

# FHWA Bridge Preservation Research Roadmap

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## FOREWORD

In recent years, State departments of transportation (DOTs) have established bridge preservation programs and made significant progress in bridge preservation practice and research. More bridge preservation technologies, planning strategies, and tools have been investigated and adopted to extend the service life and restore serviceability of existing bridges. The concept of using high-performance and durable materials, low-maintenance structure types, and details to extend the maintenance-free service life of new construction has become more widely accepted. In addition, developments in data technologies have enhanced data-driven performance evaluation, risk-based decisionmaking, and lifecycle analysis capabilities. As more bridges in poor condition are replaced, proactive bridge preservation is becoming increasingly important to maintain bridge inventories in states of good repair in a cost-effective way.

In 2008, the Federal Highway Administration (FHWA) collaborated with the American Association of State Highway and Transportation Officials (AASHTO) Transportation System Preservation Technical Services Program and the Transportation Research Board to develop the *Transportation System Preservation Research, Development, and Implementation Roadmap*.<sup>(1)</sup> Significant advances in bridge preservation prompted FHWA to produce an updated research roadmap reflecting the progress made and identifying current research gaps. This update was developed by examining publications and research led by FHWA, State DOTs, and AASHTO from 2010 to 2022 to assess accomplishments and remaining gaps. Additional research gaps were also identified that support FHWA initiatives in sustainability, infrastructure resilience, risk evaluation, digital twins, and data integration related to bridge preservation and management. This roadmap is intended for use primarily by FHWA. Other agencies or organizations may also use the roadmap in selecting and funding research in bridge preservation programs.

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16. Abstract Since the publication of the <i>Transportation System Preservation Research, Development, and Implementation Roadmap</i> in 2008, most State departments of transportation (DOTs) have established bridge preservation programs and have made significant progress in the areas of bridge preservation practice and research. <sup>(1)</sup> State DOTs have investigated, developed, and used bridge preservation technologies, materials, planning strategies, and tools to extend the service life and restore the serviceability of existing bridges. The use of high-performance materials and low-maintenance structure types and details to extend the maintenance-free service life of new construction has become more widely accepted. In recent years, developments in data technologies have enhanced data-driven performance evaluation, risk-based decisionmaking, and lifecycle analysis capabilities. As more bridges in poor condition are replaced, proactive bridge preservation is becoming increasingly important to cost-effectively maintain bridge inventories in states of good repair. Considering the advances mentioned, the 2008 roadmap needs to be reevaluated to determine whether those gaps are still valid and identify new ones. The author reviewed publications and research led by the Federal Highway Administration (FHWA), State DOTs, and the American Association of State Highway and Transportation Officials (AASHTO) from 2010 to 2022 to assess accomplishments and remaining gaps. Additional gaps were also identified to support FHWA initiatives in sustainability, infrastructure resilience, risk evaluation, and big data as they relate to bridge preservation and management. The author also investigated FHWA initiatives in climate change, infrastructure resilience, and big data related to bridge preservation to identify new gaps. This roadmap is intended for use primarily by FHWA. Other agencies or organizations may also use the roadmap in selecting and funding research in bridge preservation programs.			
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## SI\* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yard	0.836	square meters	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
NOTE: volumes greater than 1,000 L shall be shown in m <sup>3</sup>				
<b>MASS</b>				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
<b>TEMPERATURE (exact degrees)</b>				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa
<b>APPROXIMATE CONVERSIONS FROM SI UNITS</b>				
Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m <sup>3</sup>	cubic meters	35.314	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
<b>MASS</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
<b>TEMPERATURE (exact degrees)</b>				
°C	Celsius	1.8C+32	Fahrenheit	°F
<b>ILLUMINATION</b>				
lx	lux	0.0929	foot-candles	fc
cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>				
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

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

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## LIST OF ABBREVIATIONS AND ACRONYMS

3D	three dimensional
AASHTO	American Association of State Highway and Transportation Officials
ADE	Agency Developed Elements
AE	acoustic emission
AI	artificial intelligence
BEAST®	Bridge Evaluation and Accelerated Structural Testing
BME	Bridge Management Elements
BPETG	Bridge Preservation Expert Task Group
BIM	bridge information modeling
CFRP	carbon-fiber-reinforced polymer
CGR	continuously galvanized rebar
DOT	department of transportation
EDC-6	Every Day Counts-6
FHWA	Federal Highway Administration
FRP	fiber-reinforced polymer
GFRP	glass-fiber-reinforced polymer
HPMS	Highway Performance Monitoring System
LCCA	lifecycle cost analysis
LTBP	Long-Term Bridge Performance
MFL	magnetic flux leakage
MMF	magnetomotive force
MSEW	mechanically stabilized earth wall
NBE	National Bridge Elements
NBI	National Bridge Inventory
NBMD	National Bridge Maintenance Database
NCHRP	National Cooperative Highway Research Program
NDE	nondestructive evaluation
NHI	National Highway Institute
ROI	return on investment
SHM	structural health monitoring
SM	structural monitoring
SME	subject matter expert
TC3	Transportation Curriculum Coordination Council
TRB	Transportation Research Board
TSP2	Transportation System Preservation Technical Services Program
UAV	unmanned aerial vehicle
UHPC	ultra-high performance concrete
WG	working group
WIM	weigh-in-motion
XML	Extensible Markup Language



## EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) worked with the American Association of State Highway and Transportation Officials (AASHTO) in 2008 to develop the *Transportation System Preservation Research, Development, and Implementation Roadmap* to reach consensus about the most pressing research needs to move the preservation of roads and bridges into more common practice.<sup>(1)</sup> Since then, most State departments of transportation (DOTs) have established bridge preservation programs and have made significant progress in bridge preservation practice and research. State DOTs have investigated, developed, and used bridge preservation technologies, materials, planning strategies, and tools to extend the service life of existing bridges in a cost-effective way. Equally important is considering bridge preservation and service life during the planning and design stages of new construction. Adopting higher performance materials and lower maintenance structure types and details to extend maintenance-free service life is also an important research area for bridge preservation. In recent years, dramatic developments in data collection, analysis, and modeling technologies have made data-driven performance evaluation and risk-based decisionmaking more practical and efficient. Given the promotion of bridge preservation as a cost-effective approach to maintaining bridges in states of good repair, there is a need to reevaluate the 2008 roadmap to determine whether the gaps are still valid and identify new gaps.

Publications and research led by FHWA, State DOTs, and AASHTO from 2010 to 2022 was reviewed to gain useful information for the gap assessment. Research topics were identified to cover the gaps and investigated bridge-preservation-related research topics representing emerging technologies and new initiatives. They are ranked to show current FHWA priorities and national interests. Data-driven planning and decisionmaking are major research areas proposed in this roadmap. Additional gaps and research topics were also identified to support FHWA initiatives in climate change, resilience, infrastructure digitization, AI and big data related to bridge preservation.

This roadmap is intended for use primarily by FHWA. Local, State, and other Federal agencies or other interested parties may also use the roadmap in selecting and funding research in bridge preservation programs. The roadmap should be updated regularly.



## CHAPTER 1. BACKGROUND

In 2008, the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), and highway preservation industries worked together to identify the most needed research, document critical knowledge gaps in pavement and bridge preservation, and determine the research necessary to fill those gaps.<sup>(1)</sup> This effort resulted in an infrastructure preservation research publication called the *Transportation System Preservation Research, Development, and Implementation Roadmap*. The purpose of the 2008 roadmap was to reach consensus about the most pressing research needs to move the preservation of roads and bridges into more common practice and to provide decision tools to assist agencies with proper project selection, use of materials and specifications, quality construction, and appropriate performance monitoring. The 2008 roadmap was developed when many States were in the earliest stages of implementing preservation practices. Recently, FHWA updated and published the pavement portion of the roadmap.<sup>(2)</sup>

In 2008, many agencies limited bridge preservation to joint repairs, preservation coatings, and protective deck treatments. The bridge portion of the 2008 research roadmap identified 25 research topics and developed research needs statements amounting to a total estimated cost of \$12.7 million.<sup>(1)</sup> The 25 topics were distributed among six topic areas as follows:

- Asset management: 7.
- Decks and joints: 4.
- Superstructures: 5.
- Substructures: 5.
- Selection of preservation actions: 2.
- Performance of preservation actions: 2.

Since the 2008 roadmap's publication, coupled with the Moving Ahead for Progress in the 21<sup>st</sup> Century Act<sup>(3)</sup> and the Fixing America's Surface Transportation Act<sup>(4)</sup>, significant progress has been made in bridge preservation and management research and practice and the impact on the performance of individual bridges and bridge networks. States recognize that maintaining an aging bridge inventory in a state of good repair with limited budgets is challenging. A worst first bridge management approach that focuses only on replacing poor bridges while ignoring the preservation and maintenance needs of good- or fair-condition bridges is inefficient and cost prohibitive in the long term.<sup>(5,6)</sup> The National Bridge Inventory (NBI) had 42,966 bridges (with a total deck area of 217 ft<sup>2</sup>) in poor condition.<sup>(7)</sup> The replacement cost would be \$49 billion based on the replacement unit cost reported to FHWA, which was \$228 per ft<sup>2</sup> on average in 2022 (<https://www.fhwa.dot.gov/bridge/nbi/sd2020.cfm>).<sup>(8)</sup>

Additionally, if no preservation actions are undertaken, the total replacement cost would increase exponentially due to the average age of existing highway bridges—which was 45.9 yr in 2022. In contrast, delaying the need for costly rehabilitation and replacement while bridges are still in good or fair condition through bridge preservation and, at the same time, keeping a good balance between bridge preservation, rehabilitation, and replacement are proven effective and practical ways to maintain and possibly improve the bridges' overall service levels.<sup>(5,6)</sup> Using preservation

to maintain system conditions and extend bridge service life is a valuable tool for achieving the asset management goals FHWA is promoting.

Currently, most State departments of transportation (DOTs) have established bridge preservation programs to promote effective and sustainable bridge preservation practices. The success of those programs relies not only on funding and organizational support but also on innovative research that includes the following:

- Develop and validate cost-effective and ecofriendly bridge preservation and maintenance techniques.
- Validate the performance of new materials (e.g., corrosion-resistant, high-strength, high-durability, and ecofriendly materials) that extend bridge service life.
- Validate and apply early damage and deterioration detection techniques and use the data in bridge preservation planning.
- Collect and use high-quality data—including nondestructive evaluation and structural monitoring (NDE/SM) data—to support meaningful data-driven decisionmaking (e.g., lifecycle planning considering cost, performance, and risk).
- Consider resilience and sustainability in bridge preservation planning.
- Develop data modeling strategies to support innovations in decisionmaking spurred by digital deliverables and digital twin technologies, which include bridge information modeling (BIM) for bridge implementations.

This roadmap assesses the bridge portion of the 2008 roadmap in terms of what has been accomplished and initiated since then, whether the gaps are still valid, and what new gaps exist.<sup>(1)</sup> This roadmap aims to identify current research needs for bridge preservation and rank them according to FHWA's priority and national interest. The author's review of publications and research led by FHWA, State DOTs, and AASHTO from 2010 to 2022 provides useful information for this gap assessment. The report proposes research topics to cover the gaps and identifies research needs that represent emerging technologies. The identified research topics are ranked to show current FHWA priority and national interests. This roadmap was developed primarily for FHWA use because the topics discussed are broad and address national needs, but it can also guide local, State, other Federal agencies, or other interested parties in selecting and funding research in bridge preservation and management programs. The roadmap is expected to be updated regularly.

