TRC2103

Evaluating Arkansas Weathering Steel Bridge Performance

Yessenia Gonzalez E.I.
Ernie Heymsfield Ph.D., P.E.

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Final Report

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16. Abstract

Weathering steel enhances corrosion-resistant steel features over conventional steel when a patina properly forms on the weathering steel surface. Weathering steel is a low-carbon steel of less than 0.3 percent carbon by weight. The steel material's chemical composition includes other alloying elements such as nickel, copper, and chromium. These components help in developing a dense protective oxide film layer, the patina, on the steel member surface. The patina protects the steel member surface from corrosion by preventing moisture, oxygen, and contaminant penetration. However, long periods of moisture and/or deicing chemicals applied during wet wintry conditions can hinder proper patina formation. Without proper patina formation and appropriate ambient environmental conditions, the weathering steel corrosion rate may increase and be similar to that of plain steel. Weathering steel bridges in Arkansas are normally uncoated. Consequently, the steel surface of these bridges is not protected with paint or primer. In addition, many of these bridges are in geographic regions where ambient conditions may promote steel corrosion. This report presents the approach used by the authors to relate weathering steel bridge corrosion to the overall bridge condition. These results were then used to rank Arkansas Department of Transportation (ARDOT) bridges as a function of their oxide film degradation severity. The authors visited more than 25 ARDOT UWS bridges during the study to examine the bridge characteristics that lead to oxide film degradation. The inspection protocol used by the research team is summarized as inspection guidelines to aid ARDOT bridge inspectors in locating, identifying, and grading oxide film degradation. The potential for incorporating the use of an unmanned aircraft system (UAS) to help with bridge inspections is discussed.

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METRIC CONVERSIONS

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 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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 (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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List of Abbreviations, Acronyms, and Symbols

AASHTO……. American Association of State Highway and Transportation Officials

ARDOT……… Arkansas Department of Transportation

ASTM………. American Society for Testing and Materials

BHI………… Bridge Health Index

CS………….. Condition State

DOT……….. Department of Transportation

FHWA…….. Federal Highway Administration

FPV………… First person view

GPS……….. Global Positioning System

NBIS………. National Bridge Inspection Standards

NCHRP…… National Cooperative Research Program

NSBA…….. National Steel Bridge Alliance

ppm………. Parts per million

TOW………. Time of Wetness

UAS………… Unmanned Aircraft System

UA………….. Unmanned Aircraft

USD………… United States Dollars

UWS………. Uncoated weathering steel

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EXECUTIVE SUMMARY

STUDY PURPOSE AND RESEARCH NEED

Weathering steel bridges in Arkansas are normally uncoated, having no additional paint or primer to prevent corrosion. These bridges are referred to as Uncoated Weathering Steel (UWS) bridges. From the ArDOT UWS database, seventy-one of ArDOT's 859 UWS bridges have 90 percent or more of the exposed girder area experiencing some level of oxide film degradation. The TRC2103 study objectives were to inspect a representative group of UWS bridges to determine commonalities in UWS bridges experiencing oxide film degradation and then rank UWS bridges in most need of remediation.

RECOMMENDATIONS

Clear trends between the bridge site's ambient conditions on the macro level scale and the level of oxide film corrosion are indefinite. However, similarities among the inspected bridges experiencing significant oxide film degradation include deteriorated and/or missing bridge deck compression strip seals, presence of vegetation near or in contact with the steel superstructure, and inadequate girder-water clearance. Deicing applications are not a major contributor to UWS corrosion at these bridges since minimal deicing is used in Arkansas. Remediation at bridges experiencing oxide film degradation should include cleaning poor condition, (Condition State 3, CS 3) and severe condition (Condition State 4, CS 4) areas; clearing vegetation; and in certain cases, applying an extra protective coating such as paint or primer near problematic areas. A weighted factor approach was developed in this TRC2103 study to prioritize 20 ArDOT UWS bridges that are in most need of oxide film rehabilitation.

JUSTIFICATION

The authors inspected 25 uncoated weathering steel (UWS) bridges. Six ArDOT Districts were included in the suite of inspected bridges. Four of these bridges were constructed using seismic design criteria and are in ArDOT District 10. Condition State rating is based on visual appearance and severity of the corrosive steel area. Condition State ratings between the District bridge inspectors were consistent.

CHAPTER 1. INTRODUCTION

The purpose of the TRC2103 study was to determine commonalities in Uncoated Weathering Steel (UWS) bridges experiencing oxide film degradation, rank UWS bridges in most need of remediation, and develop guidelines to assist bridge inspectors when inspecting UWS bridges. In 2016, approximately 10,000 UWS bridges existed in the United States (Hopwood et al. 2016). The primary benefit of using UWS over regular conventional coated steel is the cost savings that UWS provides by negating maintenance costs for initial and periodic painting. The beneficial effects of weathering steel result from common alloying elements like copper, phosphorus, chromium, nickel, and silicon (Albrecht and Naeemi 1984). UWS produces a thick oxide film protective coating called a patina, which forms and adheres to the steel. As the member ages, the steel member takes on a light-brown color. The patina formation is not instantaneous but gradually develops over a three-to-seven-year period (Krivy et al. 2017). In suitable environmental conditions, the protective coating forms and protects the steel bridge superstructure by preventing moisture, oxygen, and contaminants from penetrating the steel surface. The protective coating reduces the steel corrosion rate and, therefore, negates the need for bridge painting. However, if exposed to severe conditions, the patina may not properly form. With the patina not properly forming, the weathering steel will corrode at the same rate as uncoated conventional carbon steel (Crampton et al. 2013).

CHAPTER 2. BACKGROUND

The first patents for high-strength, low-alloy steel products resistant to corrosion were issued to the US Steel Corporation in the 1930s. Corrosion resistance was developed through alloying base steel with different elements, particularly copper (Crampton et al. 2013). Additionally, the steel yield strength increased thanks to the alloys. Weathering steel specifications were developed for ASTM A242, A588, and A709, in 1941, 1968, and 1974, respectively (Albrecht and Naeemi 1984). A242 Type 1 steel has a high phosphorus content, which limits weldability and toughness. Consequently, A242 Type 1 steel was primarily used in architecture, but its use was prevented in bridge construction (Albrecht et al. 1989). A242 Type 2 steel is a low-phosphorus version of A242 Type 1 and is, therefore, appropriate for bridge construction. A242 Type 2 steel includes mild steel alloyed with two percent or less of various elements, including copper, phosphorus, chromium, nickel, and/or silicon. Alloying steel with copper and other selected elements increases steel's corrosion resistance by approximately four times that of structural carbon steel without copper (Crampton et al. 2013). A242 Type 2 is also referred to as ASTM A588 Grade (Gr.) 50W and A709 Gr. 50W (Albrecht et al. 1989). Weathering steel is available in yield strengths of 50 to 100 kips per square inch (ksi).

The first bridge using weathering steel was constructed over the New Jersey Turnpike in 1964. Other states using weathering steel soon followed (McDad 2000). Michigan initiated the use of weathering steel in its bridge projects but soon found that the patina did not properly form on the steel surface. This resulted in Michigan banning all uses of UWS, which caused other states to reevaluate the use of UWS for their bridge construction. Consequently, a task force was formed to inspect weathering steel bridges in other states. These inspections concluded that approximately 30 percent of weathering steel bridges were in good performance condition, 58 percent exhibited moderate corrosion, and 12 percent presented heavy corrosion (Hopwood et al. 2016). In the mid-1990s, there were 2,000 weathering steel bridges in the United States, increasing to approximately 10,000 in 2016 (Hopwood et al. 2016).

Corrosion is an oxidation process between steel and the environment, causing steel bridges to deteriorate (Stephens 2019). It occurs at both the micro-environmental and macro-environmental levels. Micro-environment corresponds to how the localized area and bridge design impact the bridge behavior. This includes collected debris on the girder (poultice), short scuppers, water drainage at bridge joints, and the use of deicing chemicals. Poultice consists of granular or fibrous materials that form on steel structures, becoming water-saturated from rain discharge (Albrecht et al. 1989). Scuppers allow surface water to drain from the top of the bridge. However, short scuppers do not provide adequate girder clearance to prevent water discharge from contacting fascia girders. Conversely, the macro-environment corresponds to local and regional weather conditions such as humidity, precipitation, temperature, pollution, and air chemical composition (Stephens 2019). Bridges that overpass water, and locations with nearby industry, high humidity, low-level crossings, and frequent rainfall experience conditions that promote steel corrosion.

UWS bridge design should prioritize minimizing water flow from the bridge deck to the steel superstructure and preventing water ponding on bridge steel surfaces (NSBA 2022). Any water runoff flow on the bridge should be designed to promote bridge self-cleaning. Girder splice plates should be clipped to encourage water shedding and minimal ponding. Corrosion problems at I-Girder bridges typically occur underneath leaking bridge deck joints. Therefore, a sacrificial 1/16-inch thickness may be considered in severe corrosion conditions. Minimizing bridge deck runoff is attained by limiting the number of bridge deck joints. The National Steel Bridge Alliance (NSBA) recommends eliminating deck joints by designing jointless bridges (NSBA 2022). Conversely, for long, continuous girder bridges, link slabs can be used to eliminate bridge deck joints. When deck joints are required, they should be placed at the backside of the abutment backwall to prevent water drainage from flowing onto the girders. At integral abutments, the encased section of the beam should be treated with a protective primer. In addition, the primer coating should be applied to the exposed beam section beyond the beam-abutment interface to protect against moisture due to sweating. Drip grooves should be used on bridge deck overhangs to prevent water flow from the bridge parapets flowing to the girders. Uncoated weathering steel corrosion due to galvanic effect should be avoided when dissimilar metals are in contact by ensuring material compatibility. For UWS bridges over water, adequate vertical clearance above water should be ensured to allow the bridge girders to experience proper wet-dry cycling. The potential for repeated flooding and long-term flooding at a bridge site should be considered. Prior to bridge erection, mill scale should be removed using blast cleaning to prevent surface irregularities and ensure proper patina development.

Maintaining joints and drainage systems should be a priority at UWS bridges (NSBA 2022). At water crossings where intermittent flooding exists, debris should be removed from the bridge structure after flooding. In many cases, bridge deck runoff flowing to girders is unavoidable. Consequently, DOTs should implement measures that protect UWS bridge superstructure by coating girder ends and pier tops. UWS bridge washing and cleaning are warranted in any bridge maintenance management program to prevent oxide film degradation. The NSBA recommends that bridge decks be washed on a one to two-year interval (NSBA 2022). Conversely, the bridge superstructure and substructure should be washed at two to four-year intervals. Overgrown vegetation in proximity to a UWS bridge should be cut and removed at a one to two-year interval. See AASHTO/FHWA's "A User's Guide to Bridge Cleaning" (2019) for bridge cleaning guidelines.

Steel corrosion affects a bridge's structural integrity and results in increased regular maintenance or, in severe conditions, bridge replacement. Corrosion still occurs at UWS bridges even though the weathering steel patina is designed to protect against corrosion. Therefore, regular UWS bridge inspections during the bridge's service life play an essential role in normal maintenance and remedial rehabilitation (Yan et al. 2014). The National Bridge Inspection Standards (NBIS) categorize oxide film degradation as a function of texture and color. According to the Federal Highway Administration (FHWA) (1989a), there are four condition states (CSs): good (1), fair (2), poor (3), and severe (4). The Manual for Bridge Inspection is used for guidance for allocating these CSs to bridge elements. Some existing methods to minimize deteriorating corrosion at steel bridges include using weathering steel, adding extra protective coatings such as paint or rust inhibitor, galvanizing (the manufacturing process of adding a coating of zinc to the steel), or using stainless steel.

During this research study, the oxide film degradation at Arkansas's weathering steel bridges was evaluated in collaboration with the Arkansas Department of Transportation (ArDOT). Existing ArDOT

UWS bridges were cataloged along with their corresponding CS. This information was used to measure the extensiveness of oxide film degradation experienced by UWS bridges and to correlate bridge conditions with steel characteristics and ambient conditions.

The report is presented in the following order. First, Chapter 3 identifies and classifies ArDOT's UWS bridges and reviews national UWS usage. Chapter 4 presents the UWS cost benefits. Next, Chapter 5 addresses the conditions that influence UWS performance. An overview is provided, followed by sections that address each of the conditions (time of wetness, precipitation, temperature, and vegetation) in detail. Chapter 6 categorizes degradation as a function of the oxide film CSs and includes a ranking of the bridges for oxide film severity. Chapter 7 describes the bridge inspection process and bridge inspections using an unmanned aircraft system (UAS). Chapter 8 introduces a protocol for prioritizing bridges and developing a ranking system for UWS bridges that need remediation. Chapter 9 analyzes and evaluates the UWS bridges inspected during the field study. Chapter 10 describes the bridge inspections conducted at UWS bridges designed based on seismic requirements. Chapter 11 summarizes the field-testing methods available to use for UWS condition evaluation. Afterward, Chapter 12 describes lab testing for UWS behavior in a severely corrosive environment. Chapter 13 provides the proposed guidelines for inspecting UWS bridges. The guidelines are presented as a flowchart. Finally, the study findings are summarized in the Conclusions section.

2.1 OBJECTIVES

This TRC2103 study's objectives are summarized below:

- Identify the UWS bridge structures in Arkansas that are in poor condition and exposed to corrosion based on environmental factors.
- Prioritize UWS ArDOT bridges for remediation.
- Relate UWS corrosion to bridge characteristics and ambient conditions.
- Summarize the protocol employed by the researchers to inspect UWS bridges in flowchart form.

CHAPTER 3. UWS BRIDGE INVENTORY

The UWS bridge inventory used in the TRC2103 study was generated from the ARDOT UWS database. The UWS database included the bridge's latitude, longitude, construction year, location, District, and oxide film degradation percentage as a function of condition state (CS). To investigate the primary factors that lead to poor bridge performance, the research team categorized the bridges by the year they were built and the percentage of the bridge superstructure experiencing oxide film degradation. The categorized bridges were then plotted using Google Earth and ArcGIS as a function of the construction year and girder area percentage experiencing oxide film degradation.

3.1 NATIONWIDE UWS USAGE

An email survey was designed and sent to all 50 states' Department of Transportation (DOT). Each state was requested to respond within two weeks. The survey comprised seven short questions. After two weeks, 26 responses were collected. The DOTs' responses to the seven questions are summarized in the following figures and tables.

Survey Questions and Responses:

1. Are you currently or will you be designing any uncoated weathering steel bridges (UWS) in upcoming projects? (26 responses)

    a. Yes

    b. No

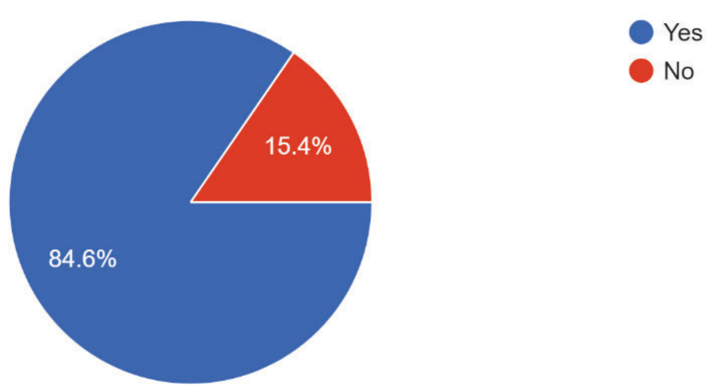


Figure 1. Question 1 Results

2. What criteria do you follow to determine if you will use weathering steel or not? (26 responses)

    a. Structural

    b. Aesthetic

    c. Environmental

    d. Economic (Maintenance)

    e. Other

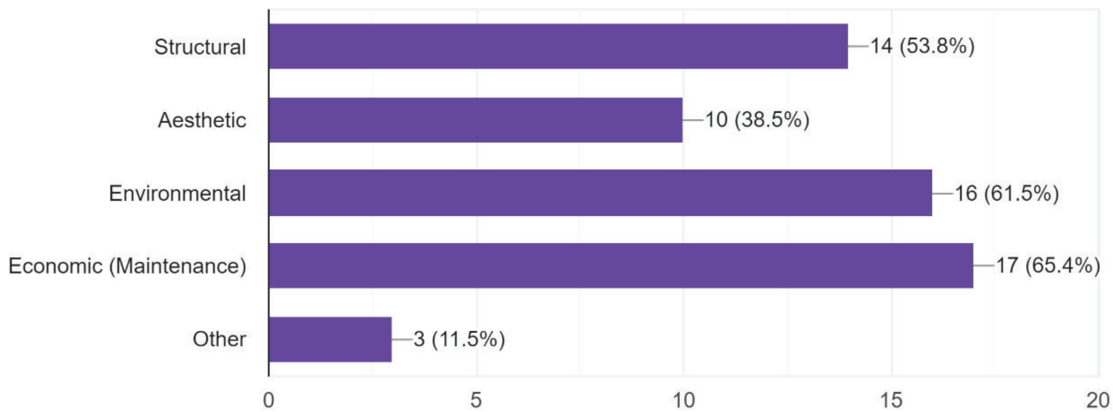


Figure 2. Question 2 Results

3. Approximately, how many UWS bridges exist in your state? (24 responses)

    a. <100

    b. 100-200

    c. 200-300

    d. >300

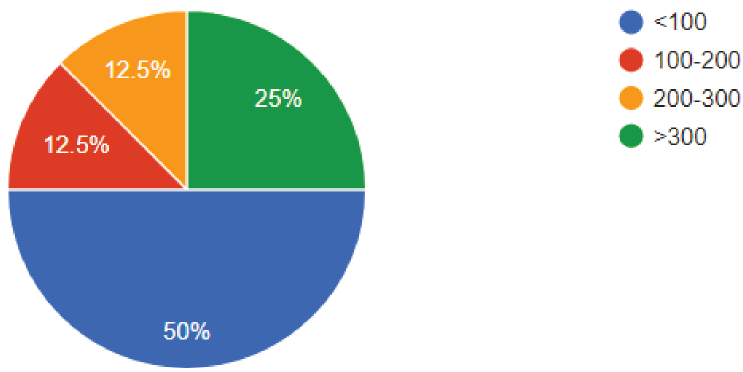


Figure 3. Question 3 Results

4. About what percentage of bridges are UWS in your state? (21 responses)

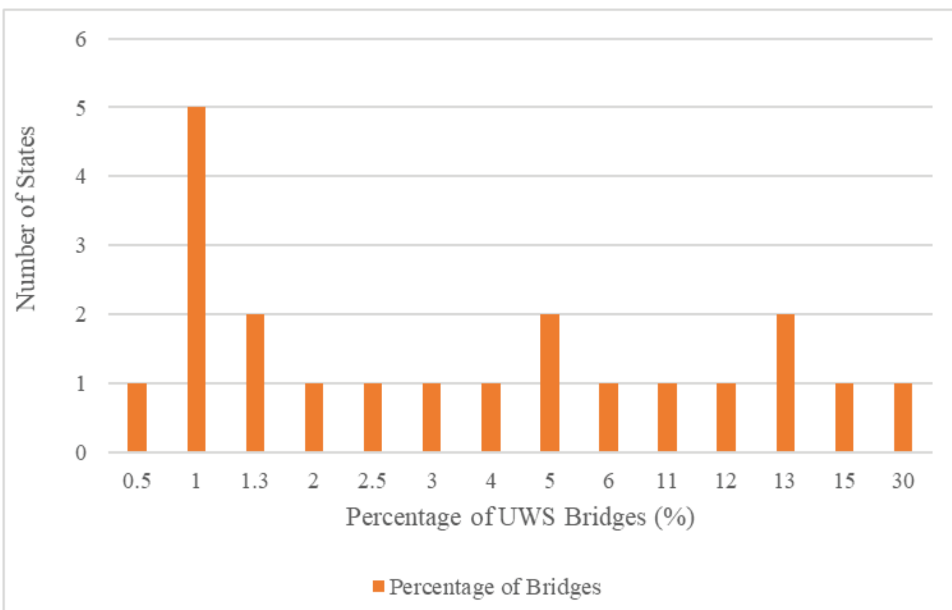


Figure 4. Number of States vs. Percentage of UWS Bridges in State

5. What are the contributing factors to UWS bridges experiencing excessive steel deterioration within your state? Please check all that apply. (26 responses)

    a. Climate

    b. Physical Surroundings

    c. Exposure to Deicing Agents

    d. Exposure to Water

    e. No Complications

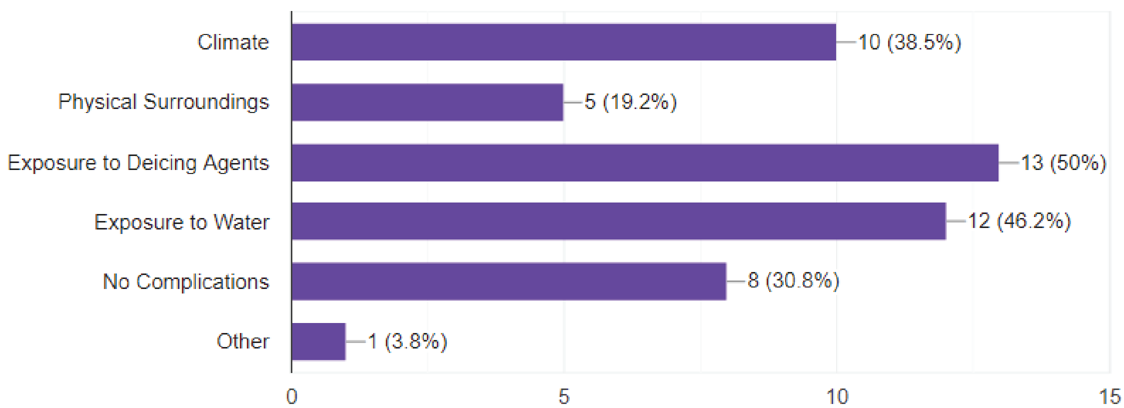


Figure 5. Question 5 Results

6. What corrective measures are you implementing at UWS bridges that are experiencing excessive weathering steel deterioration? (26 responses)

Table 1. Question 6 Corrective Measure Results

What corrective measures are you implementing at UWS bridges that are experiencing excessive weathering steel deterioration?
Plating or retrofitting if needed. Adding protective coating.
Better drainage collection. Prime coating vulnerable surfaces
Painting Bridge Ends/Eliminating Bridge Joints.
MDOT has a policy of painting weathering steel elements.
We tried washing but discontinued due to the maintenance of traffic issues.
UWS bridges perform well in Montana.
Ends of girders under expansion joints are painted.
None yet
N/A
Repair beam end plating.
Painting
Please review the Ohio DOT Bridge Design Manual for limitations on UWS Bridges. Any deterioration that effects structural capacity is reinforced and painted.
Paint beam ends and bearings. Use in the correct situation.
We are painting the ends of new structures to prevent excessive deterioration but have not implemented any rehabilitative measures for existed deteriorated bridges.
N/A
We paint the beam ends of all UWS structures.
Paint the ends of the girders over expansion joints.
Blast cleaning rusted surfaces and adding a paint coating.
No experience
We have painted all existing UWS in our state.
Additional section for sacrificial corrosion, painted ends of beams

Table 1. Question 6 Corrective Measure Results (Continued)

What corrective measures are you implementing at UWS bridges that are experiencing excessive weathering steel deterioration?
Abrasive blast and coat with paint
None
Painting girder ends/locations at open joints.

