare measurements with measurements from previous inspections of the same structure to make sure values make sense. Compare measurements with photo documentation to make sure results shown in photos are consistent with items measured.

If an element's condition is improved compared to the condition documented in a previous inspection, check with the State's department of transportation to determine if any maintenance, repair, and/or bridge preservation actions have occurred. If so, document these maintenance, repair, and/or bridge preservation actions using the appropriate protocols.

COMMENTARY/BACKGROUND

This protocol provides guidance on identifying corroded areas on steel superstructure elements and documenting their extent and location on the element. Guidance is also provided for measuring the extent and depth of any pitting of the steel that is present.

Steel superstructures, such as trusses (deck, through, and pony), multigirder beams, girder/floor beam/stringer systems, box girders, etc., that are not built of weathering steel and are not protected by galvanizing or metalizing are usually protected by one or more coats of paint to guard against oxidation (rusting) of the steel.

The most common types of defects in bridge coatings include chalking, cracking, loss of adhesion, and peeling. Data collection involves identifying areas where coating defects are evident and documenting the location and size of the affected areas.

The main cause of steel corrosion in coated bridges is the lack and/or breakdown of the protective coating. Once this occurs, the exposure to corrosive agents (water, salts, and chemicals) begins a disintegration process on the surface metal. Corrosion grows from a few, small starting points and then expands as steel molecules that are directly in contact with the corroded area also corrode; eventually, small, medium, and large contiguous areas of corrosion become evident. Data collection involves identifying areas where corrosion is evident and documenting the location and size of the affected areas.

Steel superstructures built of unpainted weathering steel are not normally provided any extra protective coating (although it has become a common practice to paint weathering steel near joints and bearings). Protocols specific to unpainted weathering steel are included in appendix A so that the performance of this specific type of steel can be tracked over time.

Pictures of corroded and noncorroded areas should be taken in order to document the coating condition. The intent of this documentation is to show the extent of the coating breakdown in such a manner that that breakdown can be tracked over the course of several years of inspection. The primary concern with coating breakdown is the subsequent corrosion (deterioration) of underlying structural steel. The metal section loss that eventually occurs at defects in coatings is what causes concern for the structural integrity of the bridge.

REFERENCES

Long-Term Bridge Performance Program Protocols

This protocol should be used in conjunction with the following LTBP protocols (Hooks and Weidner 2016):

- PRE-PL-LO-004, Personal Health and Safety Plan.
- PRE-PL-LO-005, Personnel Qualifications.
- FLD-OP-SC-002, Structure Segmentation and Element Identification System.
- FLD-OP-SC-003, Determination of Local Origins for Elements.
- FLD-DC-VIS-003, Steel Superstructure—Section Loss.
- FLD-DC-PH-002, Photographing for Documentation Purposes.
- FLD-DS-LS-001, Data, Document, and Image Storage—Local.
- FLD-DS-RS-001, Data, Document, and Image Storage—Remote.

External

Other references that may be relevant to consult include:

ASTM D3330, *Standard Test Method for Peel Adhesion of Pressure-Sensitive Tape* (ASTM 2004).

FHWA-NHI-12-049, *Bridge Inspector's Reference Manual* (Ryan et al. 2012).

APPENDIX B. PROTOCOL FOR IMAGE ANALYSIS OF TAPE TEST

This appendix describes the process used for image analysis of the field samples collected in this study. The research team recommends that this procedure be directly implemented in future protocols on this topic.

DATA COLLECTED

These data include rust particle size distribution of unpainted weathering steel tape samples.

EQUIPMENT

The following is a list of the equipment needed to execute this protocol:

- Scanner with minimum resolution of 300 dpi.
- Computer with MATLAB software installed or other means of image processing.

METHODOLOGY

The following steps will result in computing the information needed to report rust particle sizes in the protocol given in appendix A. Once the image is scanned, the MATLAB script provided at the end of this protocol will automate the remaining steps:

- Scan the tape sample on the sheet of white paper using a scan resolution of 300 dpi.

- Convert the grayscale image to a black and white pixel-only image.