## CHAPTER 2. FHWA'S BRIDGE PRESERVATION PROGRAM

Research conducted in response to this roadmap is intended to feed into FHWA's broader bridge preservation program. The following are key activities in the broader program.

FHWA's bridge preservation program published *Bridge Preservation Guide: Maintaining a State of Good Repair Using Cost Effective Investment Strategies* and *Bridge Preservation Guide: Maintaining a Resilient Infrastructure to Preserve Mobility* in 2011 and 2018, respectively.<sup>(5,6)</sup> The guides define bridge preservation terms and identify commonly practiced bridge preservation activities. The guides also provide information for State DOTs and other bridge owners regarding establishing or improving existing bridge preservation programs as part of an asset management program.

In 2020, FHWA published the *FHWA Bridge Preservation Expert Task Group [BPETG] Strategic Plan FY2020–FY2024*.<sup>(9)</sup> The plan identified four strategic objectives:

1. Share cost-effective bridge preservation strategies that include the following actions:
  - a. Develop documents on practices adopted or conducted by States or bridge owners.
  - b. Develop apps for mobile devices.
  - c. Develop case studies.
  - d. Determine the duration of bridge preservation treatments from a bridge condition rating perspective.
  - e. Study next-generation data framework for developing data-driven preservation performance estimates.
2. Promote bridge preservation as a component of asset and performance management that includes the following actions:
  - a. Integrate bridge preservation into asset management.
  - b. Support the development of bridge deck preservation portals.
  - c. Communicate how bridge preservation extends the lives of bridges at other venues.
3. Develop educational materials on bridge preservation that include the following actions:
  - a. Design Web-based training.
  - b. Communicate the importance of bridge preservation as a component of an asset management strategy.
  - c. Explore the development and deployment of curricular modules on bridge preservation—including appropriate references to asset management and lifecycle costs—for undergraduate and graduate courses.
  - d. Provide technical assistance for local agencies.
4. Foster a collaborative environment that encourages the innovation and adoption of new technologies for bridge preservation that include the following actions:

- a. Explore opportunities to improve States’ qualified product list process for owners, suppliers, and contractors that identifies new technologies, gaps, and key performance indicators.
- b. Assist other research sponsors in promoting bridge preservation research.

Since the publication of the strategic plan, BPETG has completed the following case studies:

- *Case Study: Utilization of Cathodic Protection to Extend the Service Life of Reinforced Concrete Bridges – An Overview of the Installation and Maintenance of the Cathodic Protection Systems Protecting the Howard Frankland and Crescent Beach Bridges* (in response to a U.S. Government Accountability Office report dated September 28, 2021).<sup>(10)</sup>
- *Case Study: Eliminating Bridge Joints with Link Slabs – An Overview of State Practices*.<sup>(11)</sup>
- *Case Study: Response to Bridge Impacts – An Overview of State Practices*.<sup>(12)</sup>

The FHWA BPETG developed many pocket guides for bridge preservation activities, which can be found at <https://tsp2bridge.pavementpreservation.org/technical/fhwa/pocket-guides/>.<sup>(13)</sup>

Recently, FHWA published a report entitled *Prioritizing Preservation for Locally Owned Bridges*.<sup>(14)</sup> The report highlights local agency project selection processes for bridge preservation activities, funding sources, typical bridge preservation actions, bridge asset management practices, and successes and challenges for funding locally owned bridge preservation programs.

In 2022, FHWA published the *Reference Guide for Service Life Design of Bridges*.<sup>(15)</sup> This document is intended to act as a nonbinding “roadmap” of service life design concepts and methods for bridge owners and designers.

For bridge preservation training, several Web-based training courses were developed and are available through the AASHTO Transportation Curriculum Coordination Council (TC3) website (<https://transportation.org/technical-training-solutions/>).<sup>(16)</sup> Examples of courses include the following:

- TC3MN036: Bridge Preservation Guide.
- TC3MN037: Bridge Cleaning.
- TC3MN038: Thin-Polymer Bridge Deck Overlay Systems.
- TC3MN039: Removal and Replacement of Bridge Coatings.
- TC3MN042: Concrete Bridge Deck Patching.
- TC3MN043: Spot, Zone, and Overcoating Existing Bridge Coatings.
- TC3MN044: Repair of Bridge Concrete Substructure Elements.
- TC3MN049: Maintenance and Repair of Bridge Bearings.

Many National Highway Institute (NHI) training courses were also developed, including the following examples:

- FHWA-NHI-130106A: Bridge Preservation Fundamentals.<sup>(17)</sup>
- FHWA-NHI-130106B: Establishing a Bridge Preservation Program.<sup>(18)</sup>
- FHWA-NHI-130107A: Fundamentals of Bridge Maintenance.<sup>(19)</sup>
- FHWA-NHI-130107C: Maintenance of Movable Bridges.<sup>(20)</sup>
- FHWA-NHI-130107D: Maintenance of Masonry Bridge Elements.<sup>(21)</sup>
- FHWA-NHI-130108: Bridge Maintenance.<sup>(22)</sup>

FHWA's bridge preservation program also published the following documents:

- *Report on Techniques for Bridge Strengthening: Main Report.*<sup>(23)</sup>
- *Manual for Design, Construction, and Maintenance of Orthotropic Steel Deck Bridges.*<sup>(24)</sup> This manual covers bridge engineering topics related to orthotropic steel decks, including analysis, design, detailing, fabrication, testing, inspection, evaluation, and repair.
- *Methodology for Analysis of Soluble Salts from Steel Substrates.*<sup>(25)</sup> This report presents the results of a laboratory study of the methodology for extraction and analysis of soluble salts from steel substrates.
- *Proceedings of the 2011 National Bridge Management, Inspection and Preservation Conference: Beyond the Short Term.*<sup>(26)</sup> The conference included tracks on bridge management, inspection, and preservation, emphasizing how all three interrelated disciplines can collaborate to improve the long-term performance of the Nation's highway bridges.

More information about FHWA's bridge preservation and management program can be found at the FHWA "Bridge Preservation" web page (<https://www.fhwa.dot.gov/bridge/preservation/>) and "Bridge Management" web page (<https://www.fhwa.dot.gov/bridge/management/>).<sup>(27,28)</sup>





## CHAPTER 3. DEVELOPMENT APPROACH

The author identified research topics based on the assessment of existing and emerging research and carried out five steps to fulfill the task:

Step 1. The author worked with the FHWA Research Library to conduct a literature review of the previously mentioned 25 bridge-related topics in the 2008 roadmap, classifying the topics into 18 groups by considering their similarities and connections.<sup>(1)</sup> Results from major databases, AASHTO, the Transportation Research Board (TRB), FHWA publications, and FHWA- and State-DOT-funded projects published after 2010 were documented in a spreadsheet.

Step 2. The author considered 11 of the 18 groups more suited to FHWA research due to their fundamental research natures and current national needs. Due to ongoing research, the weathering steel-related research was not included in further. More topics can be identified later as necessary.

Step 3. The author further analyzed the literature research results of the 10 high-priority topics and related FHWA research to identify the potential knowledge gaps.

Step 4. The author proposed research topics to address the knowledge gaps identified in step 3 and investigated topics for emerging technologies.

Step 5. The research topics identified in step 4 were prioritized by bridge experts of FHWA and stakeholders and developed as project statements for selected topics.

Chapter 4 summarizes the literature review findings and gap analysis results for the 10 high-priority topics (steps 1 through 3). Based on the gap analysis, future research topics are identified (step 4) and summarized in chapter 5. The author collected FHWA internal feedback for the roadmap. A working group (WG) representing FHWA, TRB, AASHTO (State DOTs and the Transportation System Preservation Technical Services Program (TSP2)), academia, and industry was formed and provided feedback on prioritizing the topics and research statements.



## **CHAPTER 4. ASSESSMENT OF RESEARCH GAPS FOR THE 10 TOPIC AREAS FROM THE 2008 ROADMAP**

The literature review covers 10 topic areas identified from the 2008 roadmap and an analysis of related ongoing FHWA work.<sup>(1)</sup> The results from this effort were used to support research gap identification.

### **TOPIC 1: SENSING DATA IN BRIDGE PRESERVATION DECISIONMAKING**

NDE/SM technologies were developed rapidly during the past decade. However, integrating NDE/SM data into bridge condition evaluation, preservation, and management decisionmaking still needs more research. Artificial intelligence (AI) and big-data-based analysis approaches show promise in applying NDE/SM data in bridge preservation decisionmaking. Early damage detection approaches are needed to facilitate early preservation interventions. The ability to model sensing data in the context of digital deliverables—including BIM for bridges and digital twins—is important for the next-generation bridge preservation program.

#### **Background and Originally Proposed Objective and Scope**

Unexpected failures of prestressing strand embedded in concrete or encased in ducts have happened. In 2008, NDE technology was inadequate to evaluate the condition of such embedded and ducted strands for active corrosion and section loss, breakage, grout quality, etc. NDE technologies at that time were inadequate to provide condition knowledge that could support proactive actions to mitigate or prevent further deterioration or future unanticipated failure. Even though NDE technologies have improved, technologies focused on determining the current condition and identifying active corrosion or conditions favorable to corrosion are needed. This research aims to improve the current state of inspection technologies or to develop new tools and methodologies for assessing the current state of steel prestressing strand, ducts, cables, and ropes. Some of the technologies will focus on determining the current condition, and others will focus on identifying active corrosion or conditions favorable to corrosion.

#### **State of the Practice Based on Literature Review**

The literature review results showed that extensive research has been conducted in the past 10 yr for NDE/SM techniques and their applications in corrosion and damage detection for prestressed strand/tendon/rope, ducts, and grouting.

The studied NDE/SM techniques included acoustic emission (AE), eddy current, fiber-optic-based sensing technologies, ground penetration radar (GPR), impact echo (IE), impact-elastic wave, infrared and induction thermography, magnetic- and electromagnetic-based methods, magnetic flux leakage (MFL), magnetic flux methods, magnetomotive force (MMF) ultrasound, robot, sensor network, three-dimensional (3D) microwave camera, ultrasonic shear wave imaging device, and x-ray image and other radiography techniques, etc.

The most used methods for corrosion detection were AE and magnetic flux. Ultrasound and impact echo were widely used in grouting-condition evaluation. SM systems were typically used for stress and axle force monitoring and damage detection. In addition, radiography was used to

measure reinforcing configuration, cable and strand or grouting-condition evaluation, and stress levels.

Among the 315 results, 74 were from industries other than bridges. The NDE/SM techniques used by the bridge industry and other industries were generally similar. The literature review yielded the following results:

- Forty papers discussed AE or acoustic-based methods, and 13 focused on corrosion detection.
- Forty-four results were related to the magnetic flux method, including MMF and MFL, and 13 focused on corrosion detection.
- SM was used to provide real-time or near-real-time information for conditions or stresses in cables or strands. Much of the research was about fiber-optic piezoceramic sensors and sensor networks. Twenty-one results were about fiber-optic sensors, and 15 of them were used to monitor stress and axial force in prestress strands or posttensioned cable. Four results were about piezoceramic transducers used to evaluate stress level, cable condition, and grouting condition. Sensor network was widely used in cable condition evaluation.
- For dynamic testing, nine results documented systems for cable and strand stress evaluation and damage detection.
- Twelve results were found for radiography that measured stress level, reinforcing configuration, cable and strand condition, grouting condition, etc.
- One result was for an ultrasonic shear wave imaging device.
- Six results were found for eddy current. The technology was used to evaluate stress level, reinforcing configuration, wire rope condition, etc.
- Thirty-seven results were found for ultrasonic or guided ultrasonic waves. Ultrasonic waves are widely used in grouting-condition evaluation (9 papers), corrosion detection (9 papers), and stress-level evaluation (10 papers).
- Magnetic-based methods (28 results) were commonly used in stress-level evaluation.
- Two results were found for lethal-concentration oscillation, which is used in stress-loss evaluation.
- Five results were found for impulse hammer, which is commonly used in condition evaluation of posttensioned structures (e.g., grouting-condition evaluations).
- Six results were found for image-based methods, three of which were about applications for wire rope condition evaluation.