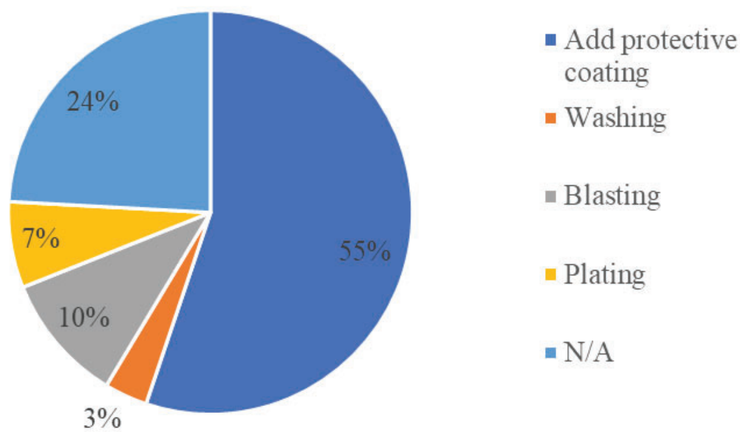


Figure 6. Corrective Measures Summary

7. Would you recommend using weathering steel in future bridge structures? (26 responses)

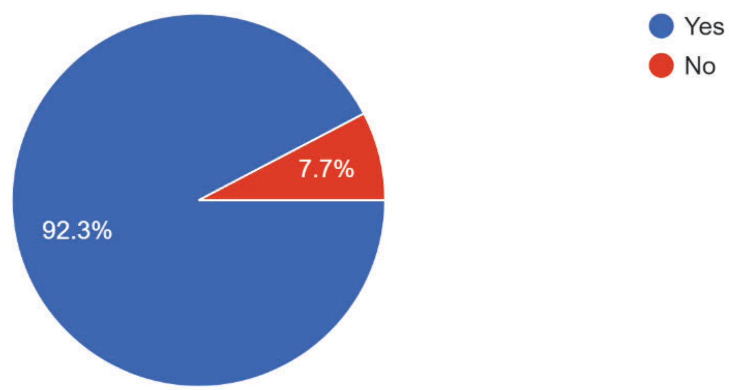


Figure 7. Question 7 Results

Based on the survey, DOTs will continue designing bridges that use UWS in future projects. The influencing factors of corrosion at other state DOT programs are deicing chemicals and water exposure. Many of the survey recommendations include adding a protective coating by painting vulnerable bridge girder locations susceptible to contact with water runoff from the bridge deck.

CHAPTER 4. UWS COST BENEFITS

State DOTs use UWS because of its economic benefits. A 2011 presentation conducted by McEleney (2011), director of the NSBA, detailed the economic benefits of using UWS. McEleney (2011) found a 10 to 18 percent initial cost savings favoring weathering steel. At the time of the presentation, UWS material costs were \$0.03 to \$0.04 per pound (\$60 per ton to \$80 per ton) more than plain steel; however, this was offset by the cost of painting plain steel at \$0.12 to \$0.20 per pound. A life-cycle cost analysis is the best economic strategy for selecting transportation projects (FHWA 2017). To examine the benefits of using UWS over plain carbon steel, a life-cycle cost comparison is presented between painted carbon steel (A709 Gr. 50) and weathering steel (A709 Gr. 50W). The four following scenarios are considered in this 60-year life-cycle cost analysis:

- Initially painting A709 Gr. 50 steel (Painted A709 Gr. 50);
- Uncoated weathering steel with no maintenance (Bare A709 Gr. 50W);
- Uncoated weathering steel requiring maintenance painting (Maintenance Painted); and
- Uncoated weathering steel that is maintained through annual washing (Bare A709 Gr. 50W with annual washing).

Life-cycle costs for the different steel scenarios are derived from Albrecht et al. (1989), McEleney (2011), Helsel et al. (2008), Okasha et al. (2012), and Kere et al. (2019). The following analysis details the economic factors and influences used to choose between these two material types. Similar costs are assumed between A588 and A709 Gr. 50W steel for the reference values. In addition, costs are assumed to increase at the inflation rate.

The analysis considered a 100 ft (30.5 m) single-span bridge and followed a similar approach as in the National Cooperative Highway Research Program (NCHRP) Report 314 (Albrecht et al. 1989). The bridge cross-section comprised four plate girders acting compositely with an 8 inch (200 mm) thick by 33.31 ft (10.16 m) wide concrete deck. The deck overhung each fascia girder by 4.17 ft (1.27 m), and the girders were spaced at 8.33 ft (2.54 m) (Albrecht et al. 1989). An annual inflation rate of 2.49 percent was used between 1995 and 2022 (CPI Inflation Calculator 2021). Conversely, a 10 percent total interest rate was used, which represented the actual future monetary value, including inflation (CPI Inflation Calculator 2021).

The study bridge was analyzed by comparing A709 Gr. 50 steel girders with A709 Gr. 50W weathering steel girders. Both the A709 Gr. 50 steel girders and A709 Gr. 50W have a 50 ksi yield strength. The A709 Gr. 50W weathering steel option was further divided into coated and uncoated weathering steel alternatives. The calculated cost in this preliminary analysis did not include the cost of diaphragms, bearings, and concrete deck. Consequently, only the cost of steel girder fabrication was used in the calculation. The girder weight, weight index, and initial cost are listed in the following text. The A709 Gr. 50W girders were assumed not to have any corrosion performance improvement enhancements or special detailing, which would increase the cost (Albrecht et al. 1989).

The life-cycle cost of A709 Gr. 50 included the unit cost for initial blast cleaning/painting and repainting. Conversely, the life-cycle cost for A709 Gr. 50W considered cases such as initial blast cleaning, maintenance blast cleaning, maintenance painting, and repainting. Unit costs were taken from Helsel et al. (2008) and revised to 2022 USD, considering the change in the value of money over time with interest. The initial painting costs assume that the painting is performed and completed in the shop. The initial A709 Gr. 50 painting with inorganic zinc, epoxy, and polyurethane unit costs include surface preparation ($0.40/ft^2 ($4.30/m^2)), paint application ($1.58/ft^2 ($17.00/m^2)), and paint material ($0.805/ft^2 ($8.66/m^2)) (Kere et al. 2019). A 1.20 factor was applied to the surface preparation and paint application for the total adjusted labor cost of $2.38/ft^2 ($25.61/m^2). Consequently, the total initial painting cost with a shop coat application was $3.18/ft^2 ($34.21/m^2) in 2008 USD. The total initial painting cost is equivalent to $4.49/ft^2 ($48.31/m^2) in 2022 USD. However, from the recent ARDOT letting in November 2023 and in speaking with local fabricators, this initial painting value is low and a better cost value for initial painting performed in shop is $16.70/ft^2 ($180/m^2). The repainting cost was estimated at $12/ft^2 ($129.10/m^2) in 2012 USD and converted to $15.34/ ft^2 ($165.10/m^2) in 2022 USD (Okasha et al. 2012). The A709 Gr. 50W surface was prepared using an SP 10 “Near White Blast” estimated at $1.72/ft^2 ($18.50/m^2) in 2008 USD and $2.43/ft^2 ($26.14/m^2) in 2022 USD. Maintenance painting was considered for A709Gr. 50W Steel. It included a spot prime application in deficient areas followed by a full coat application. The unit cost for maintenance painting, $4.71/ft^2 ($50.72/m^2) was assumed at 105 percent of the initial painting cost ($4.49/ft2, $48.31/m2) (Helsel et al. 2008). As commented in the previous text, the initial $4.49/ft^2 ($48.31/m^2) in 2022 USD painting cost is low. However, the maintenance cost will be applied to the entire girder area and therefore represents the more appropriate $16.70/ft^2 ($180/m^2) being applied over approximately 30 percent (28 percent) of the total bridge area. **Table 2** includes a summary of the unit costs previous described.

Table 2. Unit Costs for Initial Painting and Blast Cleaning (2022 USD)

	A709 Gr. 50 Steel $/ft^2 ($/m^2)	A709 Gr. 50W Steel $/ft^2 ($/m^2)
Initial SP 10 Near-White Blast	-	2.43 (26.17)
Initial Blast Cleaning and Painting with Inorganic Zinc, Epoxy, and Polyurethane (performed in the shop)	16.70 (179.80)	-
Blast Cleaning and Maintenance Painting	-	4.71 (50.72) (applied to total girder area for cost)
Repainting	15.34 (165.10)	15.34 (165.10)

The girder weight and surface area values for the 100 ft (30.5 m) single-span study bridge were obtained from the NCHRP Report 314 (Albrecht et al. 1989). These girder values were then combined with the current unit costs to obtain present worth costs. The unit costs in **Table 2** were converted to total cost using the total steel area of the single-span bridge, **Table 3**. For fabrication, a plain carbon steel plate was estimated at $886/ton ($975/tonne) in 2012 USD (Okasha et al. 2012). Assuming weathering steel is $80/ton more than plain carbon steel, weathering steel is estimated at $966/ton in 2012 USD ($1,065/tonne). These costs were converted to 2022 USD as $1,133/ton ($1,246/ tonne) and $1,235/ton ($1,362/tonne) for plain carbon steel and weathering steel, respectively. These material unit costs were then converted to total cost using the total steel bridge weight of the single-span bridge, **Table 3**, where the difference in total initial cost is due to member preparation.

Table 3. Initial Cost of One-Span Bridge (2022 USD)

	Type of Steel	
	One-Span	
	A709 Gr. 50	A709 Gr. 50W
Steel Surface Area	5,540 ft^2 (515 m^2)	5,540 ft^2 (515 m^2)
Weight	30.6 tons (27.8 tonne)	30.6 tons (27.8 tonne)
Steel Material ($)	34,670	37,791
Blast Cleaning ($)	-	13,462
Initial Blast Cleaning and Painting with Inorganic Zinc, Epoxy, and Polyurethane ($)	92,518	-
Total Initial Cost ($)	127,188	51,253
Initial Cost Index	2.48	1.00
Maintenance Painting ($)	-	26,093
Repainting ($)	84,984	-

The total present worth of multiple future maintenance costs, PW (maintenance), is the summation of the present worth of N individual future maintenance expenditures. A single current maintenance expenditure C at n years is assumed to increase at an annual inflation rate of e, so that the escalated cost at n years of service, EC, is:

$$EC = C(1+e)^n \tag{Eq. 1}$$

Where C = present maintenance cost

e = inflation rate = 2.49 percent

n = number of years during which maintenance is needed

The present worth maintenance cost, PW (maintenance), is calculated by inverting (Eq. 1) but using the total interest rate, 10 percent, (Eq. 2):

$$\text{PW (maintenance)} = \frac{EC}{(1+i)^n} \tag{Eq. 2}$$

Where i = 10%, total interest rate that includes the inflation interest rate

After EC's substitution in (Eq. 2), the present worth for maintenance for a single expenditure is:

$$\text{PW (maintenance)} = C\left[\frac{1+e}{1+i}\right]^n \tag{Eq. 3}$$

The accumulated present worth cost is the summation of the individual expenditures:

$$\text{PW (maintenance)}=\sum_{n=1}^{N} C\left[\frac{1+e}{1+i}\right]^n \tag{Eq. 4}$$

Where N = the total number of maintenance expenditures

The life-cycle cost along with the cost index for each alternative are listed in **Table 4**. A fourth option is considered with A709Gr. 50W steel; however, annually washing the bridge to remove collected poultice causing steel corrosion. Annually washing the A709 Gr. 50W single-span steel bridge is estimated at: (4 workers)(4 hours)($50/hr) = $800/year (Albrecht et al. 1989) in 1989 USD or $1801/year in 2022 USD. However, this cost does not include the maintenance of traffic cost incurred by the agency and the road users. The cost index listed in **Table 4** represents the alternative bridge scenario option cost compared to the bare cost of A709 Gr. 50W. The bare A709 Gr. 50W is the most economical, however, assumes that the material is maintenance-free. Besides the "no maintenance option," the least expensive alternative is maintenance painting the A709 Gr. 50W girders. This option is followed by annually washing the A709 Gr. 50W steel girders, which costs 47 percent more than the bare weathering steel option amount. The most expensive option is painted A709 Gr. 50 steel which is over three times as expensive as the "no maintenance option." As a caveat, these cost indices are based on preliminary cost values and should be validated based on current market costs. However, the cost index values derived from this simplified analysis demonstrate that weathering steel usage is best used at bridge locations where ambient conditions will not promote excessive corrosion so that maintenance will not be warranted.

Table 4. Life-Cycle Cost of One-Span Bridge Girder

Year	Painted A709 Gr. 50		Bare A709 Gr. 50W		Maintenance Painted A709 Gr. 50W		Bare A709 Gr. 50W w/ Annual Washing[b]	
	Escalated Cost ($)	Present Worth ($)	Escalated Cost ($)	Present Worth ($)	Escalated Cost ($)	Present Worth ($)	Escalated Cost ($)	Present Worth ($)
0	-	127,188	-	51,253	-	51,253	-	51,253
15	122,902	29,421	-	-	37,735	9,033	-	-
30	177,738	10,185	-	-	54,571	3,127	-	-
45	257,042	3,526	-	-	78,920	1,082	-	-
60	-	-	-	-	-	-	-	-
Annual Cost ($)								1,801
Life-Cycle Cost ($)[a]		170,320		51,253		64,495		74,478
Cost Index		3.32		1		1.26		1.47

Notes:

a. Calculations are based on a 2.49 percent inflation rate and 10 percent total interest, including inflation.

b. The present worth cost includes an annual $1,801 (2022 USD) washing cost for 60 years.

CHAPTER 5. PRIMARY FACTORS INFLUENCING UWS PERFORMANCE

Factors such as environmental and climatic conditions influence a bridge's condition. For UWS structures to perform optimally, constant moisture exposure must be avoided. Bridges with significant oxide film degradation occur at locations with high amounts of rainfall, fog, and/or humidity (Kubzova et al. 2020). In addition, when the patina is exposed to water runoff with high chloride concentration, it develops thicker and larger rust flakes with possible steel member section loss. Bridge age and environmental conditions at bridge sites were examined during this study to relate ambient bridge conditions to UWS corrosion. **Table 5** identifies the number of bridges experiencing different percentages of bridge girder surface area, excluding CS 1 as a function of the year built. The ARDOT bridge inspection inventory includes a total of 859 UWS bridges built between 1971 and 2020. A total of 26 UWS bridges (3 percent of the ARDOT UWS total) were constructed prior to 1980, and of these, 23 percent are experiencing extensive degradation of 90 to 100 percent. At these bridges, 90 to 100 percent of the bridge girder area is experiencing oxide film degradation (CS 2, 3, or 4). Conversely, this percentage decreases for UWS bridges constructed after 1980. A total of 833 UWS bridges (97 percent of the ARDOT UWS bridge total) were constructed after 1980 with 7.8 percent of these bridges having extensive (90 to 100 percent) oxide film degradation.

Table 5. Number of Bridges Built in Each Time Period as a Function of the Percentage of Bridge Girder Surface Area with CS 2, CS 3, and/or CS 4

	Number of Bridges					
	Time Period					
Percent of Bridge Girder Surface Area with CS 2, CS 3, and/or CS 4	1971-1980	1981-1990	1991-2000	2001-2010	2011-2020	Total
0-10%	16	76	220	253	200	765
10-20%	0	4	1	0	0	5
20-30%	2	1	2	0	0	5
30-40%	0	2	0	4	0	6
40-50%	1	1	0	1	0	3
50-60%	0	1	1	0	0	2
60-70%	0	1	0	0	0	1
70-90%	1	0	0	0	0	1
90-100%	6	16	16	30	3	71
Total	26	102	240	288	203	859
90-100% (% of Total)	23.1	15.7	6.7	10.4	1.5	8.3

Figure 8 identifies the UWS bridge locations that experience extensive oxide film degradation (90– 100 percent). The bridge locations are color-coded on the figure to identify the time at which the bridge was built. The figure also identifies the ArDOT District areas. The UWS bridge locations in **Figure 8** provide preliminary insight at the macro-environmental level in order to relate ambient conditions to UWS degradation. In regard to bridges experiencing high degradation, the plotted bridges show a pattern of problematic bridges grouped within central Arkansas, District 6. ArDOT District 6 oversees the central Arkansas area, including Little Rock. Of the UWS bridges in District 6, 37 percent have extensive

corrosion, and many of these bridges were constructed post 1980. Ambient relative humidity is typically used as an indicator to identify the potential for UWS corrosion; however, the average relative humidity in Little Rock, AR, within District 6 is not notable, 56.3 percent relative humidity (Relative Humidity in 2021).