- Determine the total number of pixels in the image and the number of black pixels in the image. Calculate the rust percentage as the ratio of the number of black pixels divided by the total number of pixels.

- Determine the conversion factor for area in square inches to area in pixels. Scan a simple object of known area (e.g., penny) using a scan resolution of 300 dpi. Convert this grayscale image to a black and white pixel-only image. Determine the area, in pixels, of the object. Measure the dimensions of the object using a micrometer; calculate the area of the object. Divide the area of the object in square inches by the area in pixels. This conversion need only be done once for any group of tape samples analyzed.

- Identify connected regions of black pixels, which are assumed to be rust particles. Determine the area, in pixels, of each connected region. Calculate the area of the particle in square inches by multiplying the area in pixels by the conversion factor determined in the previous step. Calculate the diameter corresponding to this area, assuming the area is circular. This calculated value is the equivalent diameter of the rust particle.

- Bin the particle diameters according to size, using bins 0 to 1/32 inch, 1/32 to 1/16 inch, 1/16 to 1/8 inch, 1/8 to 1/4 inch, 1/4 to 1/2 inch, 1/2 to 1 inch, and greater than 1 inch. Determine the total area of particles represented by each bin, assuming all particles are circular. Calculate the percentage of area represented by the sum of each particle size as a fraction of the total area.

COMMENTARY/BACKGROUND

This protocol provides guidance on determining the percentage and particle size distribution of rust that adheres to a piece of tape that is firmly applied to the surface of the steel.