- Twenty-three results were about impact echo and impact-elastic wave, whose most common application was grouting-condition evaluation, and 14 out of the 23 results were about impact echo and impact-elastic wave.
- The 11 results found for robot were all applications in posttension cable condition evaluation.
- Six papers used an AI data analysis approach.
- The impedance method, with five results, was most commonly used in grouting-condition evaluation.

### **Related Work From the FHWA NDE Laboratory**

FHWA's NDE Laboratory led several research projects that are closely related to bridge preservation and management. The scope of these projects are about general applications of NDE/SM in bridge condition evaluation rather than only for strand, cables, ropes, and grouting in prestressed concrete components. Following are summaries of representative products and projects:

- The *Nondestructive Evaluation [NDE] Web Manual* provides knowledge that fills the gap between highway infrastructure practitioners/asset managers dealing with highway infrastructure performance challenges and researchers developing and refining NDE technologies to support practitioners/asset managers' efforts. The manual is published through the FHWA InfoTechnology™ portal.<sup>(29)</sup>
- *Collection of Data with Unmanned Aerial Systems (UAS) for Bridge Inspection and Construction Inspection.*<sup>(30)</sup>
- *Leveraging Augmented Reality for Highway Construction.*<sup>(31)</sup>

Some of the ongoing research projects led by FHWA's NDE Laboratory aim to integrate NDE/SM data into bridge management decisionmaking frameworks. Return-on-investment (ROI) analysis was carried out in the following projects to justify the cost-effectiveness of using NDE and SM techniques in bridge preservation and management decisionmaking:

- **Incorporating NDE and SM Methods into Bridge Deck Preservation Strategies.**<sup>(32)</sup> This project includes efforts to identify state-of-practice preservation decisionmaking processes, define specific NDE/SM thresholds for specific preservation actions, develop matrices to incorporate NDE/SM methodology into bridge preservation strategies, and examine the economics of incorporating NDE/SM into bridge preservation strategies.
- **Structural Health Monitoring (SHM) Current Practice and Web Manual.** A Web manual for structural monitoring (SM) technologies will be developed and integrated into the FHWA InfoTechnology portal.<sup>(29)</sup> ROI analysis was conducted to justify the cost-effectiveness of using SM data in bridge management decisionmaking.

- **Current Practices and Policies of State Highway Agency Bridge and Tunnel Units on the Use of Deployment-ready NDE Technologies in Complementing Visual Bridge and Tunnel Safety Inspections.**<sup>(32)</sup> The primary goal of this project is to enhance NDE information and its use in managing bridge and tunnel assets. Project-level-analysis and network-level-analysis tools were developed. The ROI for using NDE data in asset management decisionmaking was evaluated.

Through the aforementioned projects, FHWA expects that standard approaches for certain SM technologies can be established and more widely adopted. By establishing the framework for integrating NDE/SM data into bridge management decisionmaking, the NDE/SM technologies would have more potential to be adopted as standard practices to supplement current bridge visual inspection.

On the data side, more work can be done for NDE/SM data governance, storage, and data analysis and visualization and to investigate AI-based data analysis and integration for deterioration modeling. NDE/SM-based model updating in the context of digital as-built and digital twin is also worth more research. In addition, NDE/SM techniques that can detect early damage and deterioration are needed to facilitate cost-effective early preservation interventions.

### **Observed Gaps**

The literature review identified the following research gaps:

- Developing/Testing NDE/SM techniques that could detect early damage/deterioration to facilitate cost-effective early preservation interventions.
- Integrating NDE/SM data into bridge components and elements in deterioration modeling and remaining service life estimation to support bridge preservation planning. AI- and big-data-based data analysis is expected to generate useful information to support data-driven bridge preservation and management decisionmaking.
- Integrating NDE/SM data into digital as-built (BIM for bridges) and digital twin models, which could be the next-generation data environment for bridge preservation decisionmaking.
- Applying existing and recently completed work conducted by FHWA’s NDE Laboratory to bridge preservation decisionmaking—such as integrating UAS, unmanned ground-based systems such as those with data collected by NDE robot, and unmanned water-based systems such as those with underwater sensing data—in bridge condition and postdisaster condition evaluation. Using virtual-reality- or augmented-reality-based bridge inspection data in model updating and data visualization would enable bridge preservation engineers to understand bridge condition more intuitively and accurately and thus improve preservation decisionmaking.

## **TOPIC 2: EFFECTS OF BRIDGE PRESERVATION ACTIVITIES**

Understanding the effects of bridge preservation activities is important in decisionmaking. Postaction deterioration modeling and remaining service life prediction have not been fully studied. For many new materials and new technologies, long-term performance data can be obtained only from accelerated laboratory testing or numerical simulation. The ability to validate accelerated testing and numerical simulation results is important for practical applications. In addition to performance modeling, the cost and ecoimpact of bridge preservation activities are important in decisionmaking.

### **Background and Originally Proposed Objective and Scope**

Bridge preservation is a systematic and proactive effort to sustainably extend the service life of a bridge or bridge elements. Limited attempts have been made to collect high-quality data, properly analyze the data, and draw conclusions about the costs, effectiveness, and longevity of preservation actions. Examining such issues as how long the service life of a bridge or bridge element is extended or the effects that various commonly used preservation actions have on the lifecycle costs of bridges is difficult. Most of the conclusions bridge practitioners reach are based on intuition or simple common sense backed by experience.

Collection of the data necessary to support the effectiveness and economic analysis of bridge preservation activities should be addressed in a logical sequence, starting with short-term studies of existing data and going on to future data collections targeting specific elements of the performance of bridge preservation actions.

Identifying the kinds of data needed, such as which performance characteristic needs improvement by means of which preservation techniques, is important. Experimental studies may be needed to collect the data and evaluate the benefits of specific and commonly used bridge preservation actions.

### **State of the Practice Based on Literature Review**

The literature review results show that most previous research focused on bridge preservation and maintenance optimization and planning at project and network levels. That focus involved research into deterioration modeling based mostly on NBI and National Bridge Elements (NBE) inventory data<sup>(33,34)</sup>, cost and depreciation modeling, and decisionmaking procedures. Some projects also studied the performance and economic impacts of bridge preservation activities. However, researchers rarely study the postpreservation deterioration models. Collecting and analyzing data to support the evaluation of service life extension of each intervention were not adequately studied.

The 138 literature review results break down as follows:

- Sixteen results discussed the effects of bridge preservation and maintenance actions, among which seven were about economic impacts, and nine were about performance impact.
- Fifteen results discussed individual bridge preservation and maintenance decisionmaking.

- Nineteen results discussed bridge network preservation and maintenance decisionmaking.
- Twenty-seven results were about maintenance prioritization and decision models.
- Sixteen results were about lifecycle planning.
- Five results were about deterioration modeling and service life prediction.
- Three results discussed cost modeling.
- Twelve results discussed performance measurements.
- Seven results were FHWA, State DOT, or AASHTO guides to bridge preservation actions.
- Eight results discussed bridge deck preservation.
- Four papers discussed preservations of historic bridges.
- One result was about data workflow for highway assets. The paper discusses the data sharing and information exchange for highway asset management.
- Five papers focused on other topics.

### **Related Work From Long-Term Bridge Performance (LTBP) Program**

The LTBP Program is a long-term research effort authorized by the U.S. Congress under the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users<sup>(35)</sup> to collect high-quality bridge data from a representative sample of highway bridges nationwide that will help the bridge community to better understand bridge performance.

LTBP InfoBridge™ (<https://infobridge.fhwa.dot.gov>) is a comprehensive bridge performance portal that enables researchers to develop tools and products that will enhance understanding of the performance of highway bridge assets and will lead to more efficient design, construction, rehabilitation, maintenance, preservation, and management of those assets.<sup>(7)</sup> The deterioration and performance prediction models and data collected by LTBP and other research programs published at this Web portal are expected to be very useful for bridge preservation and maintenance planning.

The LTBP Program published the following series of reports and papers, many of them closely related to bridge preservation, asset management, and related data needs:

- *The Summary Report: Long-Term Bridge Performance Program Data Collection Workshop* describes the input received from bridge community subject matter experts (SMEs) to assist FHWA in assessing the LTBP Program's future data collection efforts.<sup>(36)</sup> Previously identified high-priority performance issues were paired into five categories (i.e., warm-weather reinforced concrete bridge decks, cold-weather reinforced concrete decks, bridge deck joints and superstructure bearings, corrosion protection for



structural steel, and pretensioned and posttensioned strands), and five WGs were formed accordingly. The WGs consisted of SMEs from State highway departments, industry, academia, and FHWA, who provided input during group discussions. As reported, commonalities between certain data were found among the various WGs, such as climate data, joint condition data, and other data. Analysis of the input received from each of the five WGs, in addition to lessons learned from past LTBP data collection efforts, resulted in developing two overall data collection strategies.

The first strategy identified can be termed a “desk audit” type of data collection. The second involves collecting physical and visual data from bridges in the field.

Data collection requires extensive resources and a strategy to collect data to study the long-term performance of bridges. Determining the value of any data and how the data can be used when developing the LTBP Program’s future data collection approach is imperative. The LTBP Program is currently working on executing two studies to assess the overall value of already collected data—namely, data collected through an ongoing accelerated testing experiment and data available through earlier LTBP data collection efforts—to help guide the path forward.

The data collected and that will be collected by the LTBP Program constitute an important asset for the bridge preservation community’s future research.

- The report *Synthesis of National and International Methodologies Used for Bridge Health Indices* is important for bridge asset management.<sup>(37)</sup> Deterioration models based on elements and health indexes are useful in asset management decisionmaking at both the project and network levels. Deterioration models for bridge load ratings would be useful tools for evaluating the bridge capacity changes over time. More research into cost and cost modeling is needed for bridge asset management. Cost can be financial cost as well as environmental cost. With known costs, project- and network-level bridge preservation optimization tools can be developed.
- The Bridge Evaluation and Accelerated Structural Testing (BEAST®) laboratory is the world’s first accelerated testing facility for full-scale bridge systems.<sup>(38)</sup> BEAST subjects bridges to extreme environmental and traffic loading to simulate decades of deterioration in only months. The facility produces quantitative data on material and component performance that can be used to study bridges’ long-term performance and operation. The current study covers concrete decking systems, prestressed concrete girders, joints, bearings, deck drainage, latex-modified concrete overlay, and ultra-high performance concrete (UHPC) overlay systems.
- Other LTBP Program publications can be found at <https://highways.dot.gov/research/long-term-infrastructure-performance/ltpb/long-term-bridge-performance-ltpb-program-publications>.<sup>(39)</sup>

## Observed Gaps

The literature review identified the following research gaps:

- More research is needed to standardize the quality control and performance evaluation procedure for bridge preservation actions.
- More research is needed for using NDE/SM data in bridge deck or other element deterioration modeling.
- More research is needed to develop a standard data collection and governance framework for bridge preservation and maintenance activities. A uniform data framework would facilitate more efficient data query and sharing and establish a more meaningful data analysis supporting bridge preservation and management decisionmaking.
- BIM data needs and model updating to represent bridge preservation and maintenance effects is helpful for preservation decisionmaking.
- Integration of agency-collected data (e.g., Highway Performance Monitoring System (HPMS) data, weigh-in-motion (WIM) data, pavement profile and condition data, traffic data, friction index data, climate data, cost data, etc.) into bridge preservation planning and postactivity performance evaluation.
- Lifecycle and network-level bridge preservation planning are more advanced than project-level bridge preservation decisionmaking. However, research about lifecycle and network-level planning is still in the early stages, and more research is needed.
- Research into data sharing and information exchange is needed for the entire lifecycle of bridge projects—from planning to design, construction, operation, and management in BIM or a digital deliverables context so that bridge preservation and management programs can adapt to the next-generation data environment.
- More research is needed correlating accelerated testing results with field-collected performance data for testing validation. Once validated, the tests can be designed to simulate performance data that are rarely available or hard to collect in the field.