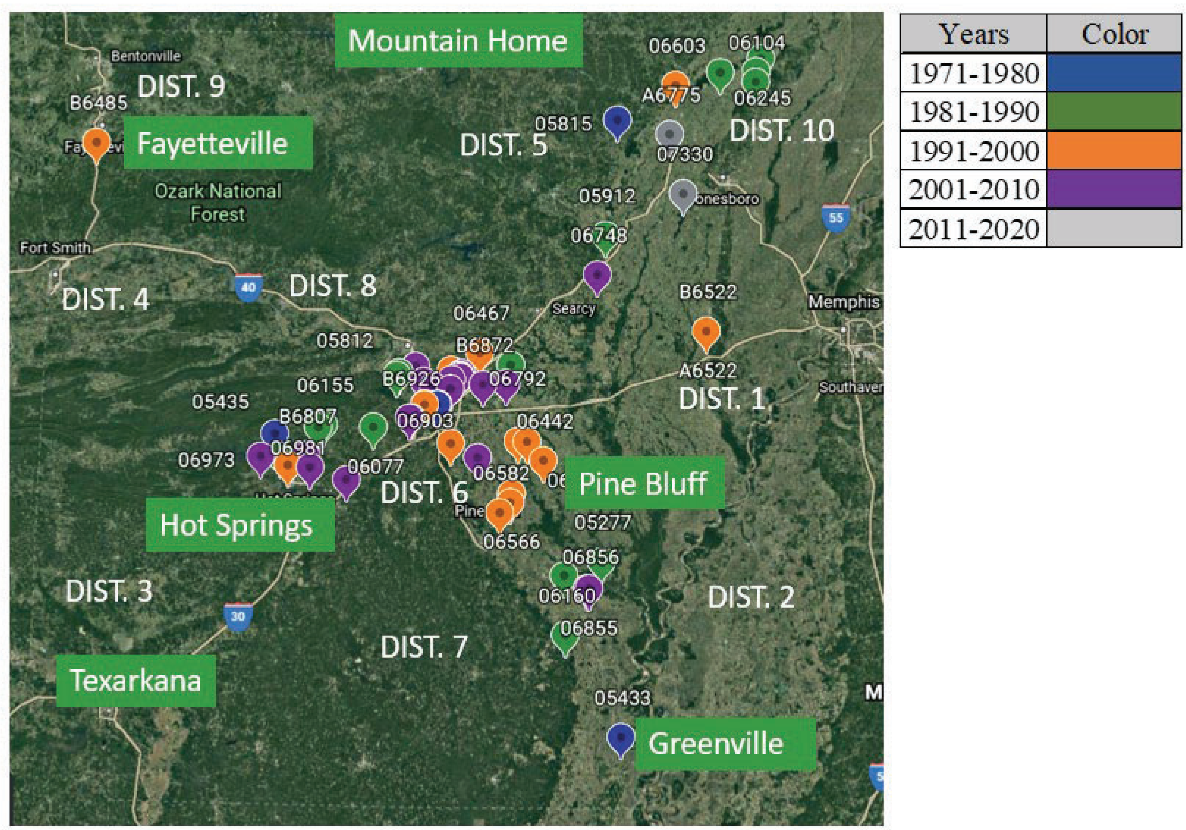


Figure 8. Bridge Location: 90-100 Percent Degradation

Table 6 identifies the UWS bridges with a CS greater than one as a function of the ARDOT District. To examine a possible correlation between UWS bridge degradation and anti-icing treatment, **Table 6** includes the number of events at which the ARDOT Districts applied anti-icing treatments. Anti-icing treatment data were provided by ARDOT for the years 2018 through 2021. Prior to 2014, ARDOT maintenance used calcium chloride liquid anti-icing treatments but currently uses salt brine and beet juice mixtures. Based on **Table 6**, a direct correlation between anti-icing treatments and bridge percentages within districts experiencing extensive corrosion is not evident. However, this was expected since Arkansas winters are generally mild, and the number of anti-icing treatments is nominal.

Table 6. Number of Bridges in Each ARDOT District as a Function of the Percentage of Bridge Girder Surface Area with CS 2, CS 3, and/or CS 4

	ARDOT District										
Percent of Bridge Girder Surface Area with CS 2, CS 3, and/or CS 4	1	2	3	4	5	6	7	8	9	10	Total
0-10%	83	55	79	107	54	75	57	79	92	84	765
10-20%	0	0	0	0	0	0	0	3	0	2	5
20-30%	0	3	0	0	0	2	0	0	0	0	5
30-40%	0	3	2	0	0	0	0	1	0	0	6
40-50%	0	1	0	0	0	1	0	1	0	0	3
50-60%	0	1	0	0	0	0	0	0	0	1	2
60-70%	0	0	0	0	0	0	1	0	0	0	1
70-90%	0	0	0	0	0	1	0	0	0	0	1
90-100%	3	11	0	1	1	46	0	0	0	9	71
Total	86	74	81	108	55	125	58	84	92	96	859
90-100% (% of Total)	3.5	14.9	0	0.9	1.8	36.8	0	0	0	9.4	8.3
No. of Icing Events During Winter Season											
# 2020-2021	9	7	4	3	-	6	3	11	7	20	
# 2019-2020	7	0	4	-	-	9	3	4	11	15	
# 2018-2019	6	4	4	-	-	8	3	4	13	10	

5.1 TIME OF WETNESS

Weathering steel corrosion coincides with the time at which a bridge experiences high amounts of dampness over long durations. A structural member's time of wetness (TOW) results from precipitation, runoff, and condensation from humidity. An average TOW exceeding 0.6 (60 percent) yearly is a predictor for potential UWS corrosion (FHWA 1989b). The relationship between TOW and humidity was evaluated by the research team by collecting humidity data for each ARDOT District for 24 hours using an hourly humidity rate (ClimateData 2021). The first three days of each month were taken as representatives of the entire month. Data from the first three days of every month in 2020 were collected for each ARDOT District. For each day, the time duration during which the humidity percentage was above 70 was identified. **Figure 9** shows a preliminary TOW for bridges within ARDOT District 6, which includes the highest number of UWS bridges with extensive corrosion. In 2020, there were six months with three-day TOW averages above 0.6 (60 percent).

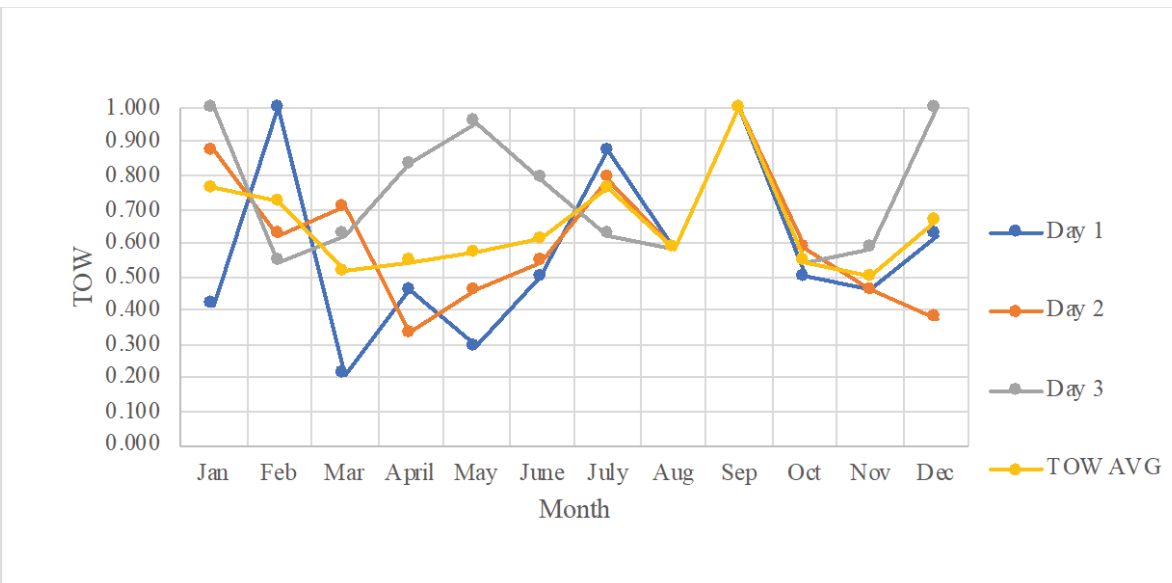


Figure 9. Time of Wetness (TOW) for ARDOT District 6 in 2020

Consequently, **Figure 9** displays, at the macro-environmental level, the time percentage during which bridges in District 6 were experiencing moist conditions for the 12-month analysis period. The TOW, as a function of the month, was examined for each ARDOT District. Each District displayed a similar TOW trend, considering the first three days of the month.

5.2 PRECIPITATION

Weathering steel performance is adversely affected by heavy amounts of precipitation and continuous moisture. Rainfall amounts from 2007 to 2019 were collected from the US Climate Data and plotted for the ten ArDOT Districts (ClimateData 2021). The total precipitation as a function of month for District 6 is shown in **Figure 10** for years 2007 to 2019. The figure shows the significant amount of precipitation that the state experiences and the variability of precipitation during the year and between the years.

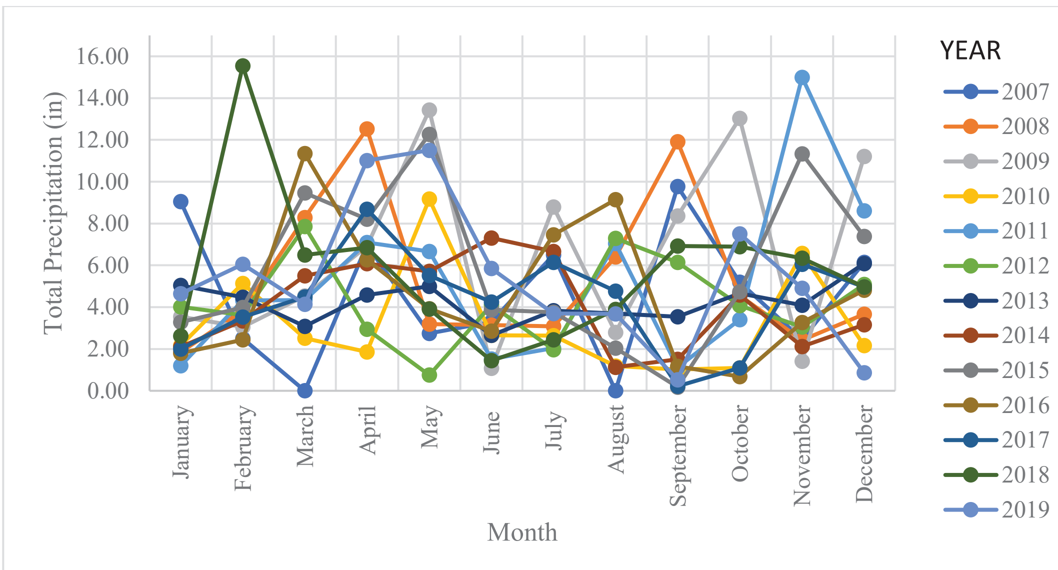


Figure 10. Average Precipitation in ArDOT District 6

An example of how precipitation varies throughout the state is shown in **Figure 11**. Bridge locations experiencing extensive oxide film degradation are superimposed on the figure.

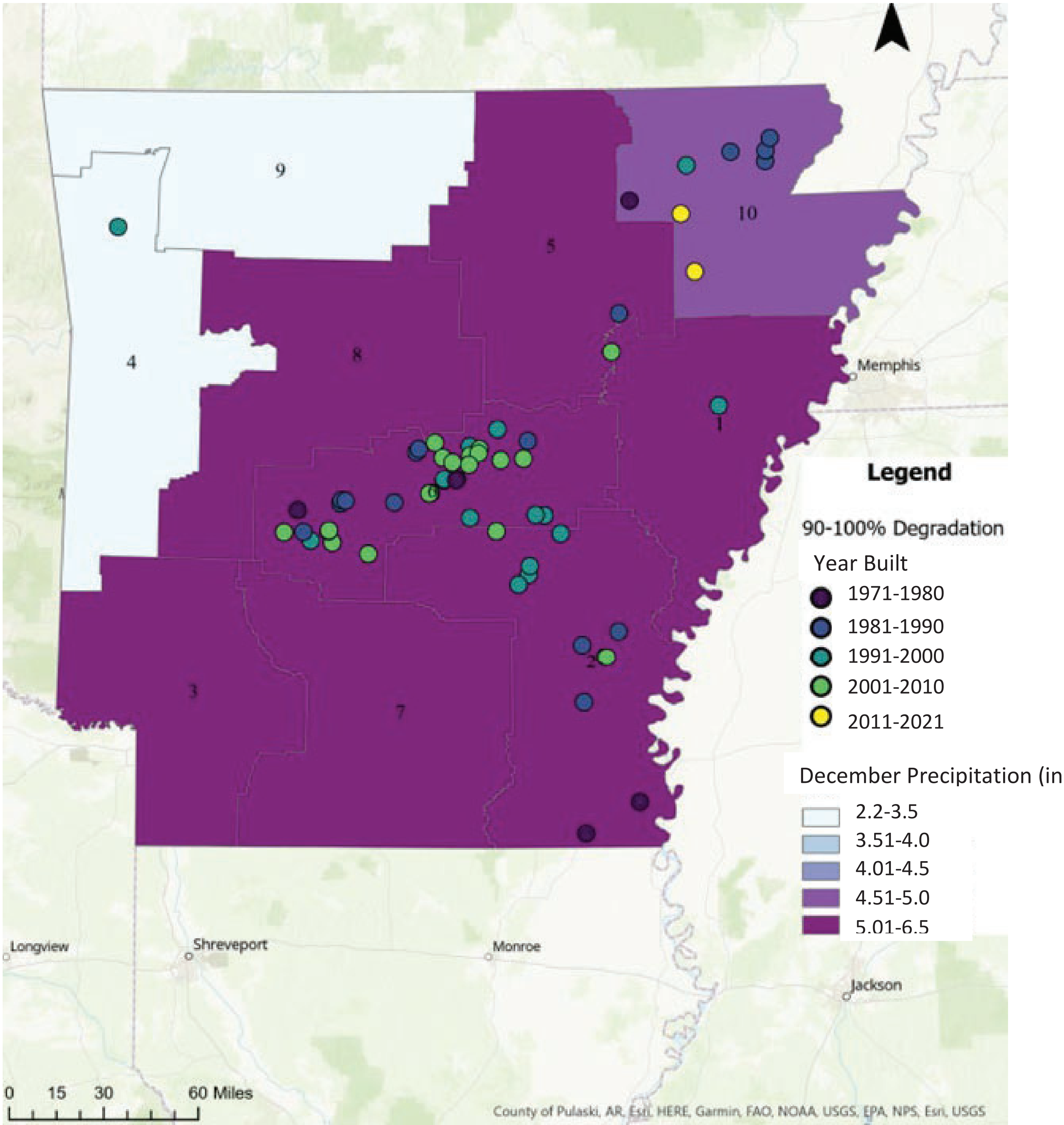


Figure 11. Average Precipitation in December with Bridges Experiencing 90-100 Percent Degradation Superimposed

Precipitation results in bridge deck runoff. Expansion joint openings and cracks (**Figure 12)** cause precipitation runoff to contact bridge girders. This runoff may include deicing chemicals during wintry precipitation, which accelerates corrosion (Bao et al. 2021). Corrosion is most apparent at girder ends below the deck joints adjacent to abutments. This was substantiated during the bridge inspections conducted in this research study. Many of the inspected bridge girders at the abutments displayed significant oxide film degradation with CS 4.

Figure 12. Bridge Deck Expansion Joint

Figure 13 shows an example of a bridge girder at an abutment area experiencing significant corrosion. A rust inhibitor was applied to the girder to delay rust development. However, this treatment did not decrease the corrosion rate. **Figure 14** is a close-up of the area, showing large rust flakes and girder pits measuring 3/16 inch (4.8 mm).

Figure 13. Rust Inhibitor at End Abutment

Figure 14. Rust with Rust Inhibitor

5.3 TEMPERATURE

Steel corrosion rate increases with temperature (Shirkhani 2020), and temperatures above 32° F (0° C) promote "favorable conditions" for corrosion (Kaur 2014). The significance of temperature and how it relates to UWS girder corrosion was investigated by reviewing ambient temperature conditions between 2007 and 2019. The average daily high and low temperatures were plotted for each year as a function of the month for ARDOT District 6, **Figure 15** (high temperature), and **Figure 16** (low temperature). Based on these figures, ARDOT District 6 temperature time histories during the 2007-2019 period exhibit similar annual behavior. The highest temperatures were experienced in July and August. Most months have a low temperature above 32° F (0° C). Consequently, these temperature conditions are conducive to corrosion.

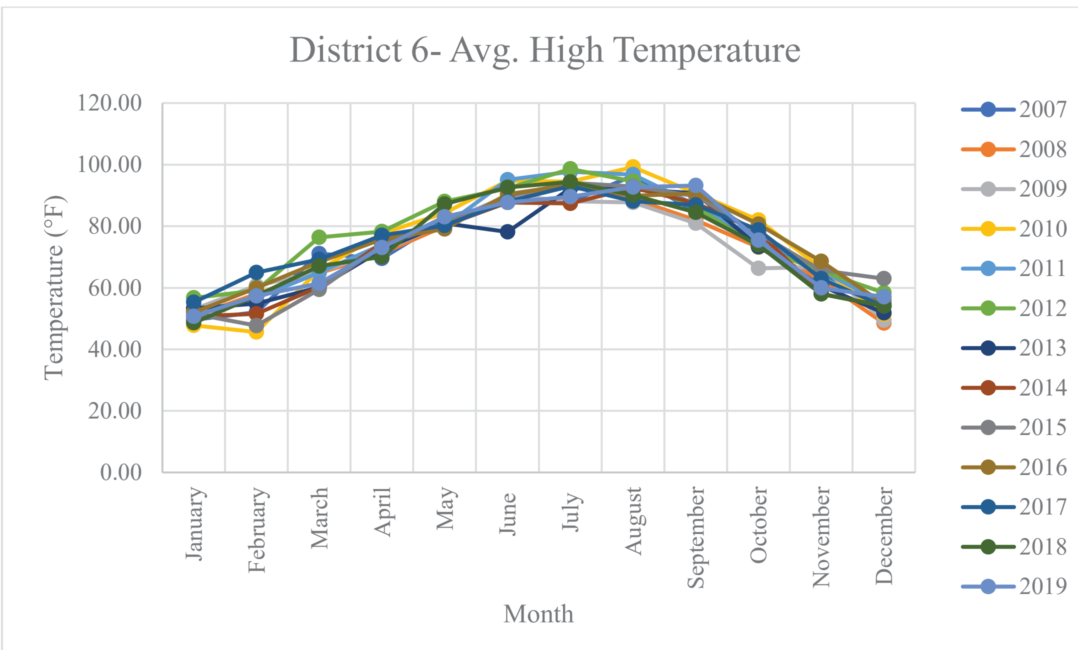


Figure 15. Average High Temperature in ARDOT District 6

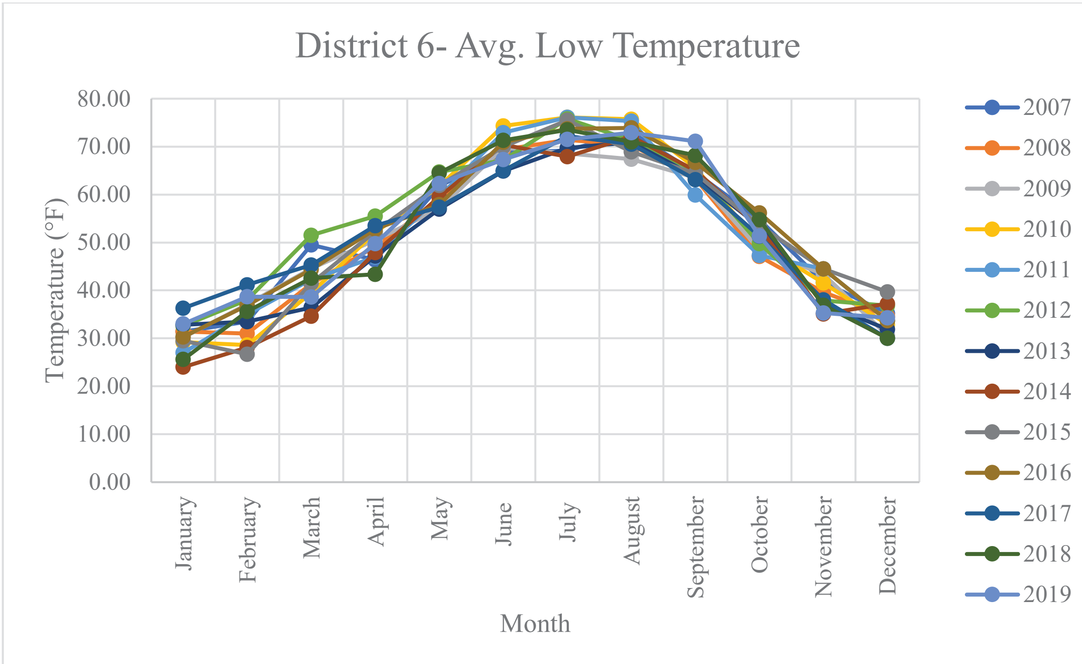


Figure 16. Average Low Temperature in ArDOT District 6

Figure 17 shows the average July high temperature, and **Figure 18** presents the average December low temperature throughout the state in order to investigate a possible correlation between temperature and the UWS bridge condition. Based on the figures, a correlation between temperature and the UWS bridge condition cannot be deduced.