MATLAB SCRIPT FOR IMAGE PROCESSING OF TAPE SAMPLES

The digital image processing can be conducted using any image processing software tool. Sample code for this purpose using MATLAB is provided as follows:

```
% *** Notes ****

% Reads all pictures in a given folder and outputs the equivalent diameter of
% each individual particle in inches.

% Computes rust percentage using *optimized* graythresh.
% Computes the equivalent diameter of each particle by converting its
area.
% Will ignore all particles below provided minimum threshold.
% Prints an rgb example image with green bounding boxes around the
% particles the program has captured (uncomment commands if this is to %
    be done)
% Output is saved to excel file called Results.xlsx.
% Excel sheet will contain 1 row per sample. The first column will contain
% the name of the tape file, the second row contains the total rust
% percentage, and the following columns include the rust percentage for
%   those % particular sizes. For instance, the column labeled 0.03125
%   (1/32) represents the percentage of particles with diameters in the
%   range of 0-1/32”. The next would represent 1/32”-1/16”, 1/16”-1/8”
%   and so on.

Clearvars
clc; %clears command window
tic;

% ******* CHOOSE THE LOCATION OF DATA DUMP *******
myFolder = ‘C:\Users\msparaci\Desktop\UWS PROGRAMS\Maryland Tape
Samples\MD 1018400\MD 8400 jpg\MD4800 new crops’;
% ***** SELECT MINIMUM THRESHOLD FOR DIAMETER (inch)(anything lower will
be
% removed)
Min_Thresh = 0;

%Throw error message if aforementioned path incorrect
if ~isdir(myFolder)
```

```
 errorMessage = 179ptimi(‘Error: The following folder does not
exist:\n%s’, myFolder);
 uiwait(warndlg(errorMessage));
 return;
end

%Reads all text files sequentially
filePattern = fullfile(myFolder, ‘*.jpg’);
%Counts total number of text files in the folder
imgFiles = dir(filePattern);

%Throw error message if data folder is incorrect
if isempty(imgFiles)
 errorMessage = 179ptimi(‘No text files in folder\n’);
 uiwait(warndlg(errorMessage));
 return; %Stops further execution of Program
end

for k = 1:length(imgFiles)

 baseFileName = imgFiles(k).name;
 fullFileName = fullfile(myFolder, baseFileName);
%Displays name of file being read
 fprintf(1, ‘Now reading %s\n’, baseFileName);

 im1=imread(baseFileName); % Reading image


 %% Evaluating Rust Density

%Computing threshold for converting original image (tape sample) to binary
% image
 gl=graythresh(im1);

% Converting to binary image with *179ptimized* graythresh value as level
% (Threshold)
 bwg=im2bw(im1,(gl+.25)/2);
% Get dimensions of the binary image. It should be same for both images
 [A1,B1]=size(bwg);

 % Finding the percentage of black (Rust in our case)
 l2=find(bwg==0);
 bldensity2=length(l2)/(A1*B1);

 %% Capturing Individual Particle Areas

 bwg=1-bwg; %inverting the binary image to make the background 0 and the
rust particles 1
 [bwg_labeled,num]=bwlabel(bwg); %labeling each individual rust particle
 example=label2rgb(bwg_labeled); %creating example image in rgb to show
distinction between particles

 %finding the area of each particle (in pixels) using regionprops
 area_vect=regionprops(bwg_labeled, ‘Area’);
```

```
 final_areas=[area_vect(:).Area];
 final_areas=sort(final_areas); %sorting for purposes of output
 area_sum=sum(final_areas(:)); %used later in calculating percentages

 %converting from pixels to inches
 conversion_factor=0.438/40000;
 final_areas=sqrt(4*(conversion_factor*final_areas)/pi);

 %creating a minimum threshold
 idx=1;
 while idx<=length(final_areas)
 if final_areas(idx)<Min_Thresh
  final_areas(idx)=[];
 else
  idx=idx+1;
 end
 end

% Uncomment these commands for bounding boxes
%      %printing green bounding boxes around each particle
% boxes=regionprops(bwg_labeled‘ 'BoundingB’x''.';
% final_boxes=[boxes(:).BoundingBox];
% final_boxes=reshape(final_boxes, [4,num]);
% %removing the boxes below the minimum threshold
% ix=1;
% finl_areas=[area_vect(:).Area];
% finl_areas=conversion_factor*finl_areas;
% while ix<=length(finl_areas)
%  if finl_areas(ix)<Min_Thresh
%  finl_areas(ix)=[];
%  final_boxes(:,ix)=[];
%  else
%  ix=ix+1;
%  end
% end
% hold on
% imshow(example);
% for indx= 1:length(final_boxes)
%  rectangl‘('Positi’n',final_boxes(:,indx’,'EdgeCol’r’,’g');
% end
% hold off

 %% Creating Histogram Table
 %Takes any 1 row vector as an input.
 %Produces two vectors, X and Y.
 %X is a 1 row vector whose values represent a range of diameters,
 % starting from the previous value and ending at the current one. i.e.
 % 0.25 means 0.125-0.25.
 %Y is a 1 row vector that contains the percentage of the total image
 % occupied by all particles in that range of diameters.
 X=0;
 Y=0;
 Am = final_areas;
 Y(1)=0;
```

```
 X_idx=1;
 X(1)=1/32;
 for q=1:length(Am)
 if Am(q)<X(X_idx)
  Y(X_idx)=Y(X_idx)+(pi*(Am(q)^2)/(4*conversion_factor));
 else
  while Am(q)>=X(X_idx)
  X_idx=X_idx+1;
  X(X_idx)=2*X(X_idx-1);
  Y(X_idx)=0;
  end
  Y(X_idx)=(pi*(Am(q)^2)/(4*conversion_factor));
 end
 end
 Y=100*Y/(A1*B1);
 %% Writing output to excel fil- - Area/Frequency of each individual
Particle

 [ext,name] = fileparts(baseFileName);
 name=str2num(name);
 filename=strca`('Resul’s’,'.xl’x'); %Creating excel file

 A =`{'Test Area ’D'` 'Densi’y'` '% of Ar’a'}; %Creates Header Row
 sheet=1;
 xlRangea ` '’1';
 xlswrite(filename,A,sheet,xlRangea);

 B = X;
 xlRangeb ` '’2';
 xlswrite(filename,B,sheet,xlRangeb);

 C = Y;
 cellc=strca`(’C', num2str(name+2));
 xlRangec = cellc;
 xlswrite(filename,C,sheet,xlRangec);

 E = sum(Y);
 cellc=strca`(’B', num2str(name+2));
 xlRangec = cellc;
 xlswrite(filename,E,sheet,xlRangec);

 D = {name};
 celld=strca`(’A', num2str(name+2));
 xlRanged = celld;
 xlswrite(filename,D,sheet,xlRanged);

end %Ends For Loop
%% Statistical Analysis

 xlswrite(filename`{'=average(B3:B5’)'},shee’,'B’0');
 xlswrite(filename`{'=STDEV.P(B3:B5’)'},shee’,'B’1');
 xlswrite(filename`{'=B60/B’1'},shee’,'B’2');
 xlswrite(filename`{'=max(B3:B5’)'},shee’,'B’3');
 xlswrite(filename`{'=min(B3:B5’)'},shee’,'B’4');
```

```
 xlswrite(filename‘{'=median(B3:B5’)'},shee’,'B’5');
 xlswrite(filename‘{'Avera’e'},shee’,'A’0');
 xlswrite(filename‘{'Standard Deviati’n'},shee’,'A’1');
 xlswrite(filename‘{'Coefficient of variati’n'},shee’,'A’2');
 xlswrite(filename‘{'Maxim’m'},shee’,'A’3');
 xlswrite(filename‘{'Minim’m'},shee’,'A’4');
 xlswrite(filename‘{'Medi’n'},shee’,'A’5');

%% Clearing temporary variables

%bar(X,Y);
%clearvars %Clears all variables

toc;
```