## TOPIC 3: BEST PRACTICES FOR BRIDGE DECK PRESERVATION

Deck preservation has been widely studied during the past decade. The ongoing pooled funded project Bridge Deck Preservation Tool (<https://www.pooledfund.org/Details/Study/701>) and *Proposed AASHTO Guides for Bridge Preservation Actions* (<https://www.trb.org/Publications/Blurbs/181532.aspx>) answered many of the previous questions about bridge deck preservation activities and selection criteria.<sup>(40,41)</sup> However, the existing research addressed mainly the single selected treatments of individual bridges. Research into individual bridge lifecycle planning and network-level planning for selected bridges is still in the early stages and deserves more research. Risk-based performance-driven decisionmaking can potentially lead to a more sophisticated and easy-to-implement approach.

Evaluations of deck sealer and overlay materials, technologies, and best practices are important in deck preservation research. Because many ongoing research projects focus on case studies and decision tool development, these areas can be revisited later. Emerging research needs for deck preservation research may include new materials, the impact of climate change, heavy live load, etc.

### **Background and Originally Proposed Objective and Scope**

In current bridge inventory, about 90 percent of bridges have concrete decks. All State DOTs recognize the importance of concrete deck preservation. The purpose of deck preservation treatments is to protect decks and maximize service life with limited resources. Typical treatments include the following:

- Concrete surface and crack sealers.
- Thin overlays.
- Periodic washing.
- Electrochemical treatments.
- Cathodic protection.
- Membranes.
- Coatings.

Research is needed to establish cost-effective lifecycle preservation programs for maintaining and preserving concrete bridge decks.

### **State of Practice Based on Literature Review**

The 90 literature reviews yielded the following results:

- Eighteen were about manuals, guides, and specifications.
- Fourteen were about overlays (not UHPC).
- Eleven were about UHPC overlays, which is also one of the major topics of Every Day Counts-6 (EDC-6).<sup>(42)</sup>
- Eleven were about decisionmaking.
- Seven were about waterproof membrane or asphalt overlay.
- Seven were about service life analysis.
- Six were about the preservation effect or field performance evaluation.
- Five were about lifecycle cost analysis (LCCA).
- Four were about high-performance or new materials.

- Three were about cathodic protection or chloride extraction.
- Two were about deck preservation protocols and tools.
- Two were about construction methods.
- Other research included sealer, high-friction surface treatment, patching, internal curing, cleaning, preservation of posttensioned bridges, link slab, bridge seats and bearings, and deck-cracking control and repair.

#### **Related Work from FHWA EDC-6** <sup>(43)</sup>

- EDC-6 work with UHPC for bridge preservation and repair lead to the publication of a report entitled *Design and Construction of UHPC-Based Bridge Preservation and Repair Solutions*.<sup>(42,43)</sup> The report contains design and construction recommendations for three promising and fastest growing UHPC preservation and repair applications: bridge deck overlays, link slabs, and steel beam end repair. The report also includes other key concepts of UHPC, such as material mechanical properties and durability. The information is valuable for all owner agencies considering the development of UHPC materials, construction, and design specifications.

#### **Observed Gaps**

The literature review identified the following research gaps:

- Bridge deck preservation decisionmaking has been thoroughly studied at the bridge and project levels. However, more study is needed for lifecycle and network-level planning.
- Fiber-reinforced concrete is gaining attention for bridge deck and deck overlays construction to prevent cracking. However, research into the material characteristics and field performance data is not yet readily available for use in decisionmaking.
- More research is needed into ecofriendly materials that can be used in bridge deck preservation or repair.
- More research is needed into the long-term field performance of corrosion resistant rebar (e.g. glass-fiber-reinforced polymer (GFRP), stainless steel, etc.) reinforced concrete deck and its preservation needs.
- More research is needed into NDE/SM integration for early deck damage and deterioration detection and preservation.
- More research is needed into collecting NDE or other sensing data from the deck bottom, such as by using an unmanned aerial vehicle (UAV) in deck preservation and management decisionmaking.

- More research is needed into the impact of climate change that causes extreme events and how changes in the number of snow and freeze–thaw cycles will affect bridge deck design, deterioration, and preservation.
- More research is needed into how live loads (e.g., heavy trucks and truck platooning) affect the deterioration of bridge decks and preservation planning.
- UHPC bridge preservation applications can be further developed and tested in the future. Examples are UHPC shotcrete, 3D printing, and UHPC for structural strengthening and repair.

#### **TOPIC 4: PRESERVATION OF CONCRETE HIGHWAY BRIDGE SUBSTRUCTURE**

Active corrosion is common for bridge substructures. Early prevention actions, such as applying surface treatments prior to chlorides reaching critical concentration at rebar depth, are effective. However, more research is needed on schedules for applying and reapplying. Once rebar corrosion has started, preservation actions that can reduce deterioration rate are needed. In addition to specific preservation techniques, strategic decision matrices and tools for preservation planning are needed.

##### **Background and Originally Proposed Scope and Objective**

States need to develop guidance that highway agencies can follow in applying technologies that prevent or delay corrosion initiation, reduce corrosion rate, extend service life, and enhance the long-term durability of concrete bridge substructures. States need to develop strategic decision matrices for when and what corrosion mitigation strategies to implement to prolong the service lives of in-service highway bridge substructures because gaps still exist.

##### **State of the Practice Based on Literature Review**

The literature review results showed that in the past 10 yr, corrosion prevention and mitigation techniques were the most studied topics for bridge substructure. Among the topics, cathodic protection has been the most studied approach, followed by inhibitor and corrosion-resistant rebars.

Marine and coastal environment and the application of chloride deicing agents were found to be the two major factors that caused corrosion. Corrosion and remaining service life modeling was widely studied. Multihazard and climate change are considered in many of the studies. Research was also conducted into corrosion management, lifecycle assessment, and critical chloride thresholds. The performance of corroded components was also studied in many previous projects. Other studies included corrosion detection for girders, structural steel, steel piles, metal culverts (pipes), and mechanically stabilized earth walls (MSEWs).

Following is a summary of approximately 270 literature review results:

- Corrosion mitigation (171 items):
  - Cathodic protection was the most studied approach (48 items).
  - Twenty-four were about inhibitors.
  - Twenty were about corrosion-resistant rebar.
  - Eighteen were about special concrete mixture design.
  - Sixteen compared different methods or literature reviews.
  - Ten were about rebar coating.
  - Eight were about fiber-reinforced-polymer (FRP) external bond/wrap/jacket.
  - Eight studies used multiple corrosion mitigation approaches simultaneously.
  - Five results were about electrochemical chloride extraction and electrochemical realkalization.
  - Ten were about other methods.
  - Four were about concrete surface coating.
- Ninety-two results were about corrosion-impacting factors:
  - Sixty-six were about marine and coastal environments.
  - Fourteen were about deicing salt.
  - Twelve were about global warming.
- Sixty-five of the results were about modeling:
  - Eight were about multihazard modeling.
  - Nine were about how climate change affects corrosion initiation and propagation.
  - Others focused on corrosion deterioration modeling, remaining-life prediction, concrete cracking and diffusion, and rebar corrosion modeling.
- Corrosion detection with NDE/SM had 29 results:
  - Half-cell potential was the most studied method and had seven results.
  - Electrochemical-based method had six results.
  - AE had three results.
  - Polarization resistance had two results.
  - Ground penetration radar had two results.
  - Corrosion rate monitoring had four results.
  - Five were about other.
- Corrosion detection for specific components: Girders (5 results), structural steel (3 results), piles (17 results), metal pipeline (1 result), MSEW (2 results).
- Sixteen of the results were about the performance of corroded components.
- Eight of the results were about corrosion management and LCCA.
- Four of the results were about critical chloride threshold.

- Six of the results were corrosion-related specifications.
- Other research included chloride permeability, chloride ponding test improvement, and concrete cover crack propagation. Studies focused on concrete crack and rebar corrosion modeling, diffusion modeling, cathodic protection modeling, deterioration, and remaining-life prediction also exist.

## **Observed Gaps**

The literature review identified the following research gaps:

- More field-collected long-term-performance data is needed for corrosion-resistant rebars (e.g., stainless steel rebar, GFRP, carbon-fiber-reinforced polymer (CFRP), and microcomposite multistructural formable steel rebar) embedded in concrete. These data are critical for bridge design as well as preservation and management decisionmaking.
- More field-collected long-term-performance data for UHPC that can be used to support preservation decisionmaking is needed.
- Many NDE/SM research projects focus on corrosion or corrosion environment detection, but very few of them apply the NDE/SM data to bridge preservation and management decisionmaking.
- More research is needed for integrating NDE/SM corrosion detection data into digital twin models or BIM models for a real-time model updating that would reflect the operational condition of bridges to support bridge preservation decisionmaking.
- More research is needed to develop an element-based data framework that supports defect inspection.
- Much research is needed on cathodic protection. However, cathodic protection's adoption by State DOTs is limited, and research is lacking about the reasons cathodic protection is not more widely accepted by States.
- More studies are needed that estimate the impact of climate-change-caused accelerated corrosion development and how such studies would affect asset management decisionmaking.
- More research is needed for bridge deck, superstructure, and substructure lifecycle corrosion management planning.

## **TOPIC 5: CORROSION PREVENTION AND MITIGATION TECHNOLOGIES FOR CONCRETE COMPONENTS**

Corrosion prevention and mitigation are important for preserving the condition and extending the service lives of concrete structural components. The cost and performance of available preservation actions are essential in decisionmaking, and they are not fully studied or documented.

## **Background and Originally Proposed Scope and Objective**

This research is proposed to conduct an extensive field evaluation of the most common concrete structure corrosion protection and mitigation technologies in use since approximately 1980. The study should address the following parameters:

- Initial cost (difference) during construction or postconstruction application.
- Complexity of installation and construction (e.g., level of effort, training, and environmental concerns).
- Performance since installation—and comparison, if possible, to the performance of similar bridges in similar environments without these protective systems.
- Required maintenance (if any) performed to keep the technology functional.
- Cost of maintenance performed to keep the technology functional.

## **State of the Practice Based on Literature Review**

Many of the results found in the previous section are also related to the state of the practice. In addition to those results, another approximately 110 papers and reports were found from the literature review. Most of them focused on preserving concrete bridge decks and superstructures. The most studied corrosion prevention and mitigation approach for concrete structures is cathodic protection, followed by concrete sealers and sealants or surface-applied inhibitors.

The approximately 110 papers and reports yielded the following results:

- Thirty-three were about cathodic protection.
- Fifteen were about concrete sealer and sealant or surface-applied inhibitors.
- Nine were about corrosion-resistant rebars.
- Eight were about inhibitors.
- Six were about concrete or asphalt overlays.
- Five were about epoxy-coated or other coating systems for rebars.
- Four were about the use of lower permeate concrete or special concrete mixtures.
- Four were focused on LCCA.
- Four compared multiple methods.
- Three were about corrosion prevention of posttension components.