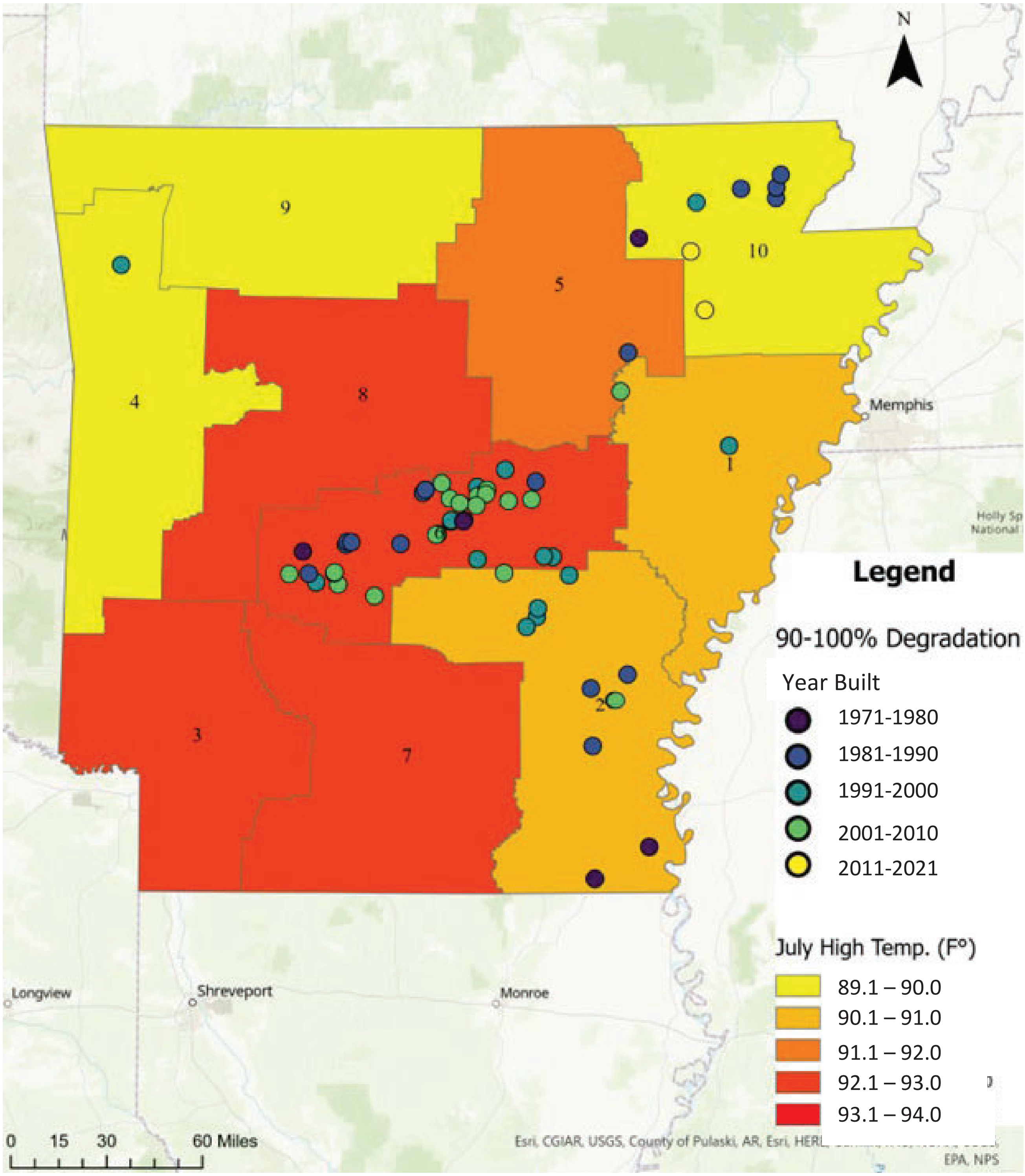


Figure 17. Average High Temperature in July with Bridges Experiencing 90-100 Percent Degradation Superimposed

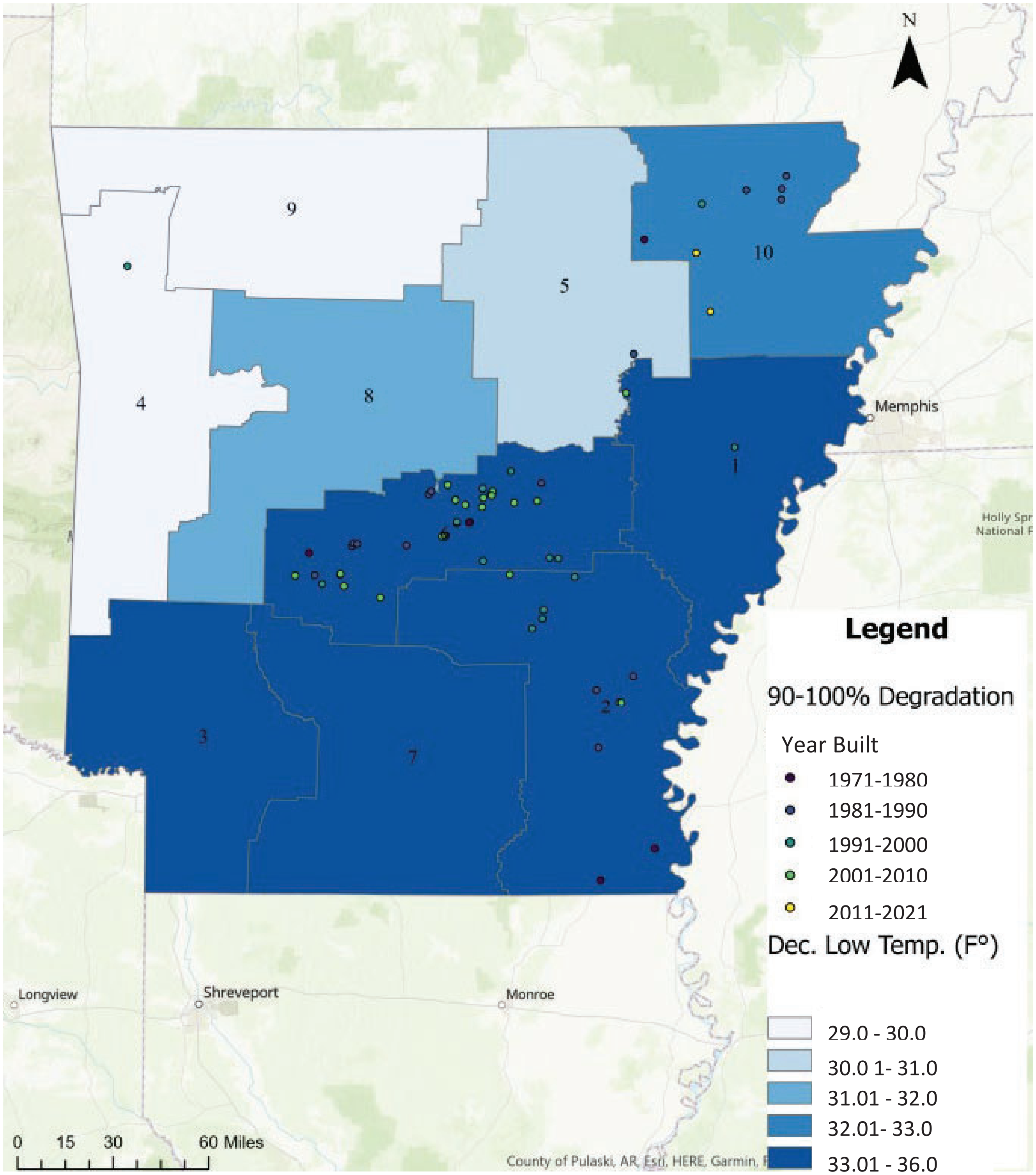


Figure 18. Average Low Temperature in December with Bridges Experiencing 90-100 Percent Degradation Superimposed

5.4 VEGETATION

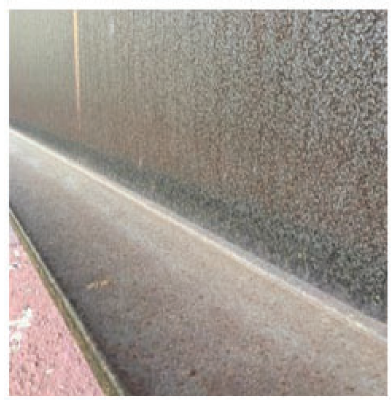
Uncontrolled vegetation at a bridge site restricts air circulation, resulting in high humidity, captured moisture, and long-term wetness. Due to uncontrolled vegetation, the patina does not form properly, and the UWS corrosion rate is similar to that of bare carbon steel (Wong 2010). **Figure 19** displays uncontrolled vegetation surrounding the bridge structure. The vegetation at the bridge site leads to the steel superstructure experiencing long-term wetness and limited air circulation. Generally, vegetation in urban areas is normally better maintained than in rural areas.

Figure 19. Bridge A6820 Enclosed with Vegetation

CHAPTER 6. UWS BRIDGE OXIDE FILM CONDITION STATES

As the patina develops a yellow-orange color oxide layer forms on the weathering steel. Subsequently, the patina takes on a light brown color. As the patina further develops, it transitions to a chocolate brown, purple-brown color. In contrast, a non-protective oxide film layer will blacken. Current guidelines for evaluating oxide film layer conditions at UWS bridges focus on the oxide film's texture and color. A fine-grained, chocolate-brown to purple-brown, tightly adhered, stable rust layer indicates good patina performance (AASHTO, 2019). In contrast, thick, loose rust flakes in the patina are symptomatic of high chloride concentrations (Crampton et al. 2013). The NBIS are used by bridge inspectors to appropriate a consistent oxide film CS number (1-4) (FHWA 1989a). Each CS identifies the oxide film degradation that the UWS member is experiencing (AASHTO 2019). CS 1 corresponds to "Good." CS 2, 3, and 4 correspond to "Fair", "Poor", and "Severe", respectively. **Figure 20** provides examples for each condition state. Typically, UWS girder corrosion occurs at the top of the bottom girder flange where water ponds and poultice collect. A CS 3 girder web and web stains from dripping water are shown in **Figure 20 (c)**. CS 4 is shown in **Figure 20 (d)** at the bridge bearing. Bridge bearings at the abutment are common locations of CS 4 since the bridge deck expansion joint at the abutment allows draining water mixed with anti-icing chemicals access to the steel superstructure.

(a) ARDOT Bridge A6284: CS 1



(b) ARDOT Bridge B6503: CS 2

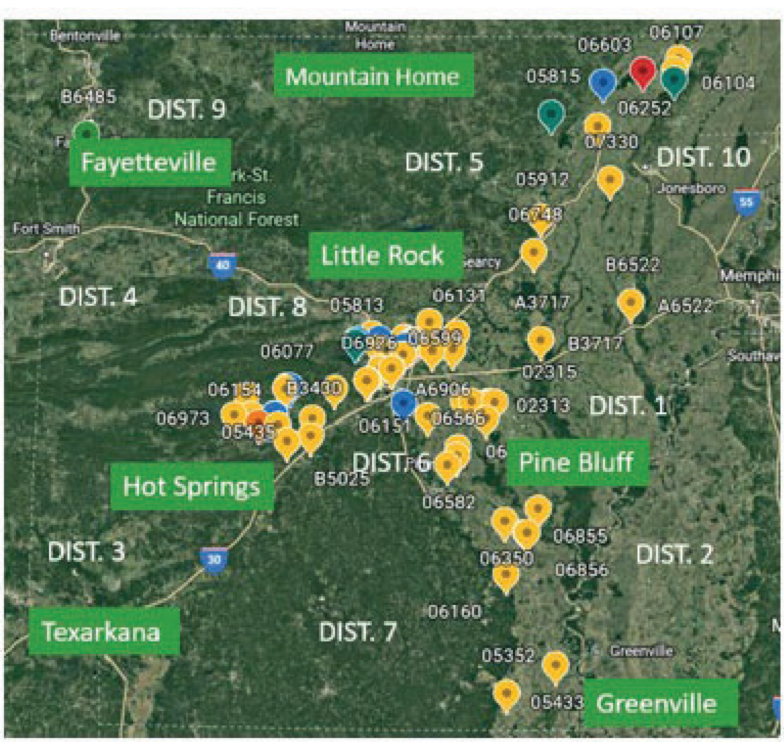
(c) ARDOT Bridge B6507 with an 1/8" pit: CS 3

(d) Abutment bridge girder joint: CS 4

Figure 20. Oxide Film CS

6.1 RANKING BRIDGES FOR OXIDE FILM SEVERITY

Further research was performed to develop a protocol for prioritizing bridges that need remediation as a function of condition state and the percentage of the bridge girder area experiencing oxide film degradation. Initially, this research study prioritized bridges based on the percentage of the bridge experiencing degradation. However, this approach discounts the significance of the specific CS that the bridge experiences. For example, a bridge experiencing 90 to 100 percent bridge element degradation but with a CS 2 is less critical than a bridge experiencing 0 to 10 percent degradation with a CS 3 or CS 4. Consequently, an approach using weighted factors was developed, including both bridge percentage experiencing oxide film degradation and CS. A total of 83 ArDOT UWS bridges have 90-100 percent degradation. The CSs are shown for these bridges experiencing 90-100 percent oxide film degradation in **Figure 21**. These bridges are also listed in **Table A-1** in the Appendix, along with the girder area and corresponding CS. Six bridges in the 90 to 100 percent degradation group experience CS 4 degradation, as shown in **Table 7**. The other 77 bridges presented higher total degradation percentages; however, this degradation includes either a combination of CS 2 and CS 3, or only CS 2. Out of the 83 bridges, 67 experience only CS 2 degradation. Most bridges experiencing a compromised condition state are in the central Arkansas area with a CS 2 rating.



Condition State	Color
2	
1,2	
2,3	
2,4	
1,2,3	
2,3,4	
1,2,3,4	

Figure 21. Bridge Location with 90-100 Percent Degradation as a Function of CS

Table 7. Area Percentage of Each CS for Bridges Experiencing 90-100 Percent Degradation

Bridge Number	CS 1	CS 2	CS 3	CS 4
05815	2.84	90.38	0.32	6.46
06104	9.10	77.40	9.85	3.64
05698	0.00	98.11	0.00	1.89
06252	0.00	96.28	2.93	0.79
05813	0.09	97.20	1.98	0.72
B6485	0.00	99.93	0.00	0.07

CHAPTER 7. BRIDGE INSPECTION

Bridge inspections at UWS bridges require recording girder surface condition and potential oxide film degradation initiators. Patina performance is best identified through patina adherence (NSBA 2022). However, patina texture and patina color should be considered. ArDOT bridge inspectors use the ArDOT Bridge Inspection Manual (ArDOT 2022), which satisfies AASHTO's Manual for Bridge Element Inspection specifications (AASHTO 2019). Bridge inspections are conducted using a hands-on visual inspection approach. For steel corrosion at UWS bridges, the inspection focuses on ranking the CS of the patina based on its visual characteristics, including flake size, color, texture, and adherence to the steel. Consequently, a mechanical lift system or ladder is often required to gain access for inspecting bridge elements (ArDOT 2022). Additional inspection tools include a geologist hammer, brush, and pit depth gauge. A routine inspection is performed on a two-year cycle. The bridge inspection process includes recording the bridge deck expansion joints that are dislodged, clogged, or deteriorated. Deteriorated strip seal expansion joints collect debris and provide runoff water mixed with deicing chemicals passage to the UWS superstructure, as shown in **Figure 22.**

Figure 22. Corrosion and Debris Collected in the Expansion Joint

Bridge girder bearings beneath deteriorated bridge deck expansion joints are a common location for significant deterioration, as shown in **Figure 23**.

Figure 23. Bearing Corrosion: CS 4

ARDOT inspectors record bridge element findings using a tablet device. Each bridge inspection is unique. The uniqueness stems from traffic, access to elements, and required inspection equipment. In some cases, a snooper truck may be enlisted to enable inspectors to verify the beams, girders, and other bridge elements. When traffic is a concern, traffic control is warranted. The inspection protocol consists of searching for damaged or deteriorated bridge elements, assessing their condition, and picture recording, which will be included in the bridge inspection report.

The inspection starts with an elevation view photo of the bridge. Next, pictures of the abutment, where the inspectors begin the verification, are taken. When the concrete bridge deck and parapets are inspected, the amount and length of cracks, along with the occurrences of efflorescence, are recorded. The expansion joints at the abutments are also inspected. Expansion joints are hammered to check for bonding. If the expansion joints are compromised, deicing chemicals and runoff water will have access through the strip seal cracks to the weathering steel below the bridge deck. Additionally, if present, clogged scupper drains can cause water to drain improperly. All member deterioration is noted by the bridge inspector. Pictures are taken to include in the inspection report. Next, the inspection moves to below the bridge deck, where the bearings and the bearing pads are inspected. If the bridge deck condition is compromised near the expansion joints, there is a high probability that the UWS girder condition is severe below the bridge deck near the bearings. After the abutment condition is noted, the beams and girders are verified. Weathering steel's visual inspection includes the appearance and condition of the patina by considering its color, texture, size, density, and adherence. The CS for the beams, girders, and diaphragms is assigned based on the inspector's visual inspection.

After inspecting the abutment at one end of the bridge, inspectors make their way under the bridge to the abutment at the other end of the bridge. Along the way, piers, pier caps, and columns are checked for concrete cracking along with girder corrosion condition, **Figure 24**. Where overgrown vegetation exists, vegetation must be cleared to access bridge elements. At bridges where water crossings exist, proper outerwear must be worn. When vehicular traffic is present, traffic safety is paramount, **Figure 25**. Binoculars help inspectors to view bridge elements outside of hand reach. An exposed fabric bed near the bank beneath riprap indicates scouring issues, **Figure 26**. After the full inspection, the bridge inspection report is submitted to ARDOT Bridge Operations Division for their review and recommendations for remediation.

Figure 24. Girder Corrosion due to Improper Deck Drainage

Figure 25. Overpass Where Vehicular Traffic Safety Management is Warranted

Figure 26. Exposed Fabric Bed near Pier Columns

7.1 BRIDGE INSPECTIONS USING UAS

To avoid dependency on special access equipment (i.e., snooper), an unmanned aircraft system (UAS) was enlisted for this study. A specific UAS, DJI Matrice 300 RTK, was selected for this study due to its suitability for bridge inspection work. The Unmanned Aircraft (UA) payload included a high-resolution camera with a 30x zoom lens. A top-mounted camera was implemented for improved underdeck superstructure inspection. The camera was connected to an upward gimbal attached to the UA. In addition to the camera, the UA payload included a spotlight below the UA, as shown in **Figure 27.**

Figure 27. UWS Bridge Inspection Using UAS

The zoom lens camera mounted on the top of the UA pitches up, enabling the authors to conduct the bridge underdeck inspections for oxide film corrosion. The spotlight greatly enhances the picture recording capability of the UA by illuminating the superstructure areas typically shaded by the bridge deck, **Figure 28.**

Figure 28. Gimbal Spotlight

Bridge inspection using the UAS begins with ensuring favorable weather conditions and checking the bridge's location in proximity to local airports. If required, the UA pilot needs to request the airport's permission to perform the UA mission. Flying conditions for a UAS are highly dependent on temperature, wind, and moisture conditions. At the bridge site, the inspection setup begins by assembling the UA and positioning the UA landing pad in a clearing to avoid any obstacle interference. This location represents the UA home point. The landing pad provides a smooth surface for UA takeoff and landing without propeller interference, **Figure 27**. Each UA mission requires the UA to be checked for damaged parts. Two remote controllers were used during this study. One remote pilot controlled the UA flight pattern, while the second pilot controlled the camera and spotlight to photograph structural element images. The camera and spotlight are calibrated and synchronized so that the camera and spotlight move in tandem. Consequently, the calibration ensures the camera is viewing an illuminated bridge element. When ready for take-off, the remote pilot in control of the UA must always have a visual line-of-site to the UA. The DJI Matrice 300 RTK includes obstacle avoidance that alerts the remote pilot when the UA is nearing an obstacle during the flight. This is especially important for under-deck inspections where wind plays a significant factor in controlling the UA. The UA is flown to avoid flying over traffic or pedestrians. Two rechargeable batteries are required to fly the DJI Matrice 300 RTK. Due to the camera-spotlight payload, each battery pack is limited to support approximately 25 minutes of flying time.

Interstate 49 (I-49) in northwest Arkansas crosses Winn Creek north of the Bobby Hopper Tunnel. The bridge is 1367 ft (417 m) long and was built in 1997, **Figure 29**.

Figure 29. Image Taken by the UA of I-49 Bridges over Winn Creek

The images in **Figure 29** and **Figure 30** were taken from the UA and demonstrate the benefits of incorporating a UA in the inspection process by negating the need for special inspection equipment. The camera's optical zoom capability enables the remote pilot to record clear images while maintaining a safe distance between the UA and the bridge element, **Figure 30.**

(a) Bridge pier cap (normal view)

(b) Close-up of girder bearing at bridge pier cap using zoom from UA location in (a)

Figure 30. I-49 Pier Cap Taken by the UA with Zoom Capability

More detailed picture information, including the picture location, is recorded in a screenshot using the camera's laser range finder, **Figure 31**. The screenshot records the picture's geographic location by using GPS coordinates, as shown in the image's lower left corner. The lower right corner picture is the First Person View (FPV), toward which the UA is directed.

Figure 31. UA Screenshot

CHAPTER 8. BRIDGE PRIORITIZATION

For the TRC2103 study, seven weighted factor approaches were used by the research team for ranking the 859 UWS bridges included in the ARDOT bridge inspection database. A weighted scale approach was incorporated by considering different weighted factors as a function of condition state (CS). The weighted factors were used to capture the significance of the CS based on safety and cost to remediate the compromised beam from its current CS. Rankings were reviewed for multiple weighted factor scenarios.