APPENDIX C. PROTOCOL FOR ION CHROMATOGRAPHY ANALYSIS OF RUST SAMPLES

This appendix describes the process used for ion chromatography analysis of the field samples collected in this study. The research team recommends that this procedure be directly implemented in future protocols on this topic.

DATA COLLECTED

These data include soluble concentrations of Cl^{-}, NO_3^{-}, and SO_4^{-2} ions in rust samples via IC.

ONSITE EQUIPMENT

The following is a list of the onsite equipment needed to execute this protocol:

- Ion chromatograph calibrated per ASTM D4327 and with a metal trap column, AS20 anion exchange column, AG20 anion guard column, and NaOH eluent (ASTM 2017).
- Centrifuge.
- Scale with at least 3.53E-5 oz graduation.
- Mortar and pestle.
- Number 20 or smaller sieve.
- Glass beaker of 1.69 fl oz or larger.
- Centrifuge tubes of 0.51 fl oz.
- IC vials of 0.17 fl oz.
- Syringe.
- Syringe filter, 7.87E-6 inches or smaller.
- Deionized water.
- Laboratory film.

METHODOLOGY

Prepare rust samples as described for three replicates per sample location:

- Grind the rust sample finely with a mortar and pestle so that all material can fit through a No. 20 (0.033 inch) or smaller sieve.

- Blend samples thoroughly before weighing.

- Weigh the sample to nearest 0.00004 oz and record the weight. Use 0.071 oz or more if enough sample is available. If the sample is less than 0.018 oz, note the actual weight in the comments of the data collection table. Note that samples of 0.071 oz or more require dilution in subsequent steps, and those less than 0.071 oz do not. Thus, the analyst should make temporary notes of sample weights for this purpose.

- Transfer the sample into a beaker and add 0.34 fl oz of deionized water. Cover the beaker with laboratory film and let the sample sit at room temperature for 12 to 24 h.

- Swirl the sample and then transfer it into a 0.51-fl oz centrifuge tube and centrifuge it at 4,000 rpm for 2 min.

- Remove supernatant from the sample tube without transferring solid material. Filter supernatant through a syringe filter (i.e., 7.87E-6-inch nylon membrane) into a clean 0.71-fl oz centrifuge tube.

- Refer to the temporary notes made in the earlier step regarding sample mass. If the mass of the sample is 0.071 oz or more, add 0.17 fl oz of filtered sample to a 1.69-fl oz volumetric flask and dilute to 1.69 fl oz.

- Mix the sample thoroughly by inverting the centrifuge tube or flask.

- If there is 0.51 fl oz of the sample or more, transfer 0.17-fl oz of the sample into each of three 0.17-fl oz IC vials. If there is less than 0.51 fl oz of the sample, equally divide the sample into three 0.17-fl oz IC vials.

- Load the IC sample vials into the autosampler.