- Two were about performance-testing methods.
- Other results included studies of multiple impact factors, lifecycle corrosion treatment plans and management planning, factors that affect corrosion, etc.

### **Related Work From the FHWA Coatings and Corrosion Laboratory**

Determining the corrosion performance of coating and metal materials through laboratory approaches is one of the tasks of the FHWA Coatings and Corrosion Laboratory. Publications by the laboratory can be found at <https://highways.dot.gov/research/laboratories/coatings-corrosion-laboratory/corrosion-coating-publications>.<sup>(44)</sup> The laboratory's research projects have covered the topics of coatings, corrosion of reinforcing steel, corrosion in prestressed concrete, and others.

In parallel with laboratory evaluation, field evaluation for material corrosion performance and the effect of corrosion prevention methods is still important. More corrosion-resistant materials and corrosion mitigation approaches need validation in the laboratory and in the field, with exposure to realistic highway operation environments. For example, cathodic protection is one of the most studied corrosion prevention and mitigation approaches in the literature and the laboratory, but its application in bridge preservation practice is still limited. More laboratory research and field performance data would be useful for further validation and future adoption.

### **Observed Gaps**

The literature review identified the following research gaps:

- The most studied corrosion mitigation method for concrete structural components is cathodic protection. However, its adoption by State DOTs is limited. Research into the reasons cathodic protection is not more widely accepted by States is lacking.
- More research is needed into the live-load effect on the corrosion performance of bridge decks.
- Research into cost information and LCCA or ROI analysis is limited.
- More research is needed into bridge deck lifecycle corrosion management planning.
- More research is needed into laboratory and field performance concerning corrosion-resistant materials, including UHPC.
- More research is needed into how climate change and extreme events affect bridge deck corrosion performance.
- Projects led by the FHWA Coatings and Corrosion Laboratory have provided useful knowledge that supports bridge preservation decisionmaking. However, most of the studies were based on material-level accelerated laboratory testing. Structure-level and field-performance data are needed to validate the laboratory-testing data and thereby support more accurate preservation decisionmaking and management planning.

## **TOPIC 6: DETERIORATION MODELING ACCOUNTS FOR PRESERVATION ACTIONS AND PRESERVATION EFFECTS**

Deterioration models are key in bridge preservation decisionmaking. Bridge component deterioration modeling has been widely studied during the past decade. However, the development of element-based deterioration models, early deterioration modeling that allows for early preservation intervention, and postaction modeling are all in their early stages.

### **Background and Originally Proposed Scope and Objective**

States need to study the performance of various bridge preservation actions and develop deterioration models that account for the performance of preservation actions in bridge management calculations.

States need to develop quantitative models of the time until onset of deterioration and become sensitive to adherence to preventive maintenance policies. Models would be quantified for common routine maintenance treatments, such as washing and sealing, and agencies could extend the models for other types of preventive maintenance. Such models would be developed according to the *AASHTO Guide to Commonly Recognized (CoRe) Structural Elements* and would be compatible with their standardized condition state language for visual inspection.<sup>(45)</sup>

### **State of Practice Based on Literature Review**

The literature review found 426 results, among which the most widely studied topics were deterioration modeling (153 items) and bridge asset management (60 items). Transportation Pooled Fund-5(432) Bridge Element Deterioration for Midwest States is one of the pilot projects.<sup>(46)</sup> In the project, element deterioration models were developed using new element data and taking a Markov chain approach. Relevant data were collected from participant States, and, along with inventory data and collected NDE data, the collected maintenance information was saved in a SQL database to facilitate future updates and easy data sharing. Most of the asset management topics found from the literature review focused on maintenance and inspection planning:

- One hundred fifty-three results were about deterioration modeling.
- Thirteen were about survival and transition analysis.
- Sixty-two were about bridge asset management: preservation or maintenance planning.
- Eighteen were about bridge inspection intervals and maintenance planning and optimization.
- Seventy were about bridge preservation, maintenance, and repair activities.
- Eleven were about the impact of preservation and maintenance activities or the impact of investment.
- Fifteen were about performance evaluation or new performance measurements.

- Fifteen were about cost models.
- Fifteen were about bridge service life prediction or remaining service life.
- Six were about the risk and resilience of bridges.
- Thirty-eight were about lifecycle analysis.
- Ten were about BIM or digital twin or data-sharing workflow.
- Other topics included one repair of bridge approaches, three for detection of abnormal behaviors, two for cracking predictive models, two for service life design, two for corrosion modeling, one for seismic fragility study, one for robust modeling, one about NBE and NBI conversions, one about the effect of climate change, three about health index, and two about sustainability.

### **Observed Gaps**

The literature review identified the following research gaps:

- More research is needed into deterioration modeling that considers:
  - Impact of climate change.
  - Impact of heavy truckload.
  - Effect of bridge preservation and maintenance activities.
  - Structural capacity.
- More research is needed into the environmental footprint, performance impact, and lifecycle cost impact of bridge preservation and maintenance activities.
- More research is needed into resilience and how resilience affects bridge preservation decisionmaking.
- More research is needed into substructure and foundation preservation and maintenance activities.
- More research is needed into data-sharing requirements for supporting bridge operation and asset management in BIM or digital twin environments.
- More research is needed to identify and collect data for early stage deterioration modeling that supports preservation decisionmaking.
- More research is needed into risk-based bridge preservation planning.

## **TOPIC 7: WATERTIGHT JOINTS**

Joint leakage is the major factor that caused the deterioration of adjacent decks, beam ends, and bearings. Eliminating joints by using integral abutment and link slabs is an effective way to avoid such maintenance issues. Joint maintenance, replacement, and repair actions and related performance evaluations are needed for existing bridges.

### **Background and Originally Proposed Scope and Objective**

Maintaining watertight joints is essential preserving the condition of adjacent decks, superstructures, and substructures.

### **State of the Practice Based on Literature Review**

The literature review extended the original scope to general joints-related research; 191 papers were found, of which 160 or so were about bridge deck joints. The most studied topic was joint sealant and filler. The joint maintenance, replacement, and repair of UHPC and fiber-reinforced joints and link slabs were all studied at different levels. Some studies also involved deterioration modeling for joints. Details of the literature review results are summarized as follows:

- Five papers discussed jointless bridges and eliminating joints on existing bridges. The author concluded that elimination of transverse joints is a practical and cost-effective approach to avoiding joint leakage and leakage-induced damage and corrosion of bearings, superstructures, and substructures.
- Nine papers were about link slab studies. Materials for link slabs, link slab design and construction, and analysis approaches were studied. Link slabs were effective in eliminating deck joints.
- Fifteen papers were about UHPC joints, and six papers were about fiber-reinforced concrete joints. UHPC for bridge preservation and repair is one topic of EDC-6.<sup>(42)</sup>
- Twelve papers were about longitudinal joints, which included longitudinal joints for wider decks, joints between box girders, or joints between other adjacent concrete members.
- Twelve papers were about expansion joints. Materials, installation procedure, maintenance, replacement of all types of expansion joints, and sealant and filler materials were thoroughly documented.
- Five papers discussed asphalt expansion joints (asphalt plug joints).
- Three papers discussed strip seal.
- Twenty-three papers discussed joint sealant and filler.
- Three papers discussed sealer and membranes.

- Two papers discussed modular joints.
- One paper was about ribbed loop joint, and one paper was about half joint.
- Six papers were about joint design.
- Two papers were about joint cleaning.
- Five papers were about LCCA.
- Two papers were about joint management systems and asset management.
- Eight papers were about material testing.
- Eleven papers were about material standards.
- Sixteen papers were about joint maintenance, replacement, and repair.
- Four papers were about joint monitoring.
- Seven papers were about performance assessment and deterioration modeling.
- One paper was about pier cap and beam end repair caused by joint leakage.

### **Observed Gaps**

The literature review identified the following research gaps:

- Nationwide case studies to identify and document best practices for expansion joints, jointless bridges (including joint elimination), and associated LCCA are needed.
- The link slab concept is relatively new; more studies can achieve a better understanding for material selection (fiber-reinforced concrete, UHPC, or regular concrete), behavior, and performance. Such studies could lead to the development of guidelines for link slab design, construction, monitoring, and preservation. UHPC link slab is one topic regarding the current EDC-6 UHPC for bridge preservation.<sup>(42)</sup> The advantages of replacing expansion joints with UHPC link slab were documented. The design of UHPC link slab was also studied and documented. However, the long-term performance of UHPC link slabs and their deterioration, maintenance, and preservation still need investigation. In addition, the behavior of link slabs on bridges in seismic zones needs study.
- More work is needed on bridge deck joint deterioration modeling.
- A joint selection decision tool needs to be developed.
- The problem caused by longitudinal joints was observed, but solutions need to be fully studied and recommended.

- Maximum span length for integral abutment needs to be established at the national level. Considering bridge preservation during design is also important.
- Replacement of stub abutments on existing bridges with semi-integral abutments can reduce joint maintenance needs and be economical from a lifecycle point of view. LCCA can be used to justify the cost effectiveness.
- Long-term monitoring of performance of joints is needed.
- Workflow and data sharing for joint management need to be identified as a component of BIM for bridge maintenance and management. (No work has been done to develop data dictionaries of joint elements).

## **TOPIC 8: DEVELOPMENT OF BRIDGE MAINTENANCE DATABASE**

The National Bridge Maintenance Database (NBMD) was proposed and framed in National Cooperative Highway Research Program (NCHRP) 14-15 to enable DOTs to evaluate the costs and performance of maintenance actions, execute cost–benefit analysis, and better manage bridge maintenance resources.<sup>(47)</sup> The data and data format suggested in the database are useful for understanding the performance and cost of maintenance activities. It would be helpful if State DOTs’ adoption status and update suggestions could be investigated and the system updated to reflect current needs.

### **Background and Originally Proposed Scope and Objective**

NCHRP 14-15 has developed a standardized data structure for reporting and sharing bridge work accomplishment data.<sup>(47)</sup> The researchers proposed the project to gather bridge work accomplishment data in NCHRP 14-15 format from any agency able to provide such data. The project then quantified production functions, cost functions, and outcome functions as envisioned in the 14-15 report. The production functions and cost models account for both direct and indirect resource inputs.

### **State of the Practice Based on Literature Review**

NCHRP 14-15 provided a framework for a database system—NBMD—for uniform reporting of bridge maintenance actions.<sup>(47)</sup> The database is in a uniform and readable format for bridge maintenance, condition, and inventory data. The database conforms with the NBI format. NBMD collects outputs from existing DOT data systems and casts the outputs into a standard format. The database was designed to have 13 tables presenting bridge maintenance activities along with bridge inventory and condition data. The data formats include tab-delimited text files and Extensible Markup Language (XML) documents, each conforming to a standard XML schema.

Instead of focusing only on topics related to NCHRP 14-15, the literature review was extended to include general topics of cost modeling.<sup>(47)</sup> Among the 300 or so results, 171 were bridge related; others focused more on pavement, roadway, or other infrastructure structures. The most studied topics focused on cost estimation, probabilistic modeling, prediction modeling, and risk and uncertainty estimation. The following is a summary of the results:

- Four were about State implementation of a construction cost index.
- Fifty-six were about general cost estimation.
- Forty were about maintenance cost.
- Thirty-two were about user cost, and four about user and agency costs.
- Twenty-four were about asset management.
- Fifteen were about early cost estimation—either preconstruction cost or cost estimation made during planning or preliminary design.
- Fourteen focused on construction cost only.
- Fourteen were about cost overrun.
- Thirteen were about work zone cost (most were user cost).
- Thirteen were about network-level analysis.
- Eight discussed cost data integration with BIM models.
- Eight were about the cost benefit of activity-based-costing.
- Five were about cost due to lane closure.
- Three were about construction material quantities and time estimation.
- Two were about network cost.
- Two were about congestion cost.
- Other topics included one about accident cost, one about night construction, one about pay items from the design development process, one about cost and demand forecast, one about cost comparison between using in-house staff and using a consultant, one about incentive study, one about sustainable bridge invention strategies, one about project delay cost, and one about asset valuation.