Weighted Factor Approach

Weighted factors were applied to the oxide film degradation percentage that a bridge was experiencing for each CS and used to calculate a total weighted score:

$$\text{Weighted Score}=\sum_{i=1}^{i=4} wt(i)*CS\%(i)$$

(Eq. 5)

Where wt(i) = the weighted factor applied to CS (i)

CS%(i) = the percentage of the bridge experiencing CS (i) corrosion

Seven weighted factor trial approaches were considered in prioritizing 15 bridges in most need of UWS remediation considering only UWS CS rating. Weighted factors are included in **Table 8** for the seven weighted score approaches.

Table 8. Weighted Factors Used for Each Trial

Trial	Weighted Factors Used For:			
	CS 1	CS 2	CS 3	CS 4
1	1	2	3	4
2	1	2	4	8
3	1	4	12	32
4	1	0.67	0.33	0
5	0	2.43	7.14	17.77
6	0	0	3	4
7	0	0	7.14	17.77

The first trial approach, Trial 1, simply uses a weighted factor equal to the CS number. Conversely, Trials 2-7 consider using weighted factors that better represent the significance of the CS in terms of safety and remediation cost. Trial 4 applies weighted factors using a procedure already studied by Teresa M. Adams and Kang Myungook (Adams and Myungook 2009), which incorporates the bridge element Bridge Health Index (BHI). In contrast to the other trials, Trial 4 is based on a low score and prioritizes bridges for remediation based on its low weighted score using an assumed weighted factor scale. Trials 5 and 7 include weighted factors based on costs to remediate a compromised bridge element to a CS 1 status. Consequently, the weighted factor for CS 1 is 0. Trials 6 and 7 set the weighted factor for CS 1 and CS 2 to zero since most bridges experiencing oxide film degradation are aged and have a minimum CS 2.

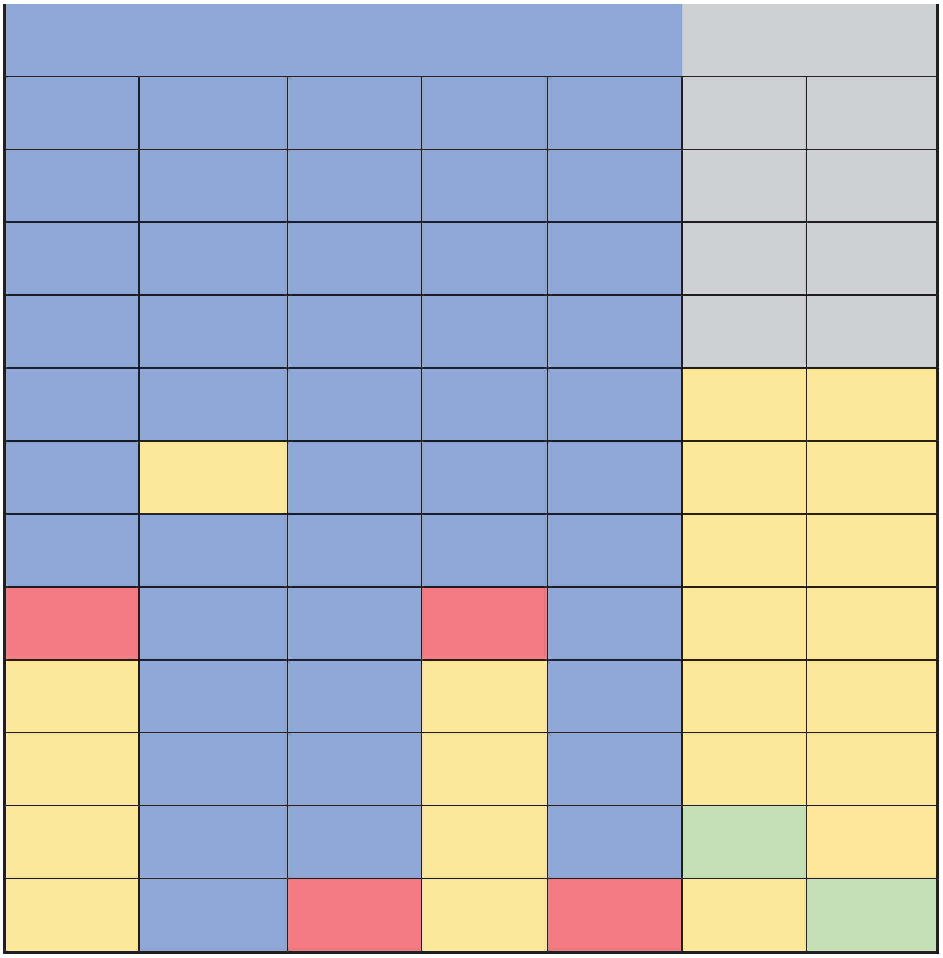
For Trial 7, the weighted factor for CS 2 is set to zero to negate its significance in the ranking decision. Trials 5 and 7 weighted factors are derived using previously presented costs in **Table 2**. Remediating a bridge element from CS 2 to CS 1 entails cleaning and power washing, $2.43/ft^2. Remediating a CS 3 bridge element to CS 1 requires cleaning and some remedial painting, $2.43/ft^2 + $4.71/ft^2 = $7.14/ft^2. Lastly, CS 4 remediation warrants cleaning and repainting, $2.43/ft^2 + $15.34/ft^2 = $17.77/ft^2. These cost values are, in turn, used as the weighted factors. **Table 9** ranks the top 20 UWS bridges based on the lowest weighted score for Trial 4, along with the highest weighted score for the other trial approaches. Trials 6 and 7 result in a significantly different listing than the other trial approaches. Trial 6 and Trial 7 each have a bridge that is listed only once in **Table 9**.

Table 9. Top 20 Bridges for Each Trial

Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
A3717	06224	05815	A3717	06224	06250	06224
05815	06324	06104	05815	05815	06224	06324
06104	05815	06224	06104	06324	06324	06250
06252	06104	06324	06252	06104	05987	05987
05698	06250	A3717	05698	A3717	06104	06104
05813	05987	06250	05813	06250	06105	05815
06609	A3717	05987	06609	05987	A3717	06105
07051	05698	05698	07051	05698	06319	06203

# of times repeated	Color
1	
2	
3	
4	
5	
6	
7	

Table 9. Top 20 Bridges for Each Trial (Continued)



# of times repeated	Color
1	
2	
3	
4	
5	
6	
7	

Rank sensitivity as a function of the trial approach is illustrated in **Figure 32** for Trials 1 through 5 and in **Figure 33** for Trials 6 and 7. The two Trial groups, 1 through 5, and 6 and 7, show a significantly different ranking. When Trials 1 through 5 are considered, the 15 bridges included in **Figure 32** have a 20 or less ranking (shown as gray or blue in **Table 9**). The remaining five bridges were selected based on Trials 1 through 5, and on the number of times repeated between the five trial approaches in **Table 9** (shown as red or yellow in **Table 9**). Of these 20 bridges, 11 are in District 6.

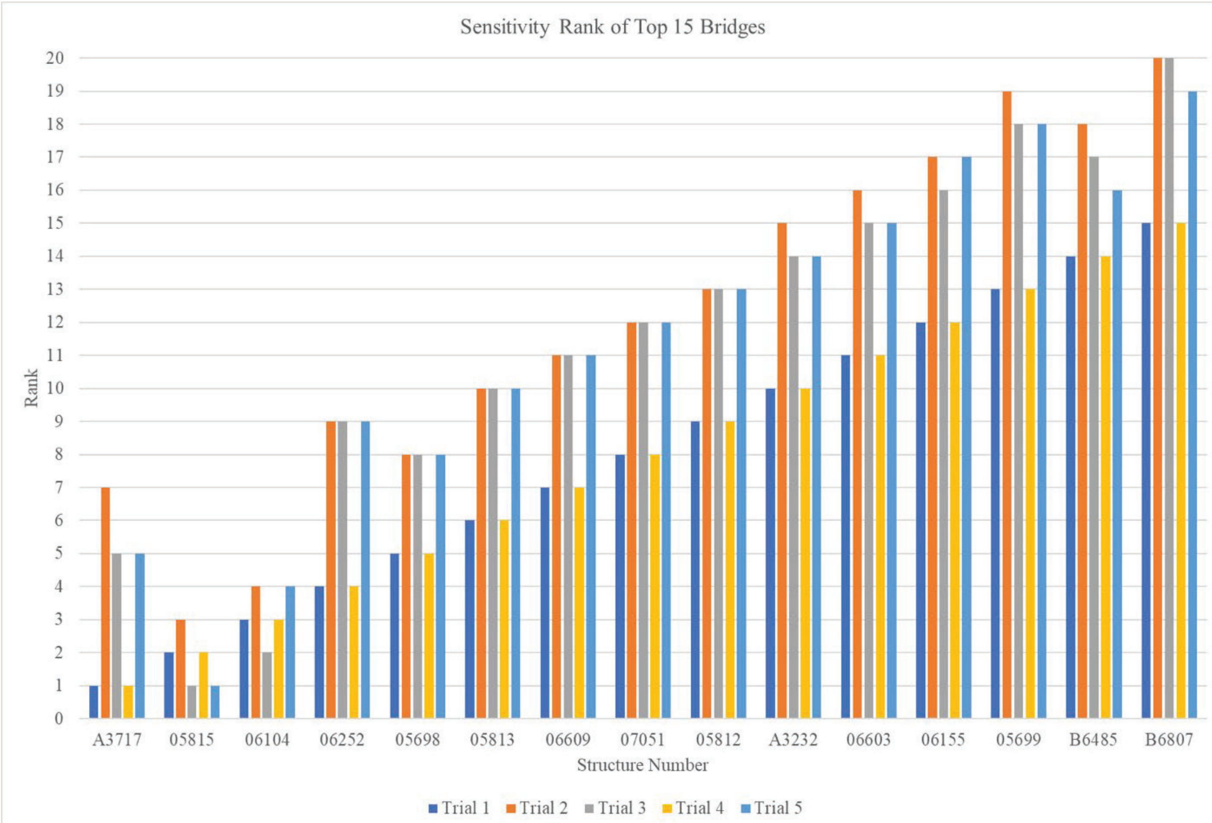


Figure 32. Sensitivity Ranking for the Top 15 Bridges for Trials 1-5

The rank sensitivity for Trials 6 and 7 is shown in **Figure 33**. The figure excludes bridges 06325 and 06469 since they are unique to their respective trial approach.

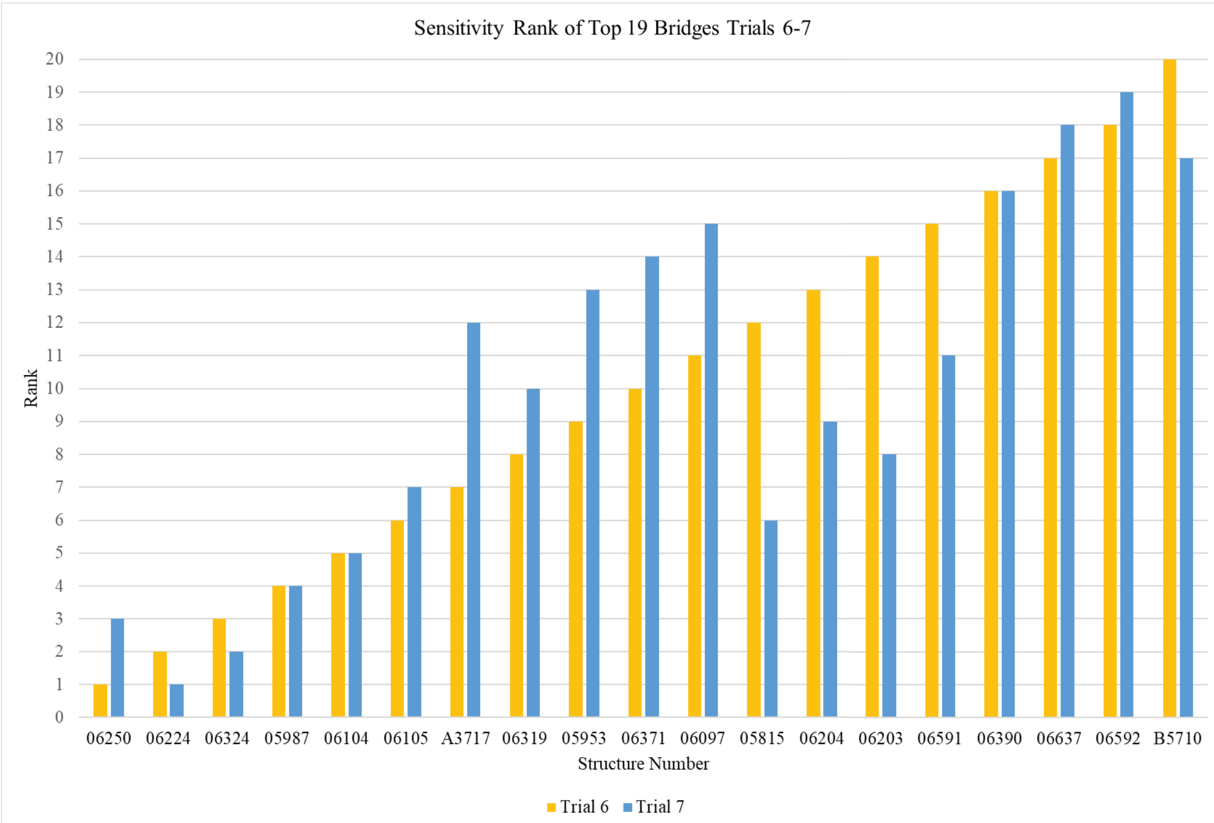
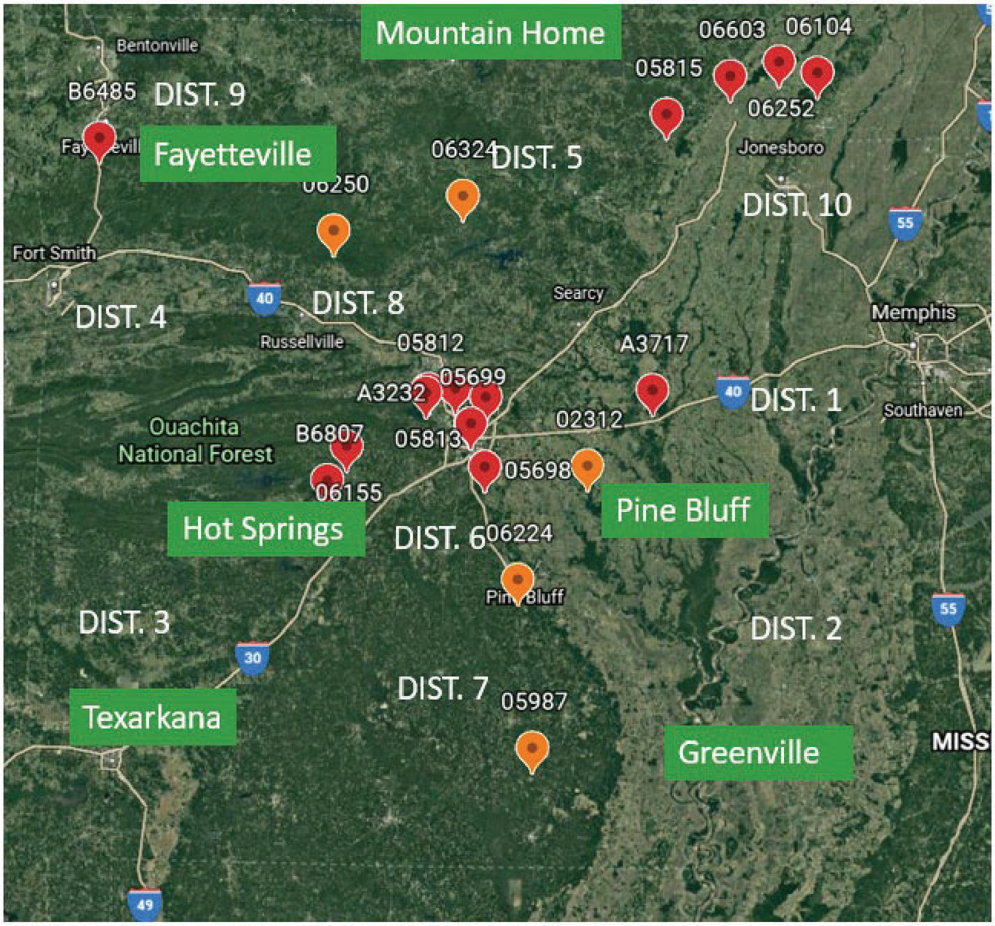


Figure 33. Sensitivity Ranking for the Top 19 Bridges for Trial Approaches 6 and 7

The bridges from **Table 9** were mapped to identify possible trends between the bridge location and ranking. The bridge locations for the top 20 bridges using Trials 1 through 5 are shown in **Figure 34**. These bridges are concentrated in Little Rock and Jonesboro, which are metropolitan areas. Little Rock is the largest city in Arkansas, and Jonesboro is the fifth largest.



Bridges	Color
Repeated in all 5 trials	
Repeated in 3-4 trials	

Figure 34. Top 20 Bridge Locations for Trials 1-5

Trials 6 and 7 disregard the significance of CS 1 and CS 2. The top 20 bridges using Trials 6 and 7 are mapped in **Figure 35**. These bridges are more uniformly distributed throughout the state compared to the Trial 1 through 5 bridges shown in **Figure 34**. The ranking results demonstrate the sensitivity of including CS 2 in the analysis.

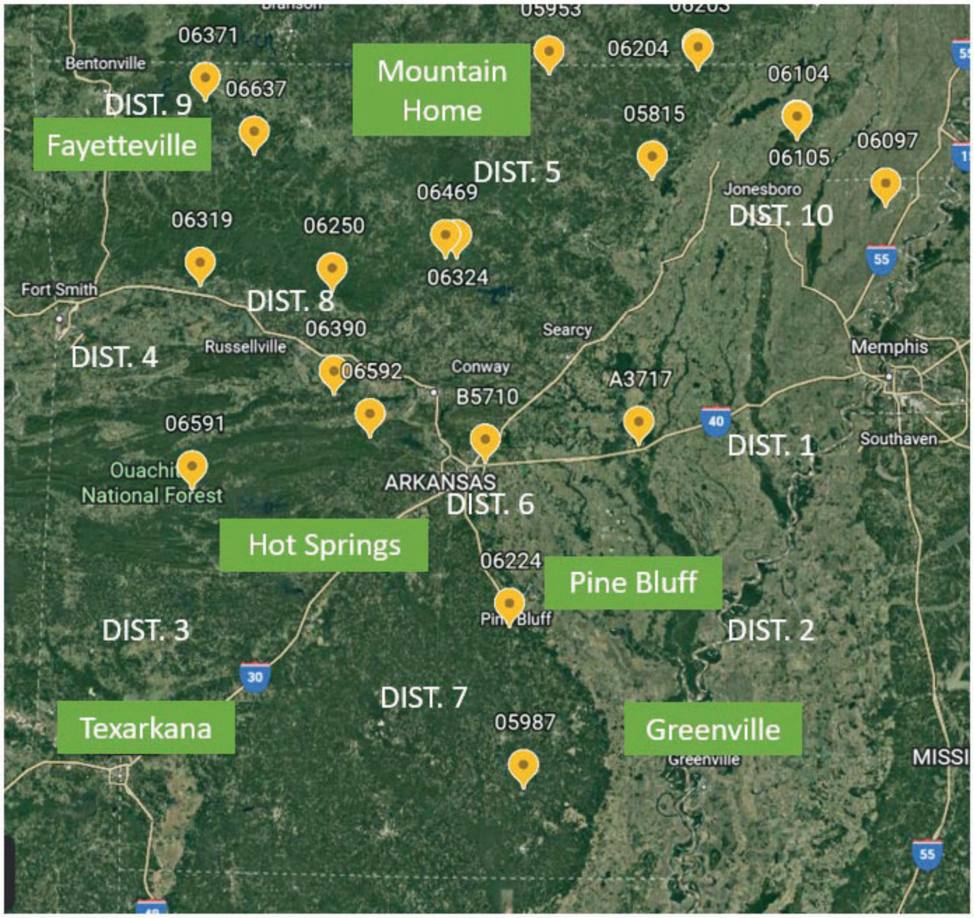


Figure 35. Top 20 Bridge Locations for Trials 6 and 7

CHAPTER 9. EVALUATION OF THE UWS BRIDGE INSPECTIONS

From Trials 1 through 5, six bridges were selected for inspection during the March 23-25, 2022, bridge tour. The bridges included four multi-simple span bridges and two continuous girder bridges, as shown in **Table 10**. The four multi-simple span bridges cross water.