Perform IC analysis in accordance with ASTM D5085 and the following equipment and settings to determine and record in the data collection table the Cl^{-}, SO_4^{-2}, and NO_3^{-} concentrations (ASTM 2002):

- Metal trap column to catch metals to protect IC from damage.
- Anion exchange column: AS20.
- Guard column: AG20.
- Eluent gradient: 10 mM NaOH hold for 4 min, ramp from 10 to 45 mM at 8.5 min and hold for 4 min.
- Effluent flow rate: 0.034 fl oz/min.
- Temperature: 30 °C.
- Detection: electrical conductivity cell.

COMMENTARY/BACKGROUND

This protocol provides guidance on determining the soluble concentration of Cl^{-}, NO_3^{-}, and SO_4^{-2} ions in rust samples collected from unpainted weathering steel.

REFERENCES

ASTM D4327–17, *Standard Test Method for Anions in Water by Suppressed Ion Chromatography* (ASTM 2017).

ASTM D5085–02, *Standard Test Method for Determination of Chloride, Nitrate, and Sulfate in Atmospheric Wet Deposition by Chemically Suppressed Ion Chromatography* (ASTM 2002).

APPENDIX D. PROTOCOL FOR X-RAY DIFFRACTION ANALYSIS OF RUST SAMPLES

This appendix describes the recommended process for quantitative XRD analysis of the field samples collected in this study. The process is described in a general format such that the procedure can be applied using alternative equipment and methods. Chapter 5 describes the specific process used in this study and examples of executing the steps of the data analysis.

DATA COLLECTED

These data include percentages of goethite, lepidocrocite, akaganeite, iron oxides, and other compounds present in the corrosion byproducts of UWS via XRD.

ONSITE EQUIPMENT

The following is a list of the onsite equipment needed to execute this protocol:

- Mortar and pestle.
- Number 45 or smaller sieve.
- Two glass slides.
- x-ray diffractometer.

METHODOLOGY

The three main components of the methodology—sample preparation, sample processing, and sample analysis—are discussed in the following subsections.

Sample Preparation

The specific procedures used for sample preparation are:

- Grind approximately 0.035 oz of the rust sample with a mortar and pestle to a fine powder (e.g., with the ability to pass through a No. 45 or smaller sieve) to randomize orientation.

- Place the rust sample on a glass slide and smear uniformly using a second glass slide to achieve a flat upper surface.

Sample Processing

Process the rust sample using a diffractometer with settings that minimize noise in the data. For example, choose a cobalt radiation source to avoid efflorescence, or use a slow scan rate with repeated scans if a copper radiation source is used. Process the scan over a 2 theta range of 5.0 to 75.0 degrees.

Sample Analysis

Background Subtraction

If necessary, perform background subtraction to remove the background intensities. This procedure can be automated using XRD postprocessing software.

Qualitative Analysis

Perform qualitative analysis to identify the compounds of interest that are present in the sample by following these tasks:

- Identify the angles of incidence producing relative intensities greater than 10 percent in each sample. These angles will be referenced as the "peak angles" for brevity. This process can be automated using XRD postprocessing software or performed through other means of analyzing the XRD sample output for local maxima.

- Identify the angles of incidence corresponding to the maximum intensities in the XRD standards for the compounds of interest. These angles will be referenced as the "standard angles" for brevity. For example, table 10 reports the standard angles when a copper radiation source is used based on the ICDD (2022).

- Compare the peak angles and standard angles to identify the intensity levels of each compound of interest that are present in the sample. Here, "intensity level" refers to the highest relative intensity being labeled intensity level 1, the next highest relative intensity being labeled intensity level 2, and so on.

- Interpret the intensity levels present in the sample to conclude whether each compound of interest was present in the sample using the following criteria in the listed sequence:

    1. If two of the first three intensity levels for a given compound were not identified, then conclude that the compound is not present in the sample. Remove this compound from further consideration when executing the following steps.

    2. If only one compound remained that matched a given peak angle, then conclude that the compound is present in the specimen

    3. For any remaining compounds that have not been classified as being present or not present in the sample, the compound is not definitively classified in the qualitative analysis. The quantitative analysis is subsequently used to evaluate the likelihood that these compounds are present in the sample.