## **Observed Gaps**

The literature review identified the following research gaps:

- More research is needed into adopting an NCHRP 14-15 national maintenance database and the need for updating.<sup>(47)</sup>
- More research is needed into data frameworks and governance for cost information collection and application.

- More research is needed into lifecycle cost savings due to emerging technologies, such as the adoption of BIM design, digital deliveries, and remote sensing and virtual reality for construction management and truck platooning.
- More research is needed into cost impacts due to climate-change-caused bridge preservation needs.
- More research is needed into lifecycle cost due to live-load changes: increasing average daily truck traffic, truck weight, and truck platooning.
- More research is needed into lifecycle costs of bridge preservation activities.
- More research is needed into element-based bridge preservation costs. Data on element-based preservation activities and costs need to be collected, and best practices established through case studies would be helpful.
- More research is needed into the use of environmental cost or carbon footprint as an optimization factor in bridge management.

## **TOPIC 9: APPLYING ELEMENT DATA IN BRIDGE PRESERVATION AND MANAGEMENT**

New AASHTO elements were adopted into bridge inspection practice in 2014, which addressed most of the research needs identified in the 2008 roadmap.<sup>(48,1)</sup> In the current NBE data system, element data do not provide damage location information.<sup>(34)</sup> The computed health index considers only damage quantity, not location. Damage location information is important for performance evaluation and preservation decisionmaking. Recent developments in project deliverables, bridge inspection and operation, and other technologies have generated new research requirements and opportunities for bridge elements.

### **Background and Originally Proposed Scope and Objective**

This research will develop a recommendation to modify and supplement the current list of elements. The proposed modified and new elements will be presented to AASHTO's bridge management community for adoption and integration into current and future bridge management systems.

### **State of the Practice Based on Literature Review**

The new AASHTO elements adopted in 2014 addressed most of the previously identified research needs for NBE data.<sup>(48)</sup> Current bridge elements have three categories: NBE, Bridge Management Elements (BME), and Agency Developed Elements (ADE). Regarding ADEs, agencies can define their own elements as subsets of NBE/BME (e.g., beam ends) or independent agency-defined elements (e.g., movable bridge components). All elements have four fixed-condition statuses. During the 8 yr of implementation of AASHTO elements inspection, more and more State DOTs have been creating different ADEs. Some of the created ADEs might also be useful for other States or bridge owners. Awareness of ADE development status will help evaluate the potential to adopt ADEs as NBE or BME.



Meanwhile, detailed information about bridge elements is more readily available due to the implementation of digital deliverables. The development of a bridge data dictionary for digital as-built, digital twin, or BIM models—along with identifying information exchange requirements for bridge operation, inspection, and management—provides the opportunity to include more information for current bridge elements or to identify the need for new elements for special bridges. In addition, planning for next-generation bridge element systems within digital deliverables and BIM frameworks can never start too early.

The literature review found 50 results. Following is a summary of the findings:

- Fourteen results were about applying element data in bridge asset management.
- Sixteen results were about element inspection manuals.
- Two results were about the UNIFORMAT II (ASTM E2103) classification of bridge elements.<sup>(49)</sup>
- Two results were about new elements.
- Five results were about BIM, a data dictionary, and 3D modeling.
- Two results were about more information for elements.
- Two results were about element data and NBI data conversion.<sup>(33)</sup>
- One result was about definitions of bridge preservation, maintenance, and replacement.
- One result was about defining significant predictors for bridge health indexes and defining bridges in poor condition with element data.
- Five results were about other content.

### **Observed Gaps**

The literature review identified the following research gaps:

- More research is needed into element inspection that supports effective and systematic defect and maintenance reporting. Development of an effective and systematic defect inspection and maintenance activity reporting framework is needed.
- More research is needed to identify new bridge elements for special bridges (e.g., movable bridges) or to incorporate additional information (e.g., location or position information like beam ends or more precise position information associated with damage and deterioration) into existing elements. Such information is important in bridge management decisionmaking.
- Research is needed to evaluate ADE and determine its potential for adoption as NBE or BME.

- More research is needed to develop next-generation bridge elements within digital as-built, digital twin, or BIM frameworks. Developing a new bridge element system in the digitalization context would never be too early.
- More research is needed to develop a risk index using inventory data and other available information (e.g., NDE/SM data, failure probability data, and failure consequence data) to support bridge preservation planning.

## **TOPIC 10: PILE PRESERVATION AND STEEL CORROSION PREVENTION**

Corrosion is the most common damage and deterioration mode for steel bridge piles. The topic covers research related to performance evaluation, corrosion prevention and mitigation, and damage repair of steel piles.

### **Background and Originally Proposed Scope and Objectives**

This research aims to develop one or more methods to determine the condition of and remaining service life of in-service exposed and unexposed steel piles in environments of varying aggressiveness and to identify methods to preserve such piles.

### **State of Practice Based on Literature Review**

Most of the previous research focused on steel pile corrosion mitigation and repair. Among the 57 results, cathodic protection was the most widely studied algorithm, followed by FRP repair. Some projects also studied NDE/SM techniques for corrosion and damage detection, factors that affect corrosion development, and the performance of corroded piles. Other topics also studied included corrosion rate and simulation, pile fatigue, coating, coating effects on force and deformation characteristic of steel piles, drilled shafts, sheet piles, pipe piles, foundation reuse, durability, soil-pile interaction modeling, fragility analysis, response to bridge foundation failure, LCCA, pile-type selection criteria, and service life of a steel structure.

The 145 literature reviews yielded the following results:

- Fifty-four were about corrosion mitigation and repair:
  - Cathodic protection was the most studied technology (18 results).
  - FRP repair was also very well studied (17 results).
  - Other approaches included coating (seven results), metal cold-air spray (one result), thermal spray (one result), petrolatum-based wrap (three results), UHPC (three results), concrete jacket (three results), and bolted or welded steel shapes or plates (one result).
- Twenty-eight were about factors affecting corrosion development:
  - Four were about the environment.
  - Three were about climate change.

- One was about expansion joint degradation.
  - One was about salt effect.
  - Four were about soil properties.
  - Four were about dissolved inorganic nitrogen.
  - Ten were about fouling and antifouling coating or microbiologic-influenced corrosion and deterioration.
  - One was about contaminated water.
- Thirteen were about the performance of corroded piles.
  - Eight were about NDE for corrosion detection:
    - Two were about ultrasonic-guided waves.
    - Two were about eddy currents.
    - One was about sonic echo impulse response.
    - Two were about pile depth estimation.
    - One was about surface topography.
  - Four were about repair methods and decisionmaking matrices.
  - Four were about the analysis, design, and construction of steel piles.
  - Two were about corrosion rate and corrosion simulation.
  - Two were about steel pile fatigue.
  - The remaining 30 reviews included coating effects on force and deformation characteristics of steel piles, drilled shafts, sheet piles, pipe piles, foundation reuse, durability, soil pile interaction modeling, fragility analysis, response to bridge foundation failure, LCCA, pile type selection criteria, and service life of steel structures.

## Observed Gaps

The literature review identified the following research gaps:

- More study of element-based steel pile deterioration modeling is needed.
- More research is needed into integrating NDE/SM data into early corrosion and deterioration modeling and prevention decisionmaking.
- More research is needed into underwater NDE technologies (e.g., underwater inspection robots) that can collect useful data to support pile management decisionmaking.
- More research is needed into SM for corroded piles to collect performance data to support decisionmaking and policy making.
- More study is needed on cost data collection and modeling that supports steel pile preservation and maintenance planning.

- More study is needed on how the performance of steel piles is affected by climate change, live-load change, and extreme events and how performance, in turn, affects preservation and management decisionmaking.
- More study is needed on why cathodic protection is not more widely accepted by bridge owners.
- More field-collected long-term-performance data on the performance of FRP pile repair is needed. Best practices and guidance for FRP pile repair were not established.
- More research is needed into steel pile lifecycle corrosion management planning.
- More research is needed into using special materials (e.g., corrosion-resistant and ultra-high performance materials) for pile construction and preservation.

## CHAPTER 5. RESEARCH TOPICS

The author proposes the following research topics to cover the gaps identified in chapter 4.

### **CORROSION EVALUATION, PREVENTION, AND MITIGATION FOR BRIDGE PRESERVATION**

Based on the identified gaps, the following research topics are proposed:

- Performance and preservation needs for corrosion-resistant rebar (e.g., stainless steel, CFRP/GFRP, chromium alloy steel, continuously galvanized rebar (CGR) and duplex coating rebar)-reinforced bridge components and elements (e.g., decks, superstructures, substructures, and piles) (C1<sup>\*</sup>).
- Identification of performance and preservation needs for bridge components and elements with duplex coatings (C2<sup>\*</sup>).
- Assessments of cost, performance, and service life extension of corrosion protection, prevention, and mitigation techniques (C3<sup>\*</sup>).
- Impacts of climate change on corrosion initiation and development and the effects on bridge preservation and management decisionmaking.
- Cathodic protection for bridge decks, superstructures, substructures, and piles; determination of best practices; and creation of guidelines.
- Live-load effects on bridge corrosion initiation and propagation and their impacts on bridge preservation and management decisionmaking.
- Use of NDE/SM data to enhance early detection of corrosion initiation and propagation and facilitate early corrosion prevention intervention.
- Identification of performance matrix and testing methods to measure the effectiveness of corrosion prevention and mitigation techniques.

### **DATA FOR BRIDGE PRESERVATION**

Based on the identified research gaps, the following research topics applying element data, NDE/SM data, and other data in bridge preservation and management are proposed.

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<sup>\*</sup>Topic identities in table 1.

## **Element Data in Bridge Preservation and Management**

The following are identified topics for element data:

- Evaluation of ADE and determination of its potential for adoption as NBE or BME.
- Element-based defect-reporting framework that includes damage location information.
- Development of an element data framework to accept BIM and digital as-built data that provide improved information for preservation and management decisionmaking (D4\*).

## **NDE/SM Data in Bridge Preservation and Management**

Following are identified topics for NDE/SM data:

- Development of bridge preservation planning, project costs, and quantity estimations for bridges, with and without NDE/SM data (D1\*).
- Integration of construction and sensing data (e.g., light detection and ranging (LiDAR), UAV, and NDE/SM data) into 3D bridge models or digital as-builts to facilitate more efficient and effective bridge preservation and management decisionmaking (D2\*).
- AI-based and big-data-based approaches for NDE/SM data analysis that support effective bridge preservation and management decisionmaking.
- Use of WIM data, NDE/SM data, and inventory data to determine the live-load effect on the performance of bridge components or elements and preservation decisionmaking.
- Use of NDE/SM data to enhance early deterioration modeling and improve preservation and maintenance decisionmaking (D3\*).
- UAV, unmanned water vehicle, and unmanned ground vehicle data in bridge preservation and asset management decisionmaking.
- The possibility of collecting NDE or other sensing data from deck bottoms (e.g., via UAV) and the use of such data in deck preservation and management decisionmaking.