Table 10. Bridge Characteristics in March Inspections

Bridge No.	Type of Bridge	Near Water	No. of Sealants Damaged / Total	Location of Degradation
05812	muti-simple span	yes	2/6	abutments & inside girder
05813	muti-simple span	no	4/7	one abutment
06609	muti-simple span	yes	3/5	one abutment
06224	muti-simple span	yes	2/4	under flanges
A3232	continuous	no	na	abutments & inside girder
02312	continuous	yes	debris	CS 1 & CS 2 on outside

Bridges in two districts were included during the March 2022 bridge tour that helped to evaluate bridge inspection recording consistency among the districts, **Figure 36**. ARDOT Research staff were on-site at each bridge inspection conducted during this research study.

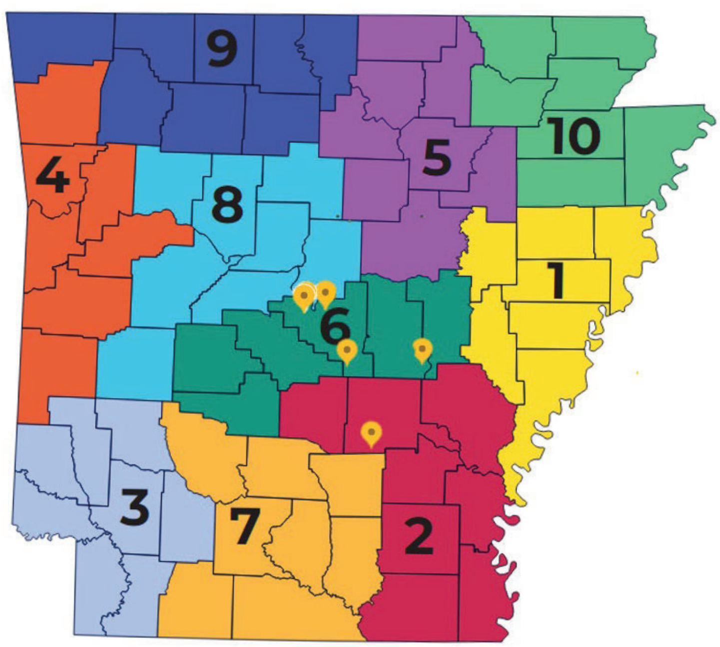


Figure 36. ARDOT District Locations of the Six Bridges

Various testing approaches were tried in order to establish a preliminary UWS inspection protocol. The testing methods included visual inspection, tape adhesion testing, eCHLOR* extract testing, and photography. The patina performance and condition were recorded using photos and notes. Assigning the oxide film CS was based on color, texture, and rust flake size. The major objective of this March bridge inspection tour was to develop a protocol that would ensure consistent visual oxide film rating throughout the ARDOT Districts. During the March tour, bridge girder condition was documented to study oxide film degradation rates among bridge inspections. These photos and notes were organized in files to be used as reference for future bridge inspections, **Figure 37**.

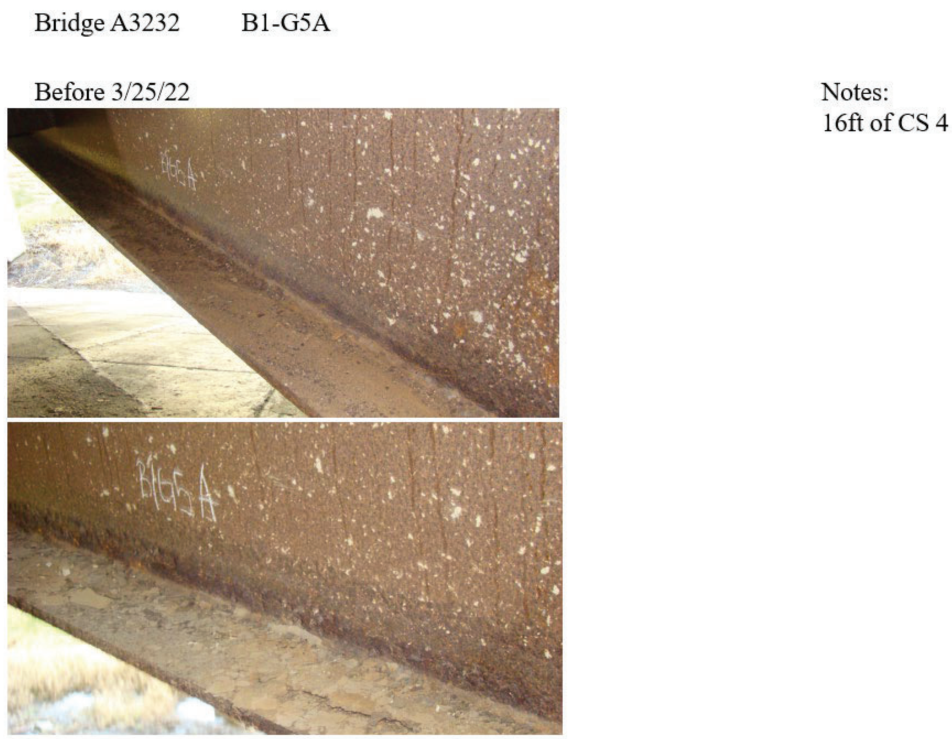


Figure 37. Before and After Cleaning Rust Flakes

An objective during this field inspection work was to prioritize the significance of oxide film CS and investigate the similarities among the inspected bridges experiencing oxide film degradation. At each bridge site, the research team recorded the location, bay, girder, and length of the girder experiencing oxide film degradation. Noticeable deficiencies in the inspected bridges were damaged strip seal expansion joints and bridges having low water clearance, **Figure 38**. In addition, downside girders at superelevated bridges experienced excessive corrosion due to high surface water runoff. Typically, water runoff drains through parapet drainage openings. However, these openings were sometimes clogged to prevent proper water runoff. Whereas fascia girders exposed to the sun dry quickly after rainstorms, interior girders experience extensive wet periods, resulting in corrosion.

Figure 38. Bridge 05812 over Water

During the March tour, the bridge inspection started with a walkthrough above the bridge deck to identify bridge deck problems. Some noticeable patterns among the bridges included compression seals at expansion joints being consistently damaged, the bridge crossing water, the bridge being skewed, the bridge being sloped, and the bridge consisting of short multi-simple spans. Each bridge compression joint seal was evaluated based on its condition and the amount of collected debris, **Figure 39.**

(a) Asphalt in Joint Sealant

(b) Damaged Sealant and Debris

(c) Asphalt Damage

(d) Missing Sealant

Figure 39. Different Damages at Joint Sealants

Afterward, the bridge deck was inspected from below to verify if the issues above it correlated with compromised girder conditions below it. For four of the six bridges, CS 1 and CS 2 were present at most bents and within the spans; CS 4 was identified at limited locations. Bridge 06609 in Woodson displayed CS 4 at only Bent 5, Bay 1, but displayed CS 1 and CS 2 at the remaining bays and bents. This correlated well with the damaged expansion joint right above the deteriorated section. Some contributing factors to corrosion include the bridge slope and surrounding water. Bridge 06609 displayed similarities to the other bridges that were inspected during this March inspection tour. When the girders and bays were analyzed, it was noted that the bridge girders were primarily experiencing CS 2 oxide film degradation and that severe CS 3 and CS 4 were limited to small girder sections, as shown in **Figure 40, Figure 41,** and **Figure 42**.

Figure 40. Bridge 02312: CS 2 Under Flange

Figure 41. Bridge 02312: CS 1 and CS 2 on the Outside Web and Flange

Figure 42. Bridge 05812: CS 2

After reviewing the first six bridges, it was evident that ranking them using the weighted factors in Trials 1 through 5 was biased by including all condition states (CS 1 through CS 4). In response, Trials 6 and 7 were developed, considering only CS 3 and CS 4. The new ranking from Trial Approaches 6 and 7 was used in selecting future bridges for field inspection. The bridges inspected based on the two new trial approaches showed a significantly different representation of the oxide film degradation severity over those inspected using Trials 1-5.

After Trials 6 and 7's development, a new set of bridges was listed for the June 2022 inspection. A total of 15 bridges were selected for inspection during June. Their locations are shown in **Figure 43**, including their respective ARDOT District. The 15 bridges include four ARDOT Districts.

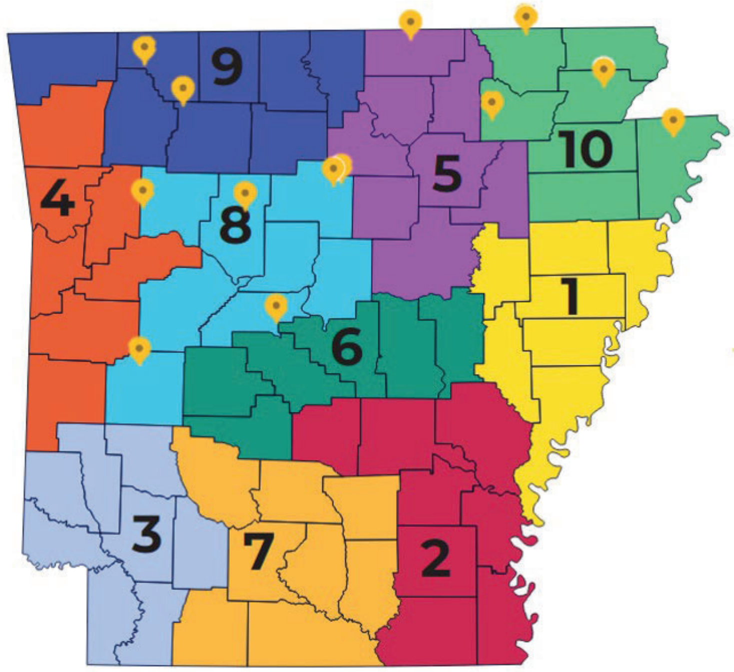


Figure 43. June 2022 Inspection Locations

All 21 UWS bridges that were inspected during March and June are shown in **Figure 44**.

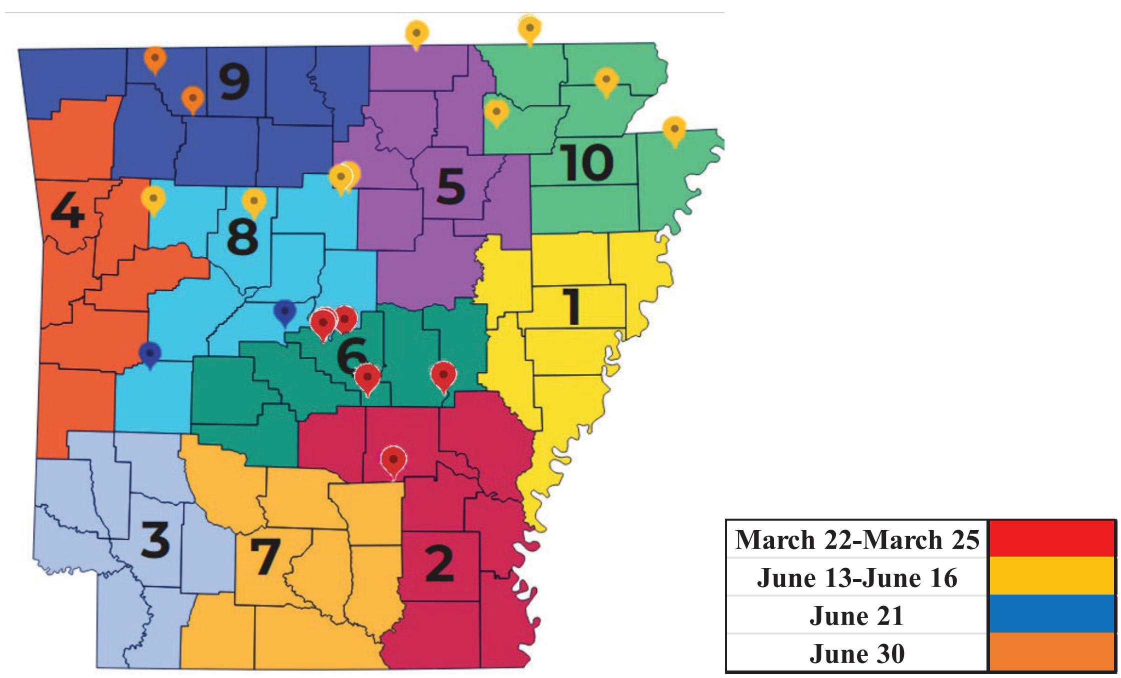


Figure 44. March and June Inspections

During the June inspections, a revised inspection approach was adopted due to time restraints. The revised approach considered the general bridge oxide film condition at the bridge site rather than recording the condition state at each bridge element since this information is already available from ArDOT bridge inspection reports.

Of the bridges visited during the March and June trips, 17 were short multi-simple span bridges crossing water. Conversely, four of the 21 inspected bridges (02312, A3232, 05815, and 06371) were continuous girder bridges. The continuous girder bridge, 06371, which is located near Kings River, showed extensive degradation and damage. The compression joint seal at Bent 1 was noted to be damaged with concrete spalling at the expansion joint. Underneath the bridge deck where the spalling occurred, there was noticeable degradation at the girder web and bottom flange. After the 21 bridge inspections, there were many similarities in oxide film behavior noted between the multi-simple span bridges and continuous girder UWS bridges. Oxide film degradation occurred underneath expansion joints and was most severe at the abutments. Also, water likely drips along the girder web and corrodes the girder web and bottom flange where there is parapet concrete spalling or a bridge deck overhang lacking a drip groove, as presented in **Figure 45**.

Figure 45. Bridge 06371: CS 2 and CS 3 on Web

Bridge 06319, located in Hunt, AR, is a multi-simple span bridge representative of the bridges inspected in June. **Figure 46** through **Figure 48** show the oxide film condition at multiple locations typically found to experience oxide film degradation.

Figure 46. Bridge 06319: CS 3 +

Figure 47. Bridge 06319: CS 3 and CS 4 on Interior Girder

Figure 48. Bridge 06319: CS 3 and CS 4 near End Abutment

A summary of the damage related to oxide film degradation is listed in **Table 11.**

Table 11. Bridge Characteristics in June Inspections

Bridge No.	Type of Bridge	Near Water	No. of Sealants Damaged / Total	Location of Degradation
05815	continuous	yes	1 damaged	web/under flange
06371	continuous	yes	1/4	web/under flange/interior girders
06592	multi-simple span	yes	0/4	under flange
06469	multi-simple span	yes	3/6	outside girder
06203	multi-simple span	yes	debris	abutments
06204	multi-simple span	yes	1/6	abutments/under flange
06319	multi-simple span	yes	1/5	abutments
06104	multi-simple span	yes	debris	abutment/interior girder
06105	multi-simple span	yes	debris	abutment
06097	multi-simple span	yes	debris	exterior web/inside girder
06324	multi-simple span	yes	4/7	under flange/inside girder
06250	multi-simple span	yes	1/11	Bent 6/11
06637	multi-simple span	yes	1/6	one abutment
05963	multi-simple span	yes	4/6	interior bents
06391	muti-simple span	yes	9/13	under web

CHAPTER 10. UWS BRIDGES INCORPORATING SEISMIC DESIGN

Four additional UWS bridges (07225, 07355, A6401, and B6401) were inspected in March 2023. These bridges were considered to examine possible correlations between oxide film degradation and weathering steel encased in concrete. The bridges were all located within ARDOT District 10, where seismic bridge design is required. Bridges 07225 and 07355 include integral abutments. Conversely, bridges A6401 and B6401 did not use integral abutments but were designed using concrete diaphragms and a "transverse bumper plate device" connected to each fascia girder to control transverse movement. Bridge locations are shown in **Figure 49.**

Figure 49. March 2023 Bridge Inspection Locations

Two bridges (07225 and 07355) were inspected on March 27, and two bridges (A6401 and B6401) were inspected on March 28. **Table 12** includes a description of each bridge and the level of oxide film degradation identified by ARDOT bridge inspectors at these bridges. All bridges were built using continuous wide flange girders. Severe oxide film degradation was limited to sections adjacent to the abutments. Implementing an integral abutment design negates the need for a compression strip seal joint at the abutment. Consequently, bridges A6401 and B6401 did have compression strip seal joints at the abutments, whereas bridges 07225 and 07355 did not. Each bridge is described in the following sections.

Table 12. March 2023 Bridge Descriptions

Inspection Date	Bridge No.	Highway	Features Intersected	Year Built	Bridge Description		Labeled as Bent 1	Oxide File Area (ft^2)	Oxide Film Degradation (ft^2)			
					# spans	# girders			CS 1	CS 2	CS 3	CS 4
3/27/23	07225	SH 148	Clear Lake	2012	3	4	East Abut.	4384	4357	0	0	27
3/27/23	07355	SH 140	Left Hand Chute Little River	2018	3	5	East Abut.	7212	7123	0	0	89
3/28/23	A6401	I-555	Big Bay Ditch	1992	3	6	South Abut.	8865	8712	0	153	0
3/28/23	B6401	I-555	Big Bay Ditch	1992	3	6	South Abut.	8678	8351	0	327	0

10.1 BRIDGE 07225

Bridge 07225 is a three-span bridge and consists of four W27x84 continuous girders, as shown in **Figure 50**.

Figure 50. North Side of Bridge 07225

The bridge is designed using integral abutments. Therefore, each girder extends beyond the abutment surface and is enveloped by concrete to prevent lateral and longitudinal movement. Oxide film degradation was limited to Girder 3 at Bent 1 (east abutment). Efflorescence staining was noted at the girder-abutment interface, **Figure 51** (a). Oxide film degradation at the girder extended along the top and bottom of the bottom flange, **Figure 51** (b).

(a) **Efflorescence at Girder-Abutment** **(b) Bottom of Bottom Flange**

Figure 51. Oxide Film Degradation at Girder 3, Bent 1

The area adjacent to the bridge was muddy when the TRC2103 research team inspected Bridge 07225, **Figure 52**. In addition, the clearance between the ground and the girder base was minimal. Riprap was especially large underneath Bent 1, Girder 3. These conditions suggest that the river rises to a level that causes the water to splash or contact the girder during rainy seasons. A marsh exists northeast of the bridge in proximity. During heavy rainfalls, this marsh likely overflows into the river along the bridge's east abutment, thus resulting in additional wet conditions for the east abutment girders. Although water seeping through the concrete integral abutment causes efflorescence and water contact with the girder, the nominal clearance between the river and girders is more likely to be the cause of the oxide film degradation.

Figure 52. Bridge 07225 Viewing East Abutment from Southside of Bridge

10.2 BRIDGE 07355

Bridge 07355 consists of five three-span continuous girders. Each girder is a W27x114. The bridge is designed using integral abutments. Oxide film degradation was limited to Girder 3 and Girder 4 at Bent 4 (west abutment), **Figure 53**.

Figure 53. Bridge 07335, North Side of Bridge Looking East

Severe oxide film degradation at a CS 4 level was noted at Girder 4, Bent 4, **Figure 54**.

Figure 54. Bridge 07335, Girder 4, Bent 4

Oxide film degradation extends along the bottom flange, **Figure 55,** and efflorescence was identified at the abutment-girder interface, **Figure 56**.

Figure 55. Bridge 07335, Bent 4, Girder 4, Bottom of Girder Flange

Figure 56. Bridge 07335, Bent 4, Girder 4, Efflorescence Close-up

Oxide film degradation extended along the bottom flange to the diaphragm connection, **Figure 57**. The diaphragm connection detail traps water at this joint.

Figure 57. Bridge 07335, Bent 4, Girder 4, Corrosion at Diaphragm Connection

Figure 58 shows the north side of Girder 3 at Bent 4. The figure shows efflorescence at the girder web-abutment interface and oxide film degradation on the girder web adjacent to the abutment face.

Figure 58. Bridge 07335, Bent 4, Girder 3

Figure 59 shows the height of the river at the time of the inspection. Having trees that are found partly underwater implies that the river experiences significant level changes. The level and extensiveness of the oxide film degradation in the abutment area were most likely due to inadequate clearance between the river surface and bridge superstructure rather than the bridge's seismic design.

Figure 59. Bridge 07335, View of River Looking South from Bridge

10.3 BRIDGES A6401 and B6401

Bridges A6401 and B6401 are parallel bridges located on Interstate 555 (I-555) north of Trumann, AR. I-555 southbound traffic crosses the Big Bay Ditch over A6401, and northbound I-555 traffic crosses the Big Bay Ditch over B6401, **Figure 60**. The design of both bridges is similar. Each bridge is a three-span continuous girder bridge with a 175 ft (53.4 m) girder length. The cross-section consists of six W27 x 94 girders.

(a) A6401 **(b) B6401**

Figure 60. Bridges over Big Bay Ditch Looking North from South Abutment

The bridges were designed to satisfy the region's seismic requirements. Consequently, seismic restrictive devices were implemented at the bridge structures. These devices are used to restrict bridge superstructure longitudinal and transverse displacement. In contrast to the previously discussed Bridge 07225 and Bridge 07335, the bridges at this location use a girder abutment detail that restricts transverse displacement without embedding the girder into the abutment rather than using integral abutments, **Figure 61**.