- For each peak angle, record the compounds that were classified as being present in the sample (from step 2) and the compounds that may be present in the sample (from step 3). This information will be subsequently used in the quantitative analysis.

Quantitative Analysis

The steps of the quantitative analysis are as follows. Using the list of compounds of interest that contribute to the intensity at each peak angle from the qualitative analysis, determine the relative intensity of each compound that was concluded as being present in the sample using the following criteria:

1. If intensity level 1 of a given compound is the only compound listed as contributing (result from step 2 of the qualitative analysis) or possibly contributing (result from step 3 of the qualitative analysis) to the measured relative intensity at the given peak angle, the measured relative intensity is directly taken as the relative intensity of the associated compound.

2. If intensity level 1 of a given compound occurs at the same peak angle as the peak intensity levels of other compounds, then identify if there is another peak angle of the compound of interest where no other compounds are known to be in the sample or possibly contribute to the sample (no other compounds resulting from step 2 or step 3 of the qualitative analysis). If so, the relative intensity of the associated compound is calculated as the measured intensity divided by the average relative value for the given intensity level (which is tabulated in table 12 for copper radiation sources).

3. If neither of the previous two scenarios occurs, identify a peak angle where the only compounds contributing to the measured intensity are the compound of interest and one or more compounds for which the relative intensity has already been determined, using an angle where as few compounds as possible exist (ideally only two compounds: the compound of interest and one other). Calculate the relative intensity of the compound of interest as the ratio of the measured intensity minus the product of the relative intensities of the compounds that have already been quantified and the relative intensity levels of those compounds at the given peak angle to the relative intensity level of the compound of interest. The relative intensity values for the compounds of interest when using a copper radiation source can be found in table 12 to assist with this calculation. Ideally, this calculation is performed at high-intensity levels because of a general trend of wider scatter in the XRD standards at lower intensity levels.

Because both step 2 and step 3 involve using the averages of XRD standards, and the averages are not necessarily precisely representative of a given situation, it may be advantageous to execute both step 2 and step 3 from the preceding list for a given compound when possible. Then the results of both approaches can be considered. Analysts may use their judgment as to which result is deemed more reasonable or may choose to use a value between the results of the two calculation approaches.

Determine if the compounds not definitively classified in step 3 of the qualitative analysis are present, and determine their relative intensities if so, using the following procedure:

1. Identify the peak angle that is associated with the highest relative intensity for which the compound of interest may be present and for which the relative intensities of all other compounds that may be present at that peak angle have already been determined.

2. Calculate the relative intensity of the compound of interest that results when executing the process described in step 3 of the previous list.

3. Calculate the sum of the products of the relative intensities of each compound and the relative intensity levels of those compounds.

4. Calculate and record the difference between the sum of the products listed in step 3 and the measured relative intensity at the peak angle of interest.

5. Repeat the calculation of the sum of the products listed in step 3, but omit any possible contribution from the compound of interest.

6. Calculate and record the difference between the sum of the products listed in step 5 and the measured relative intensity at the peak angle of interest.

7. Compare the results of step 4 and step 6. If the result of step 4 is less than the result of step 6, conclude that the compound of interest is present in the sample and record its relative intensity as the result of step 3. Conversely, if the result of step 6 is less than the result of step 4, conclude that the compound of interest is not present in the sample and its relative intensity is zero.

The analyst may elect to repeat step 4 and/or step 6 at other peak angles that have not been previously used in the data analysis, and that are associated with the highest relative intensities in the dataset, as a means of data validation. The ideal situation is that peak angles are selected that represent all compounds that have been quantified. The ideal outcome of this process is that the difference between calculated and measured intensities in step 4 or step 6 should not exceed 10 percent. If such a result is not obtained, the analyst should reconsider any assumptions previously made in the analysis to attempt to reduce this error. If the error cannot be reduced below a 10-percent difference in calculated and measured intensities, this fact should be noted as a “high error” in the published data.

Calculate the relative percentage of each compound in the sample as the relative intensity of the compound of interest divided by the sum of the relative intensities of all compounds in the sample.

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