## **Other Data for Bridge Preservation and Management**

Following are identified topics for other data:

- Development of a bridge maintenance data collection framework to understand bridge preservation activities (D5\*).
- Evaluation of potential bridge preservation applications using currently available but underused data (D6\*).

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\*Topic identities in table 1.

- Identification of data needs for post-extreme-event bridge repair or rebuild decisionmaking (D7\*).

## **BRIDGE PRESERVATION AND MANAGEMENT OF LIFECYCLE PLANNING**

Based on identified gaps, research topics are proposed for cost modeling, deterioration modeling, and decision making.

### **Cost modeling**

Following are topics for cost modeling:

- Lifecycle cost savings due to adopting new materials and new technologies in bridge preservation (P4\*).
- Quantification of the effects of bridge preservation activities (P2\*).

### **Deterioration modeling**

Following are topics for deterioration modeling:

- Development of element and health-index-based deterioration modeling (P3\*).
- Live-load effects on bridge performance and impacts on preservation and management decisionmaking (P5\*).
- Deterioration modeling that considers the impacts of climate change and other environmental factors.
- Deterioration model of structural capacity (load-rating deterioration modeling).
- Bridge resilience and how it affects bridge preservation and asset management decisionmaking.

### **Decisionmaking**

Following are topics for decisionmaking:

- Methods to integrate risk assessment into bridge preservation and management decisionmaking (P1\*).
- Quantification of the effects of bridge preservation activities through accelerated laboratory testing, field testing, and inventory data analysis (P2\*).
- Bridge preservation decisionmaking that considers environmental costs and resilience.

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\*Topic identities in table 1.

- Performance-based and risk-based bridge preservation and management planning.
- Network-level and lifecycle bridge preservation and management planning.

## **ECOFRIENDLY AND SUSTAINABLE MATERIALS AND TECHNOLOGIES FOR BRIDGE PRESERVATION AND REPAIR**

Based on the identified gaps, the following research topics are proposed:

- Sustainable and innovative techniques and materials for bridge and tunnel preservation or repair (S1\*).
- Consideration of environmental costs of bridge preservation and asset management decisionmaking and planning.
- Preservation techniques to improve bridge resilience and protect bridges from natural and man-made hazards.

## **BRIDGE DECK PRESERVATION AND MANAGEMENT**

Based on the identified gaps, the following research topics are proposed:

- Identification of standard tests for quality assurance and performance evaluation of deck preservation activity (B1\*).
- Performance of UHPC overlays:
- Accelerated testing data.
- Field data.
- Validation and calibration of testing data with field data.
- Use of testing data to predict performance.
- LCCA.
- Bridge deck lifecycle preservation and management planning.
- Performance of fiber-reinforced concrete for bridge deck and deck overlay (B2\*).
- Ecofriendly materials and techniques for bridge deck preservation and repair.
- Live-load effects on bridge deck performance and impact on preservation and management decisionmaking.

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\*Topic identities in table 1.



- Impact of climate change on bridge deck performance, preservation, and improvement in decisionmaking.

## **PRESERVATION OF SUPERSTRUCTURE AND SUBSTRUCTURE**

Based on the identified gaps, the following research topics are proposed:

- Identification of performance matrix and testing methods to measure the effectiveness of bridge substructure and superstructure preservation techniques.
- UHPC shotcrete for bridge superstructure and substructure preservation (B4\*).
- Case study for beam end repair of prestressed concrete beams, steel girders, and other beams.
- Early deterioration and damage detection and treatment and prevention of deterioration and damage of substructures.
- Fire damage monitoring, reporting, repair, and prevention (B5\*).
- Vehicle and vessel collision monitoring, reporting, repair, and prevention (B5\*).
- Identification of effective approaches to substructure and superstructure preservation (B6\*).

## **PRESERVATION OF BRIDGE PILES**

Based on the identified gaps, the following research topics are proposed:

- Impact of environmental factors and live load on bridge pile performance, preservation, and management decisionmaking.
- Bridge pile lifecycle preservation and management planning (B6\*).
- Performance and preservation needs of UHPC piles and LCCA.
- Performance and preservation needs of FRP pile in marine environments and LCCA.
- Case study for FRP repair of bridge pile.
- Underwater NDE robot or SM systems for pile performance evaluation and integration of data into pile preservation decisionmaking.
- SM for the performance of deteriorated or damaged piles and use of data in management decisionmaking.

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\*Topic identities in table 1.

- Identification of performance matrix and testing methods to measure the effectiveness of pile preservation techniques.

## PRESERVATION OF WATERTIGHT JOINTS

Based on the identified gaps, the following research topics are proposed:

- Guidelines for link slab design, construction, inspection, and preservation (B3\*).
- Case study, best practices, performance measurements, deterioration modeling, and LCCA for the following:
  - Expansion joints.
  - Link slab (guidelines for design, construction, and performance evaluation).
  - Joint elimination (semi-integral abutment, link slab, etc.) and jointless bridges.
  - Longitudinal joints.

With the comments from the FHWA internal review, the author selected high-priority topics, which are shown in table 1.

**Table 1. High-priority bridge preservation research topics.**

Category	Topic ID	Topic
Planning	P1	Develop methods to integrate risk assessment into bridge preservation and management decisionmaking.
	P2	Quantify the effects of bridge preservation activities.
	P3	Develop element- and health-index-based deterioration models.
	P4	Assess LCCA and performance of new materials and new technologies in bridge preservation.
	P5	Evaluate live-load effects on bridge performance and how they affect preservation and management decisionmaking.
Data	D1	Develop bridge preservation planning, project costs, and quantity estimations for bridges, with and without NDE/SM data.
	D2	Integrate construction and sensing data (e.g., LiDAR, UAV, and NDE/SM data) into 3D bridge models or digital as-builts to facilitate more efficient and effective bridge preservation and management decisionmaking.
	D3	Develop methods to leverage NDE/SM data to enhance early deterioration modeling and improve preservation and maintenance decisionmaking.
	D4	Develop an element data framework that accepts BIM and digital as-built data and provides enhanced information for preservation and management decisionmaking.

\*Topic identities in table 1.

<b>Category</b>	<b>Topic ID</b>	<b>Topic</b>
	D5	Develop a bridge maintenance database framework.
	D6	Identify available but underused data and evaluate the data's potential benefit in bridge preservation and management decisionmaking.
	D7	Identify unique data needs for post-extreme-event bridge repair or rebuild decisionmaking.
Sustainability	S1	Develop or identify sustainable techniques and materials for bridge preservation and repair.
Corrosion	C1	Identify performance and preservation needs for corrosion-resistant rebar (e.g., stainless steel, CFRP/GFRP, MMX, CGR, epoxy coated, and new textured epoxy rebar), reinforced bridge components and elements (e.g., deck, superstructure, substructure, and piles).
	C2	Identify performance and preservation needs for bridge components and elements with duplex coatings.
	C3	Assess cost, performance, and service life extension of corrosion protection, prevention, and mitigation techniques.
Preservation of bridge components	B1	Identify evaluation methodology (including standard tests) and data framework for quality assurance and performance evaluation for deck preservation activities.
	B2	Evaluate the performance of fiber-reinforced concrete for bridge decks and deck overlays.
	B3	Develop guidelines for link slab design, construction, inspection, and preservation.
	B4	Assess UHPC shotcrete or other applications for bridge preservation.
	B5	Develop methods to monitor, report, repair, and prevent fire damage and vehicle and vessel collisions.
	B6	Evaluate techniques for the preservation of bridge piles, substructures, and superstructures.
	B7	Develop performance criteria, corrective actions, and optimization for bridge approach systems.



## CHAPTER 6. REVIEW AND RANKING

A draft of this document went through FHWA internal and external review, and the author collected feedback. The following describes the review and feedback collection procedure:

- The first draft of the roadmap was sent for review to engineers in FHWA's Office of Infrastructure Research and Development, the FHWA senior bridge preservation engineer, the FHWA senior bridge management engineer, and all team leaders of FHWA structure disciplines. The draft was revised to address their comments, and a list of high-priority bridge preservation research topics was created. The updated version was sent to the same group of FHWA personnel for further followup.
- The revised draft was sent for external review. A small WG consisting of BPETG members was formed to conduct the first round of external review. The author received and incorporated the WG's input regarding topic grouping and ranking.

The third draft version was distributed to members of the TSP2 national deck preservation WG members, the AASHTO Bridge Preservation Technical Subcommittee (T-9), and FHWA BPETG for final external review. Presentations were given to the TRB Bridge Preservation Committee (TRB AKT60), AASHTO T-9, the small WG, and FHWA BPETG to collect feedback. FHWA BPETG members were asked to select their top three topics from the high-priority project list. Fifteen responses were received. Collective responses showed interest in the following 13 topics, in priority order:

1. P2: Quantify the effects of bridge preservation activities.
2. P1: Develop methods to integrate risk assessment into bridge preservation/management decisionmaking.
3. D5: Develop an NBMD framework. Develop a bridge maintenance data collection framework to understand bridge preservation activities.
4. B1: Identify evaluation methodology (including standard tests) for quality assurance and performance evaluation for deck preservation activities.
5. P4: Assess the LCCA and performance of new materials and new technologies in bridge preservation.
6. D3: Leverage NDE/SM data to enhance the early deterioration modeling and improve preservation/maintenance decisionmaking.
7. C1: Identify performance and preservation needs for corrosion-resistant rebar (e.g., stainless steel, CFRP/GFRP, MMX, CGR, black rebar, epoxy coated, new textured epoxy rebar)-reinforced bridge components/elements (e.g., deck, superstructure, substructure, and piles).

8. C3: Assess cost, performance, and service life extension of corrosion protection, prevention, and mitigation techniques.
9. P5: Evaluate the live-load effects on bridge performance and how they impact preservation and management decisionmaking.
10. B6: Evaluate techniques for preserving bridge piles, substructures, and superstructures.
11. P3: Develop element and health-index-based deterioration models.
12. D2: Integrate construction and sensing data (e.g., LiDAR, UAV, NDE/SM data) into 3D bridge models or digital as-builts to facilitate more efficient and effective bridge preservation and management decisionmaking.
13. D4: Develop an element data framework to accept BIM and digital as-built data that provide improved information for preservation and management decisionmaking.

A priority score for each topic was calculated for the top three topics received in the voting, and the preceding list shows the computed priorities. However, due to the limited number of votes received, the rankings may not be accurate. Research with an immediate application received more interest. Topics not receiving priority interest are typically more innovative and may be associated with relatively higher risk. If aligned well with organizational strategic goals, an innovative, high-risk project also could be an important component of the research portfolio.

## CHAPTER 7. STATEMENT FOR SELECTED TOPICS

The author developed short descriptions of the topics shown in table 1. Table 2 shows the statements for the 10 topics that were rated higher by BPETG and other stakeholders. Descriptions of other topics can be found in the appendix.

AASHTO made a 2024 NCHRP project selection recently. The project, called Incorporate Risk Management in Maintenance Practice (NCHRP 23-38), may cover some aspects of topic P1.<sup>(50)</sup> NCHRP 20-05 (Topic 55-01 State DOT Use and Policies on Implementation of Corrosion Resistant Reinforcing Bars), covers some parts of topic C1.<sup>(51)</sup> NCHRP 20-05 originated from topic C1 and ranked high in the stakeholders’ top 10 list. Close followup of those two NCHRP projects is necessary to avoid duplicate research and identify new research needs as practical.

Consider the similarities and correlations between topics D2, D3, and D4, which have been combined into a topic called Leverage Digital As-Built, Operational, and Sensing Data to Bridge Preservation and Management. The combined project will identify data needs for bridge management; evaluate the data source, collection costs, data management, and interface with bridge management systems; and manage automated data integration and model updating to optimize bridge management decisionmaking in a BIM-compatible way. The project can be part of FHWA infrastructure digitization (e.g., digital as-built, digital twin, and BIM) efforts.