Figure 61. Girder Support at Fascia Girder

At the interior bents, a transverse bumper device attached to each fascia girder was used to prevent transverse movement, **Figure 62**. In addition, longitudinal restraint devices were attached to each of the girders.

Figure 62. Bridge A6401. Seismic Restrictive Devices Used at Piers

The bridge deck strip seal joints above the abutments were in poor condition but were not missing or dislodged. Even though the strip seals were in place, a significant amount of collected debris was noted at the abutments, **Figure 63**, implying that the river rises to the level of the girders.

Figure 63. Debris at South Abutment (Bent 1)

The muddy embankment conditions at these bridge sites also suggest that the river rises to high levels. The embankments provide minimal clearance between the superstructure base and the ground surface to allow for proper water flow. In addition, the embankments were layered at the north abutment with riprap that decreased the clearance, **Figure 64**.

(a) Bridge A6401 at South Abutment **(b) Bridge B6401 at North Abutment**

Figure 64. Minimal Clearance Between Bridge Superstructure and Ground Surface

Oxide film degradation was noted at both bridges but was limited to the abutments. While A6401 oxide film degradation was limited to two girders at the north abutment, the degradation at B6401 was more extensive, including the north and south abutments. The locations of the oxide film degradation at the bottom of the bottom flange, the amount of collected debris at the abutments, and the length of girder experiencing corrosive area, **Figure 65**, suggest that the corrosion was due to the high water level attained during rainy conditions. In additon, the minimal ground to girder clearance and the detail used at the abutments significantly limit airflow in these areas, which is warranted to prevent oxide film degradation.

(a) Web-Flange Interface **(b) Bottom of Bottom Flange**

Figure 65. Oxide Film Degradation at B6401, Bent 1, Girder 2 East Side

CHAPTER 11. FIELD TESTING METHODS FOR OBJECTIVE PERFORMANCE MEASUREMENTS

For the evaluation of the weathering steel patina's performance, more in-depth inspection includes tape-adhesion testing and chloride testing. Tape adhesion testing is based on ASTM D3359 procedures. The tape strip is measured to approximately 8 to 10 inches (203.2 mm to 254.0 mm) long and is pressed for one minute onto the bridge girder section being analyzed. For best results in collecting rust flakes, the tape strip is removed at a steep angle to the girder surface. The tape strip is then placed in wax paper and kept inside a clear sample bag for future analysis of rust flake size and density. Rust flakes should be measured to the nearest 0.02 inches (0.5 mm).

The eCHLOR*TEST is used for determining the chloride concentration on the bridge girder surface, **Figure 66**. The procedure includes preparing the surface, applying a chloride extract solution to the test specimen, and analyzing the chloride extract solution for chloride content. The test surface is first cleaned. A wire brush is sometimes used to help improve the surface smoothness. The testing involves pouring a chloride extract mixture into a latex CHLOR*SLEEVE. After most of the air is squeezed from the sleeve, the adhesive ring at the sleeve opening is pressed firmly onto the test surface. It is important that the adhesive is securely attached to the test surface; otherwise, the extract solution will seep out. The sleeve is massaged so that the extract solution contacts the test surface for a minimum of two minutes. When the sleeve is removed, the extract solution is funneled through an auto vial filter to remove floating particles. The chloride extract solution is tested using the eCHLOR*TEST meter. Test results are displayed in parts per million (ppm). Results from 1-2 ppm correspond to low amounts of chlorides. Conversely, 3-5 ppm correspond to high chloride concentration (Crampton et al. 2013). Bridge 06105, located in north Pulaski County, AR, near the Oak Grove community, was measured at two ppm chloride concentration. Like Bridge 06105, most bridges visited during the bridge tours are in rural areas and were therefore not subjected to deicing treatments. In contrast, bridges in highly populated areas will be more likely treated with deicing chemicals. Consequently, bridges in urban areas will typically demonstrate high chloride concentrations. Because of corrosion, attaining proper adhesion between the sleeve and test surface was challenging, resulting in leaking chloride extract solution at the interface surface. Therefore, the eCHLOR*TEST was primarily limited to the lab component of this study.

Figure 66. Field eCHLOR*TEST Testing

CHAPTER 12. LAB TESTING

The research study lab testing component included accelerated corrosion testing to explore the effect of orientation angle and surface coating protection on corrosion development. A total of three surface coatings (bare steel, half coated, and fully coated) and four orientation angles (0°, 45°, 70°, and 90° relative to the horizontal plane) were considered for a total of 12 accelerated corrosion specimens. All specimens considered were ASTM A709 Gr50W steel plates. Each steel plate surface was blast-finished prior to the accelerated corrosion testing to replicate the surface finish of a UWS bridge, **Figure 67.**

Figure 67. Bare Weathering Steel Plates

To execute the accelerated corrosion testing, plates at each orientation angle were separated into four separate bins and subjected to continuous wet-dry cycles through periods of misting with an NaCl solution followed by a period of drying. **Figure 68** shows the experimental setup for the accelerated corrosion testing, as well as the plate coating conditions and orientations considered. As shown in **Figure 68**, a timer was used to circulate a five percent NaCl solution by weight (following ASTM G85-19) every 1.5 hours for 30 minutes allowing one hour of drying time between spray sequences. **Figure 69** shows the various plates oriented at the four different angles relative to the spray nozzles. The testing was specifically designed to determine if partially painted (similar to the conditions present on end-region coating) and fully painted surfaces adequately protect UWS from salt solution penetration. The experiments started on August 23, 2022, and results were monitored for eight weeks. The test was monitored regularly (tubs were checked three times per week) to ensure a minimum depth water level required for the intake pumps to develop proper nozzle spraying. If needed, water or salt was added to ensure consistency of five percent saltwater concentration. Saltwater spray was restricted to each tub using a plexiglass barrier between the tubs. Because of salt particles, the spray nozzles needed to be regularly cleaned and washed to ensure proper spraying.

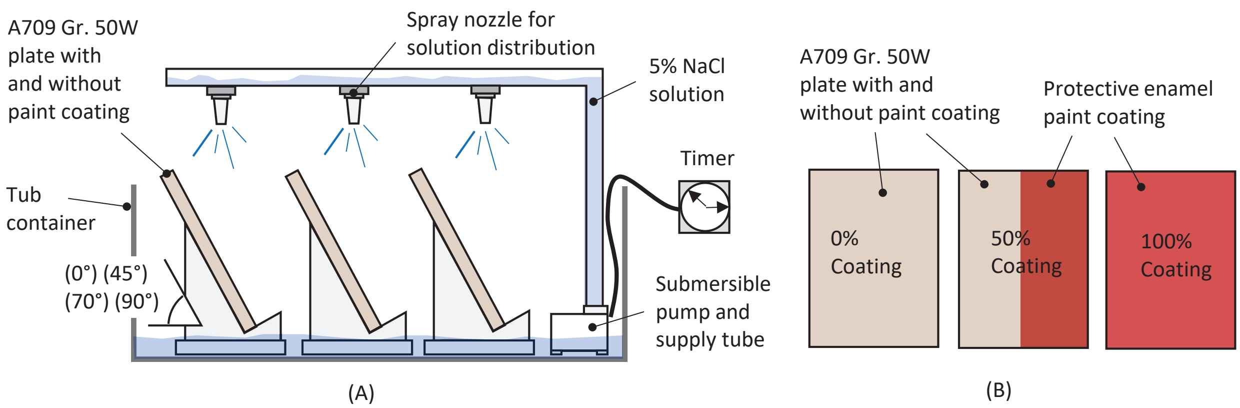


Figure 68. Experimental Setup for Accelerated Corrosion Testing

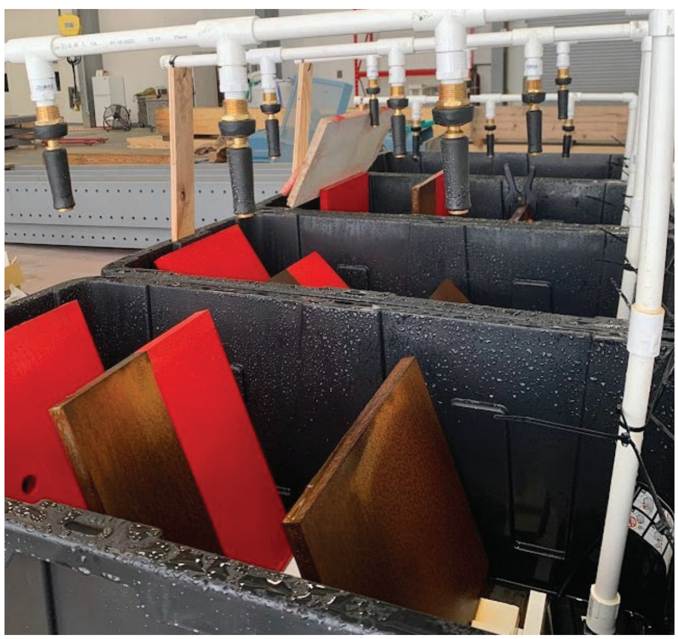


Figure 69. Weathering Steel Plates in the Four Orientations

To measure the chloride concentration on the weathering steel plate surfaces, chloride testing was attempted on the weathering steel plates using the eCHLOR*TEST. The surface was wet when the test was first attempted, causing problems with the adhesive on the test sleeve to not properly adhere to the steel plate surface. Therefore, the steel plates were allowed to dry for six hours to promote a dry surface for better adhesion. After six hours, another attempt to attach the latex sleeve to the surface was made; however, the extract solution continued to leak. Glue was applied to the sleeve in another attempt for better adhesion; however, rust continued to flake off the steel plate, preventing proper adhesion, **Figure 70**. Another attempt was made after two weeks of drying. Two attempts were made on the horizontal bare steel plate; nevertheless, the plate had developed a surface condition, preventing the extract sleeve from properly adhering to the plate. Instead, the vertical steel plate was tested. The vertical steel plate surface allowed the sleeve to adhere to the steel plate. The chloride concentration was measured successfully on this plate at 10 ppm. This value is significantly greater than what is considered a high chloride concentration, 3 – 5 ppm (Crampton et al. 2013). Consequently, the 10 ppm chloride testing result reflects the severity of the five percent chloride solution used on the lab tested plates.

Figure 70. Horizontal Weathering Steel Plate After Eight Weeks

The surface corrosion progress was recorded over the eight-week test period in a series of photos to show the oxide film degradation progression and evaluate the benefits of a paint coating, **Figure 71** to **Figure 74.** As might be expected, providing a paint barrier between the chloride solution and steel surface delayed the onset of surface corrosion. In the experiments, the painted steel surfaces had delayed corrosion compared to the bare steel surfaces; with partially painted steel experiencing a delay that fell between the bare-steel and fully painted specimens.

Orientation angle also affected the rate of corrosion, with the horizontal plates (oriented at 0° relative to the horizontal) showing the most accelerated corrosion out of the four different angles considered. At the end of the eight-week test period, degradation of the coating material was also most apparent on the horizontal (0° orientation) plates compared with the other orientations. Comparing the bare horizontal plate with the bare vertical plate demonstrates the significance of the bridge girder component orientation (flange vs. web).

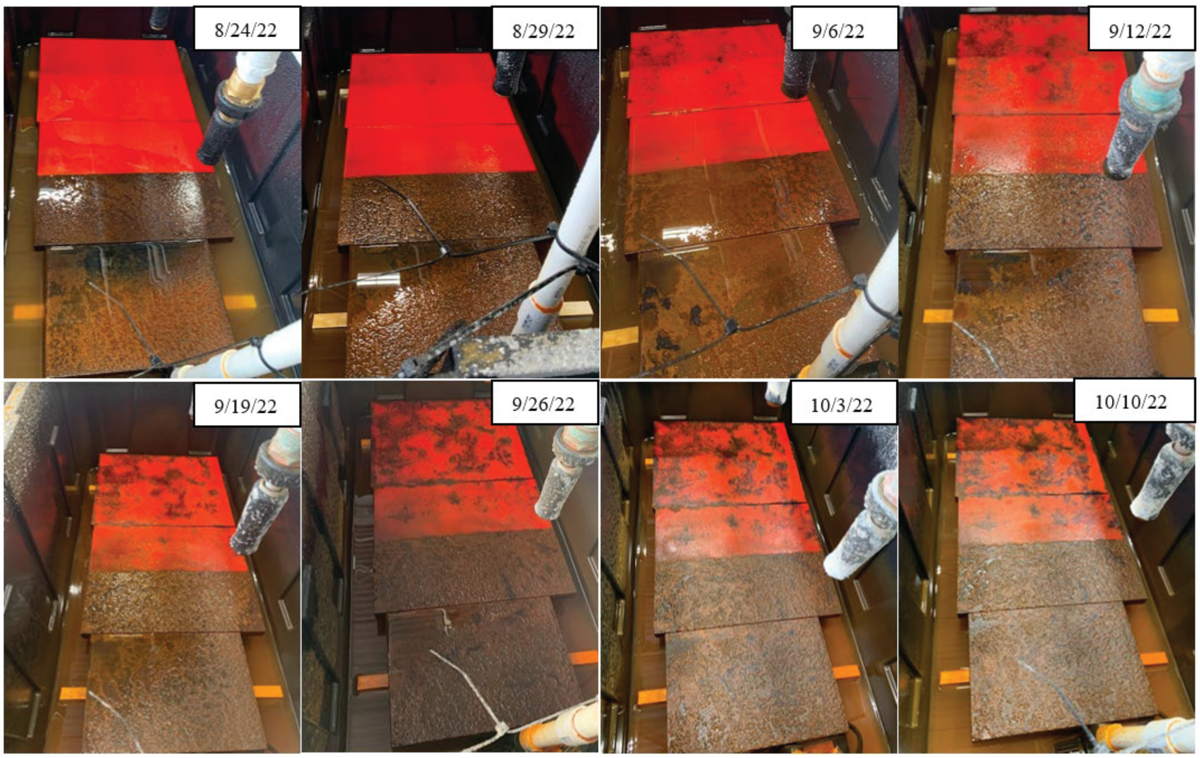


Figure 71. Horizontal Weathering Steel Plates Eight-Week Timeline

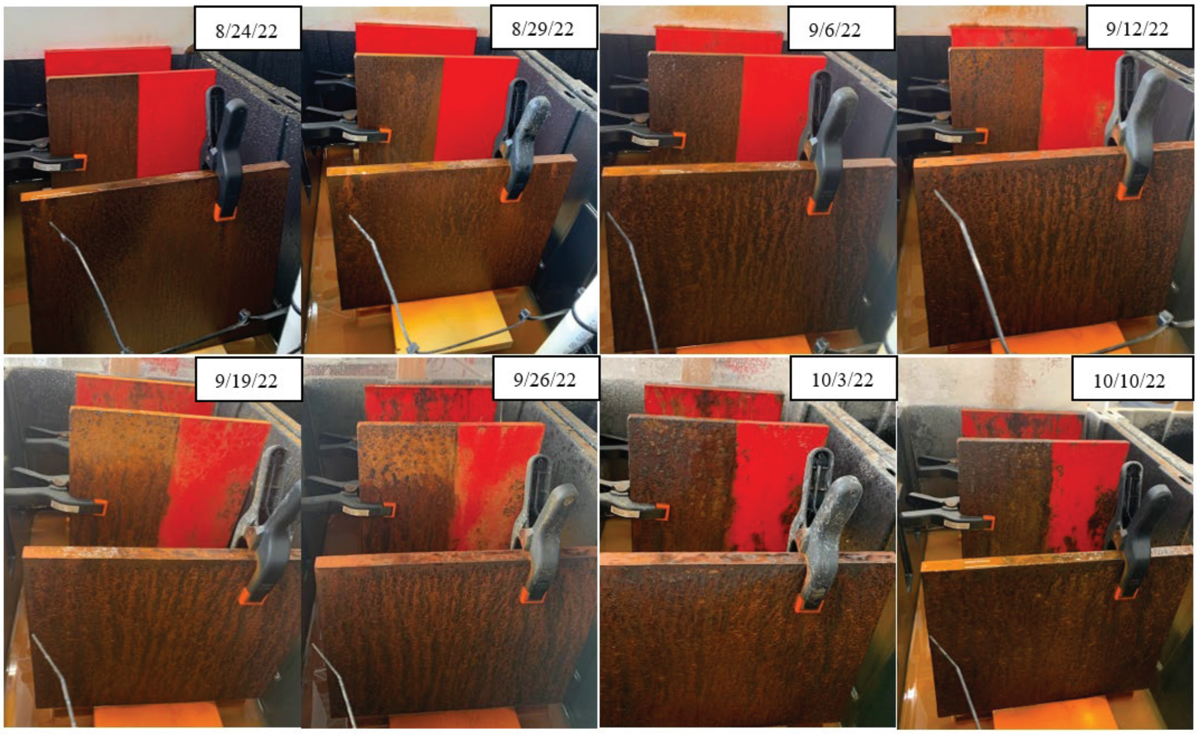


Figure 72. Vertical Weathering Steel Plates Eight-Week Timeline

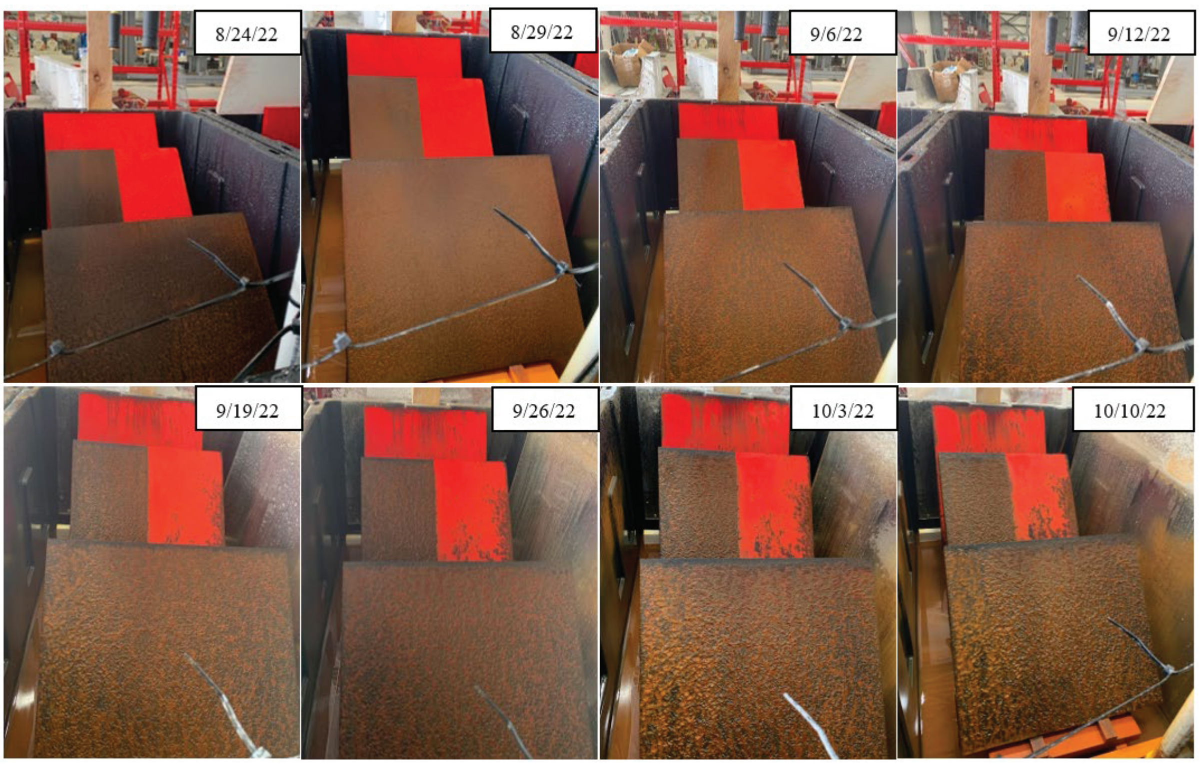


Figure 73. (45° Angle) Weathering Steel Plates Eight-Week Timeline

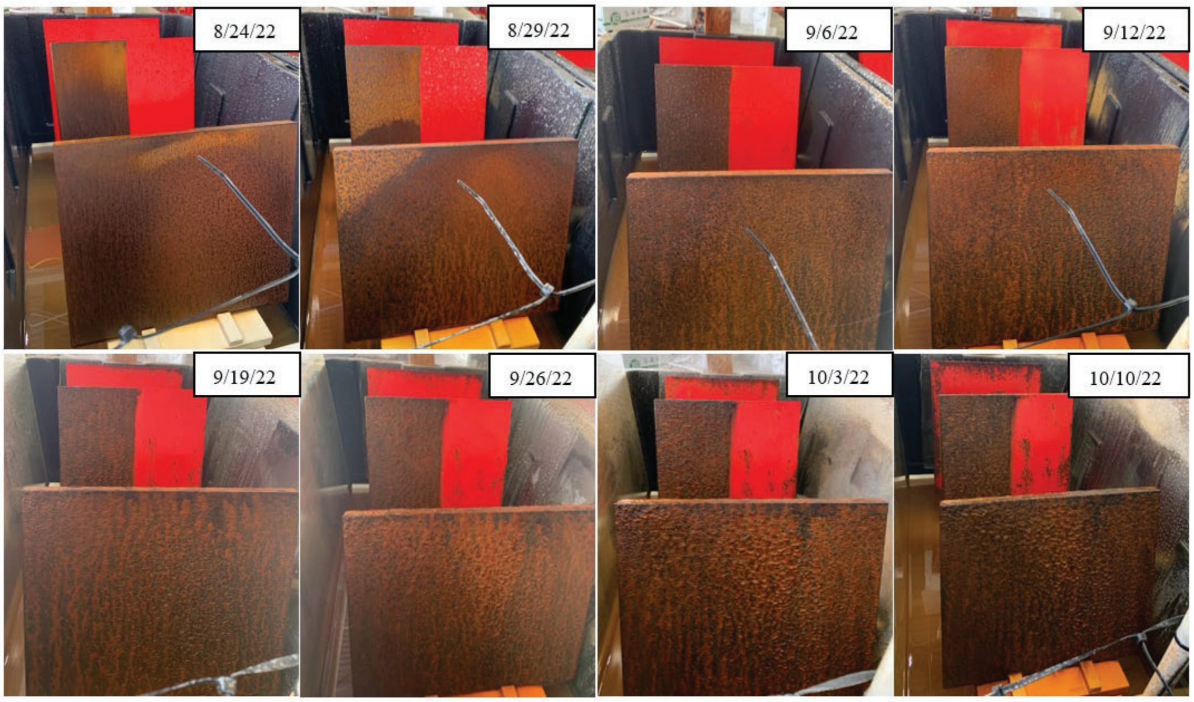


Figure 74. (70° Angle) Weathering Steel Plates Eight-Week Timeline

CHAPTER 13. GUIDELINES FOR INSPECTING WEATHERING STEEL BRIDGES

The following guidelines were developed to assist ARDOT bridge inspectors in taking the necessary steps to recognize potential UWS girder problem locations and the information warranted for recording purposes. An option that inspectors should consider is whether using a UAS is advantageous and if so, what to look for when using the UAS. If the bridge is a tall structure and the bents are difficult to visually inspect, using a UAS is beneficial. When using a UAS, scanning the bridge understructure is necessary since oxide film degradation typically occurs near abutments and beneath bridge deck expansion joints. When using the UAS, recording screenshots, including Global Positioning System (GPS) coordinates of where the corrosion is located, is the most beneficial way of recording compromised UWS locations. Taking videos while using the UAS to supplement photos helps for an overview of the bridge condition; however, this option is memory intensive. Snapshots can be created from the video as well. Conducting adhesion testing and chloride testing provides additional objective measurements. However, chloride testing is difficult to conduct because of the roughened steel surface due to corrosion. Suggested inspection steps for recording oxide film degradation are summarized in flow chart form in **Figure 75**.

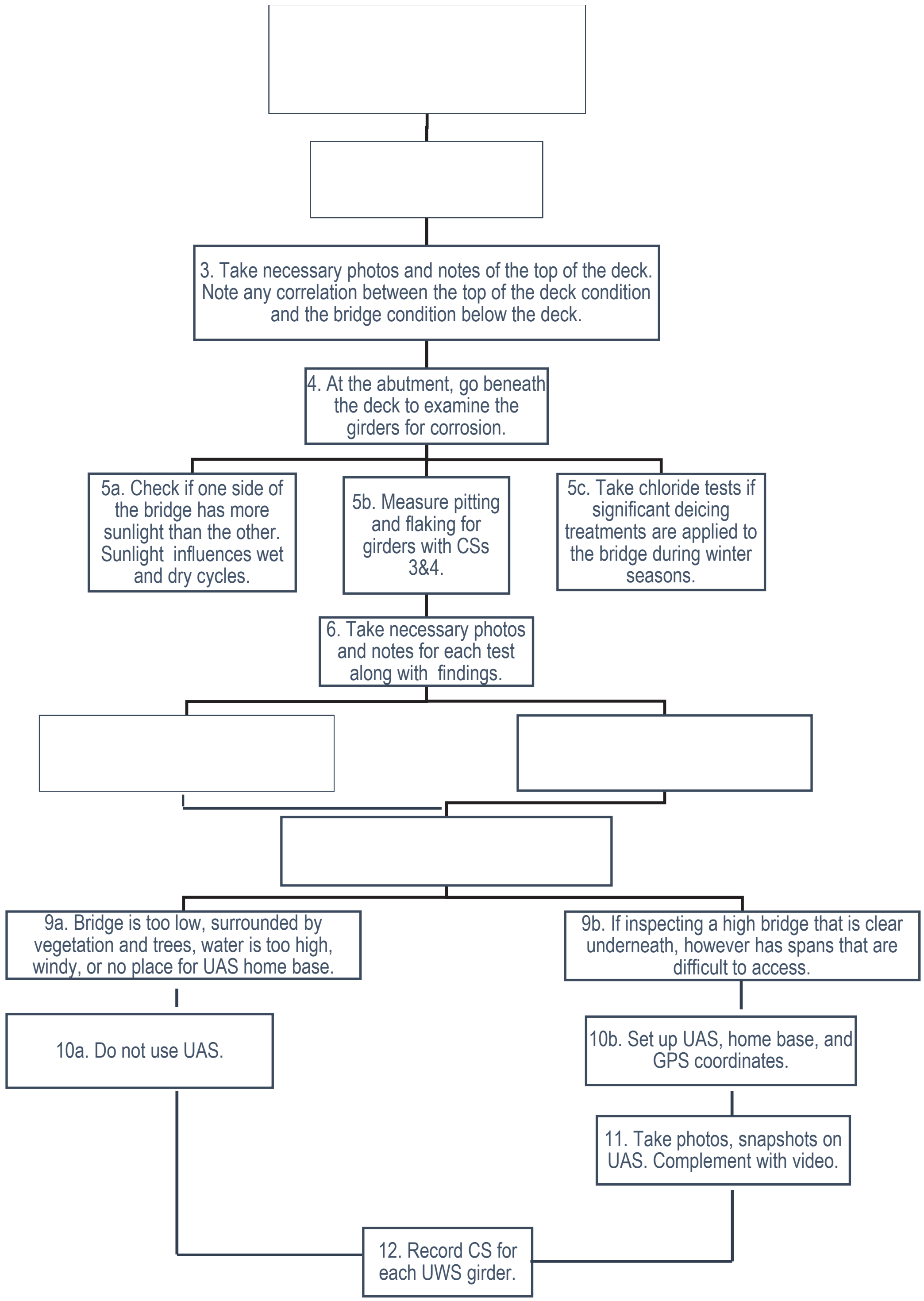


Figure 75. Inspection Steps for Oxide Film Degradation

CONCLUSIONS

During this TRC2103 research study, ARDOT UWS bridges experiencing extensive oxide film degradation were identified and ranked based on the degradation's severity. Of the 859 UWS ARDOT bridges, 71 (8.3 percent) experience extensive oxide film degradation. A life-cycle cost analysis is included in this report to demonstrate the benefits of UWS bridge usage over plain painted carbon steel and the cost benefits of incorporating a UWS maintenance program to remediate oxide film degradation. A survey of DOTs was included to view the recommendations from other state DOT programs that could be incorporated into the presented guidelines.

The protocol used to rank ARDOT UWS bridges for remediation based on oxide film degradation percentage was detailed. ArcGIS was used to display the relationships between ambient bridge condition and oxide film condition. In addition, these relationships were summarized in graphs. Clear trends between ambient bridge conditions on the macro level scale and the level of oxide film corrosion are indefinite. Similarities between the inspected bridges experiencing significant oxide film degradation include deteriorated and/or missing bridge deck compression strips seals, vegetation, and inadequate girder-water clearance. Deicing applications are minimal in Arkansas and, therefore, not a major contributor to UWS corrosion. A total of 25 UWS bridges were inspected during this study. The inspected bridges included four bridges in ARDOT District 10 that were built based on seismic design requirements. Two of these bridges use integral abutments while two use "transverse bumper plate devices." Concrete efflorescence was noted at the bridges that were constructed using integral abutments but was limited. The two bridges with an abutment design using "transverse bumper plate devices" result in a detail that restricts airflow and consequently proper wet-dry cycling.

A total of 20 bridges within Arkansas were prioritized for remediation based on the assumed weighted factors in this study as a function of oxide film degradation. Five different trial approaches were initially considered using weighted factors as a function of CS. However, after the first bridge inspection tour in March 2022, the approach was revised, and two more trials were developed for the inspection work conducted in June 2022. The two revised approaches were used during the June 2022 bridge inspection trips and proved to better identify bridges experiencing severe oxide film degradation. After the visit of 21 bridges in total during 2022, CS 4 was seen at most bridges. However, the functionality of these bridges is still viable, and it is important to note that no significant section-loss was identified. The CS ratings between the Districts were consistent.

Remedial repairs should include cleaning poor (CS 3) and severe (CS 4) girder areas at prioritized bridges based on their ranking, clearing vegetation, and/or adding elements to prevent prolonged direct water contact with the UWS. If the underlying causes of water contact cannot be addressed, an extra protective coating, such as paint or primer should be applied near problematic areas.

The objective of the field inspection work was to develop guidelines for inspecting weathering steel bridges. The guidelines were summarized as a flowchart for bridge inspectors to easily implement.

A UA was used to help in accessing bridge structural elements that would otherwise warrant special bridge inspection equipment. The benefits of using a UA with a zoom lens and spotlight were described.

Experimental lab testing examined the effects of subjecting weathering steel plates to an accelerated chloride testing using a five percent chloride solution. The testing was conducted over the course of eight weeks to bare, half-painted, and painted steel plates. Various plate orientations were investigated. While the experiment was monitored, the chloride solution was checked consistently to ensure a five percent solution by weight. Experimental data and photos were collected weekly. The photos were shown in the report in a timeline format to display how corrosion progresses. Corrosion was evident within a couple of weeks from when the experiment was initiated and worsened over time. The painted, half-painted, and bare plates all experienced corrosion. From the eCHLOR*TEST, the chloride concentration at the end of the eight-week lab test was higher than expected at 10 ppm.

REFERENCES

Adams, Teresa M., and Kang Myungook. *Sensitivity Analysis of Bridge Health Index to Element Failure Costs and Conditions.* No. MRUTC 08-07. Madison, Wisconsin: Wisconsin Department of Transportation, 2009.

Albrecht, P., and A. H. Naeemi. *A.H. Performance of Weathering Steel in Bridges.* National Cooperative Highway Research Program Report 272. Washington, D.C.: Transportation Research Board: 1984.

Albrecht, P., F. Coburn, M. Wattar, G. L. Tinkleberg, and P. Gallagher. *Guidelines for the Use of Weathering Steel in Bridges*. National Cooperative Highway Research Program Report 314. Washington, D.C.: Transportation Research Board: 1989.

American Association of State Highway and Transportation Officials (AASHTO). *Manual for Bridge Element Inspection (MBEI)*. Washington, D.C. (AASHTO, 2019).

American Association of State Highway and Transportation Officials / Federal Highway Administration (AASHTO/FHWA). *A User's Guide to Bridge Cleaning*, American Association of State Highway and Transportation Officials Transportation System Preservation Technical Services Program (TSP2), Federal Highway Administration Bridge Preservation Expert Task Group (BPETG), Washington, D.C., 2019.

Arkansas Department of Transportation (ARDOT). *Arkansas Department of Transportation Bridge Inspection Manual* , Accessed June 10, 2022. https://www.ardot.gov/wp-content/uploads/2022/05/ARDOT_BIM_20220507.pdf, 2022

Aulthouse, F. D. "Economics of Weathering Steel in Highway Structures.", FHWA Publ. FHWA-TS-89-016, Federal Highway Administration Forum on Weathering Steel for Highway Bridges, Alexandria, VA (1989).

Bao, Amanda, Caleb Guillaume, Christopher Satter, Alana Moraes, Peter Williams, Tucker Kelly, and Ying Guo. "Testing and Evaluation of Web Bearing Capacity of Corroded Steel Bridge Girders." *Engineering Structures*, vol. 238, Article 112276 (2021).

"ClimateData." U.S. Climate Data, Accessed June 10, 2021. www.usclimatedata.com.

CPI Inflation Calculator (2021). "Inflation Rate Between 1995-2021: Inflation Calculator." *$299 In 1995 → 2021 | Inflation Calculator*. 2021.www.in2013dollars.com/us/inflation/1995?amount=299.

Crampton, Douglas, Kurt Holloway, and John Fraczek. (2013). *Assessment of Weathering Steel Bridge Performance in Iowa and Development of Inspection and Maintenance Techniques*. Ames: Iowa Department of Transportation, 2013.

Federal Highway Administration (FHWA). *Improving Transportation Investment Decisions Through Life-Cycle Cost Analysis.* Accessed July 22, 2023, https://www.fhwa.dot.gov/pavement/lcca/lccafact/

Federal Highway Administration (FHWA). *National Bridge Inspection Standards.* McLean, VA: Office of Infrastructure Research and Development: 1989a.

Federal Highway Administration (FHWA). *Uncoated Weathering Steel in Structures.* Technical Advisory 5140.22. McLean, VA: Office of Infrastructure Research and Development: 1989b.

Helsel, J. L., R. Lanterman, and K. Wissmar. "Expected Service Life and Cost Considerations for Maintenance and New Construction Protective Coating Work." *Proceedings, Corrosion Conference and Expo, Vol. 4, 2438– 2459*, Association for Materials Protection and Performance (AMPP), (Houston, TX: NACE International, 2008).

Hopwood, Theodore, Palle Sudhi, Meade Bobby, and Younce Rick. *Evaluation of the Use of Painted and Unpainted Weathering Steel on Bridges*. KTC-16-09/SPR10-407-1F, Kentucky Transportation Center, University of Kentucky: (2016).

Kaur, Dhilvinder. "Development and Use of a GIS Database for the Evaluation of Uncoated Weathering Steel Highway Bridge Performance." Master's thesis, University of Delaware, 2014.

Kere, Kiswendsida J., and Qindan Huang. "Life-Cycle Cost Comparison of Corrosion Management Strategies for Steel Bridges." *Journal of Bridge Engineering*, vol. 24, no. 4, 2019.

Krivy, Vit, Monika Kubzoba, Katerina Kreislova, and Viktor Urban. "Characterization of Corrosion Products on Weathering Steel Bridges Influenced by Chloride Deposition." *Metals*, vol. 7, no. 9 (2017): 336

Kubzová, Monika, Vit Krivy, Vikton Urban, and Katerina Kreislova. "Corrosive Environment Factors and their Influence on the Development of Weathering Steel Corrosion Products.*" Key Engineering Materials*, vol. 832 (2020): 137-146*.*

McDad, Bashar, David C. Laffrey, Mickey Dammann, and Ronald D. Medlock. *Performance of Weathering Steel in TxDOT Bridges*. Texas Department of Transportation, 2000.

McEleney, Bill. "Weathering Steel, The Other Corrosion Protection System." Powerpoint*, Steel Bridge Forum, Raleigh, NC,* 14 September 14, 2011, https://connect.ncdot.gov/resources/Structures/Structures%20Seminars/09%20-%20Weathering%20Steel.pdf, 2011.

National Steel Bridge Alliance (NSBA). *Uncoated Weathering Steel Reference Guide.* American Institute of Steel Construction, 2022.

Nickerson, R. L. *Performance of Weathering Steel in Highway Bridges: A Third Phase Report.* Washington, D.C., USA: American Iron and Steel Institute: 1995.

Okasha, Nader M., Dan M. Frangopol, Fred B. Fletcher, and Alex D. Wilson. "Life-Cycle Cost Analyses of a New Steel for Bridges." *Journal of Bridge Engineering*, vol. 17, no. 1 (2012): 168–172.

"Relative Humidity in Little Rock, Arkansas, USA." Relative Humidity in Little Rock, Arkansas. Accessed July 21, 2021. www.little-rock.climatemps.com/humidity.php.

Shirkhani, Hamidreza, Jieying Zhang, and Zoubir Lounis. "Ensemble Analysis of Climate-Change Impacts on Design-Service Life of Reinforced Concrete Bridge Decks Across Canada." *Natural Hazards Review*, vol. 21, no. 3 (2020

Stephens, Max T. *Steel Bridge Corrosion Prevention and Mitigation Strategies.* IRISE-19-P19-01-01, IRISE, University of Pittsburgh: 2019.

Wong, C. Jerry. "Fact or Fiction - Weathering Steel Can Provide Effective Corrosion Protection to Steel Structures." In *Electrical Transmission and Substation Structures 2009: Technology for the Next Generation*, 1-8. West Palm Beach, Florida: DHW Engineering, 2010.

Yan, Banfu, Satoshi Goto, Ayaho Miyamoto, and Hua Zhao. "Imaging-Based Rating for Corrosion States of Weathering Steel Using Wavelet Transform and PSO-SVM Techniques." *Journal of Computing in Civil Engineering*, vol. 28, no. 3, 2014

APPENDIX

BRIDGES EXPERIENCING 90-100 PERCENT OXIDE FILM DEGRADATION

Table A-1: 90-100 Percent Bridges and Square Footage of Each Condition State

Bridge Number	CS 1 ft^2	CS 2 ft^2	CS 3 ft^2	CS 4 ft^2
05815	265	8,423	30	602
06104	340	2,891	368	136
05698	0	44,021	0	850
06252	0	4041	123	33
05813	11	11,708	239	87
B6485	0	56,445	0	40
A3717	3	31,202	3,960	0
07051	0	14,872	122	0
A3232	0	29,338	96	0
06609	0	8,087	84	0
05699	0	41,925	60	0
05812	0	10,200	55	0
B6807	0	43,531	44	0
06603	0	11,531	34	0
06155	0	6,290	16	0
06179	45	205,890	0	0
02312	0	4,363	0	0
02313	0	9,817	0	0
05872	0	129,720	0	0
05912	0	158,100	0	0
06077	0	5,525	0	0
06107	0	3,242	0	0

Table A-1: 90-100 Percent Bridges and Square Footage of Each Condition State (Continued)

Bridge Number	CS 1 ft^2	CS 2 ft^2	CS 3 ft^2	CS 4 ft^2
06131	0	2,552	0	0
06151	0	10,101	0	0
06154	0	5,022	0	0
02314	0	5,454	0	0
06160	0	2,552	0	0
06245	0	3,377	0	0
06350	0	3,255	0	0
06440	0	6,545	0	0
06442	0	14,784	0	0
06467	0	44,316	0	0
06566	0	25,338	0	0
06567	0	12,960	0	0
06582	0	51,478	0	0
06599	0	34,870	0	0
06600	0	18,886	0	0
02315	0	12,000	0	0
05277	0	21,024	0	0
06655	0	6,788	0	0
06656	0	6,461	0	0
06748	0	113,364	0	0
06792	0	61,042	0	0
06793	0	185,231	0	0

Table A-1: 90-100 Percent Bridges and Square Footage of Each Condition State (Continued)

Bridge Number	CS 1 ft^2	CS 2 ft^2	CS 3 ft^2	CS 4 ft^2
06855	0	6,433	0	0
06856	0	4,784	0	0
06903	0	21,697	0	0
06973	0	19,080	0	0
06981	0	9,282	0	0
07033	0	6,507	0	0
05433	0	6,300	0	0
07066	0	2,625	0	0
07093	0	46,267	0	0
07330	0	4,336	0	0
05435	0	6,996	0	0
A3430	0	11,540	0	0
A5025	0	12,619	0	0
A6522	0	11,952	0	0
A6775	0	32,312	0	0
A6808	0	8,014	0	0
A6821	0	17,808	0	0
A6872	0	12,362	0	0
A6873	0	8,075	0	0
A6906	0	9,638	0	0
A7037	0	9,912	0	0
A7093	0	41,395	0	0

Table A-1: 90-100 Percent Bridges and Square Footage of Each Condition State (Continued)

Bridge Number	CS 1 ft^2	CS 2 ft^2	CS 3 ft^2	CS 4 ft^2
B3430	0	11,540	0	0
B3717	0	35,165	0	0
B5025	0	12,619	0	0
B5700	0	934,559	0	0
B6357	0	5,586	0	0
B6522	0	11,952	0	0
B6754	0	333,141	0	0
B6775	0	32,312	0	0
05352	0	10,050	0	0
B6808	0	8,014	0	0
B6821	0	17,808	0	0
B6872	0	12,362	0	0
B6873	0	8,075	0	0
B6906	0	9,577	0	0
B6926	0	7,182	0	0
D6357	0	3,969	0	0
D6926	0	5,103	0	0

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