**Table 2. Statements for the top 10 research topics.**

ID	Topic	Short Statement	Estimated Project Duration
D5	Develop a bridge maintenance data collection framework to understand bridge preservation activities.	<ul style="list-style-type: none"> <li>• Conduct a survey for the state of practice of maintenance data collection.</li> <li>• Improve the efficiency and effectiveness of data collection, sharing, and utilization with a consistent data framework.</li> <li>• Develop guidelines for maintenance data collection by analyzing existing State-collected data and updating the NCHRP 14-15 framework to reflect new NBI and BIM requirements.<sup>(47,7)</sup></li> <li>• Develop a tiered data collection strategy so stakeholders can collect data at a minimum level or include more data.</li> <li>• Understand bridge preservation activities from collected data.</li> </ul>	2–3 yr

<b>ID</b>	<b>Topic</b>	<b>Short Statement</b>	<b>Estimated Project Duration</b>
P2	Quantify the effects of bridge preservation activities.	<ul style="list-style-type: none"> <li>• Select activities for this study.</li> <li>• Collect/acquire bridge preservation/maintenance data and testing data if available.</li> <li>• Evaluate the benefits of the activities through inventory data analysis, accelerated laboratory testing, and field testing.</li> <li>• Evaluate the lifecycle cost (in terms of financial and environmental costs, if possible) for each activity.</li> </ul>	3 yr
Combined D2, D3, and D4	Leverage digital as-built, operational, and sensing data in bridge preservation and management decisionmaking.	<ul style="list-style-type: none"> <li>• Define the bridge asset management workflow and data needs.</li> <li>• Determine the data sources and data collection cost associated with each data requirement.</li> <li>• Optimize the data items for bridge preservation/management decisionmaking through cost-benefit evaluation.</li> <li>• Make the identified data items available or accessible for bridge management systems. BIM compatibility will also be studied.</li> <li>• Automate the data-leveraging procedure.</li> <li>• Conduct a pilot case study to demonstrate the work.</li> </ul>	3 yr
B1	Develop a quality control procedure and performance evaluation of bridge preservation activities.	<ul style="list-style-type: none"> <li>• Establish quality control procedures and performance evaluation procedures for bridge preservation activities.</li> <li>• Research and develop guidelines for quality control procedures and performance evaluation procedures for selected preservation activities.</li> </ul>	3 yr



ID	Topic	Short Statement	Estimated Project Duration
P4	Assess the lifecycle cost and performance of new materials and new technologies in bridge preservation.	<ul style="list-style-type: none"> <li>• Identify new materials and new technologies for study.</li> <li>• Collect/acquire cost data for new materials and new technologies.</li> <li>• Develop lifecycle preservation plans that use new materials and new technologies based on LCCA.</li> </ul>	2–3 yr
P5	Evaluate live-load effects on bridge performance and how they affect preservation decisionmaking.	<ul style="list-style-type: none"> <li>• Identify live-load impacts on bridge performance, which is important due to the ever-increasing truck weight, next generation trucks and truck operation.</li> <li>• Investigate how WIM data can be used to establish general and bridge specific live load model</li> <li>• Investigate how to quantify live-load effect on bridge deck deterioration, fatigue service life, and capacity etc. through analysis and/or field testing which may involve NDE/SM data and inventory data</li> <li>• Investigate preservation activities that are more effective for heavy load-caused deterioration.</li> <li>• Investigate preservation and management decisionmaking strategies considering live load effects</li> <li>• Demonstrate the work with one or two case studies</li> </ul>	2–3 yr
C1*	Identify performance and preservation needs for corrosion-resistant rebar (e.g., stainless steel, CFRP/GFRP, MMX, CGR, epoxy coated, new textured epoxy rebar) reinforced bridge components/elements (e.g., deck, superstructure,	<ul style="list-style-type: none"> <li>• Establish a database for bridges with corrosion-resistant rebar (starting with stainless steel rebar and bridge deck) and reinforced components and elements. Develop a data dictionary and start populating it with data.</li> <li>• Determine field performance from inventory data or laboratory or field-testing data if available.</li> <li>• Correlate field performance (from inventory or field testing) with</li> </ul>	

<b>ID</b>	<b>Topic</b>	<b>Short Statement</b>	<b>Estimated Project Duration</b>
	substructure, and piles).	<p>accelerated laboratory-testing data, if available, to validate the testing. After validation, laboratory testing can be used to predict future performance data, which is rarely available or expensive to collect.</p> <ul style="list-style-type: none"> <li>• Collect cost data and perform LCCA to show the benefit of using stainless steel rebar, GFRP rebar, and other corrosion-resistant rebar in bridge deck and corrosion-prone zones.</li> <li>• Recommend using the stainless-steel rebar type in bridge deck, superstructure, and substructure. Investigate maintenance needs, if any.</li> <li>• Quantify the benefit of using corrosion-resistant rebar in service life design.</li> </ul>	
B6	Evaluate techniques for the preservation of bridge piles, substructures, and superstructures.	<ul style="list-style-type: none"> <li>• Identify effective preservation techniques through a literature review.</li> <li>• Conduct an indepth survey/interview with bridge owners to document the state-of-practice procedure.</li> <li>• Conduct LCCA if practical.</li> <li>• Identify and document best practices.</li> </ul>	2–3 yr
P1*	Develop methods to integrate risk assessment into bridge preservation and management decisionmaking.	<ul style="list-style-type: none"> <li>• Develop a risk evaluation framework that includes or facilitates the following: <ul style="list-style-type: none"> <li>○ Investigate bridge deterioration-caused risks.</li> <li>○ Investigate climate change (e.g., changes in temperature, precipitation, freeze–thaw cycle)-caused risks.</li> <li>○ Evaluate extreme events (e.g., hurricane, wildfire, flood, earthquake)-caused risks.</li> <li>○ Investigate the combined multihazard risk.</li> </ul> </li> <li>• Investigate bridge resilience and sustainability.</li> <li>• Develop a data collection framework for before, during, and after event</li> </ul>	3 yr

<b>ID</b>	<b>Topic</b>	<b>Short Statement</b>	<b>Estimated Project Duration</b>
		<p>condition evaluation. Sensing technologies are needed in data collection.</p> <ul style="list-style-type: none"> <li>Investigate and develop a risk-based preservation and management decisionmaking framework and demonstration tool. AI and big-data approaches can be used.</li> </ul>	
C3**	Assess the costs, performance, and service life extensions of corrosion protection, prevention, and mitigation techniques.	<ul style="list-style-type: none"> <li>Identify corrosion protection, prevention, and mitigation technologies (e.g., galvanic coating, cathodic protection) to be studied.</li> <li>Collect cost and performance data.</li> <li>Conduct a case study to develop practice guidelines for identified techniques.</li> </ul>	3 yr

\*Recently funded project NCHRP 23-38 is closely related to topic P1. FHWA will follow up to avoid duplicate research and identify new needs as practical.<sup>(50)</sup>

\*\*More specific research needs will be identified after the report on FHWA corrosion peer exchange is available.<sup>(51)</sup>



## CHAPTER 8. CONCLUSIONS

As State DOT bridge preservation programs mature and more bridges in poor condition get replaced, proactive bridge preservation is becoming a cost-effective tool for maintaining the bridge inventory in a state of good repair. In the meantime, considering service life during bridge design and balancing bridge rehabilitation and replacement are also important preservation decisions. Increasing knowledge of bridge preservation materials, technologies, and decisionmaking strategies is becoming more helpful in optimizing limited funds. This roadmap represents a strategic approach to bridge preservation research needs for FHWA and may also be used by other agencies or organizations. In addition to addressing research gaps, this roadmap addresses emerging technologies and innovative techniques. This roadmap is a living document and will be updated periodically to reflect completed work and new research needs.



## APPENDIX. STATEMENTS FOR OTHER TOPICS

In table 3, short descriptions were developed for high-ranking topics that were not selected for the top 10 list.

**Table 3. Statements for other topics.**

ID	Topic	Short Description
P3	Develop health-index-based and risk-based deterioration models for bridge preservation decisionmaking.	<ul style="list-style-type: none"> <li>• Conduct a literature review and case study.</li> <li>• Compile AASHTO element or component data from NBI.<sup>(7)</sup></li> <li>• Develop a health index from element data (consider including extra data).</li> <li>• Develop element-based and health index-based deterioration models using AI and big-data approaches.</li> <li>• Investigate if risk-based deterioration models are practical.</li> <li>• Investigate the framework for integrating NDE/SM data into element-based deterioration modeling (optional).</li> </ul>
D3	Develop methods to use NDE/SM data to enhance the early deterioration modeling and improve preservation and maintenance decisionmaking.	<ul style="list-style-type: none"> <li>• Research NDE/SM techniques (including load testing) that are effective for enhanced condition evaluation, especially for early damage and deterioration detection.</li> <li>• Improve preservation and maintenance decisionmaking by integrating NDE/SM data into the decision procedure.</li> </ul>
D2	Integrate construction or sensing data (e.g., LiDAR, UAV, NDE/SM data) into 3D bridge models or digital as-builts to facilitate more efficient and effective bridge preservation and management decisionmaking.	<ul style="list-style-type: none"> <li>• Integrate bridge construction data (including cost and sensing data) into the project information model to obtain digital as-builts.</li> <li>• Develop workflow and an information delivery manual for BIM-based bridge asset management framework.</li> <li>• Develop a process to update the project information model with sensing data (e.g., NDE/SM data, UAV data, and LiDAR data).</li> <li>• Use model in preservation, management, and postevent decisionmaking.</li> <li>• Determine lifecycle cost savings due to adoption of BIM-based design, construction, and asset management approaches.</li> </ul>

ID	Topic	Short Description
D4	Develop an element data framework to accept BIM and digital as-built data that provide improved information for preservation and management decisionmaking.	<ul style="list-style-type: none"> <li>• Develop a data framework that provides more element-data information (e.g., report damage systematically).</li> <li>• Allow seamless BIM or digital twin model updating for any element data update.</li> </ul>
D1	Develop bridge preservation planning, project cost, and quantity estimation for bridges— with and without NDE/SM data.	<ul style="list-style-type: none"> <li>• Investigate how deterioration models can be improved by NDE/SHM data.</li> <li>• Investigate network-level bridge preservation planning for bridges with and without NDE/SHM data.</li> <li>• Investigate how NDE/SHM data can improve preservation planning at the project level.</li> </ul>
D6	Identify available but underused data and evaluate the data’s potential benefit in bridge preservation and management decisionmaking.	<ul style="list-style-type: none"> <li>• Incorporate data currently collected by State DOTs or FHWA programs or projects. Many bridge preservation engineers are not aware of this data, and therefore, such data are not fully used in bridge preservation decisionmaking: <ul style="list-style-type: none"> <li>○ Design and construction data (digital as-built).</li> <li>○ HPMS, such as WIM data.</li> <li>○ Traffic data and collision data.</li> <li>○ Climate data.</li> <li>○ Other data to be identified.</li> </ul> </li> <li>• Collect bridge damage and deterioration reported by the public on social media sites (may consider establishing a system for the public to report this type of finding in the future).</li> <li>• Evaluate the data to determine their applications in bridge preservation decisionmaking.</li> <li>• Develop a decisionmaking tool that uses the identified data.</li> <li>• Evaluate the results and benefits.</li> </ul>
D7	Identify unique data needs for post-extreme-event bridge repair, rehabilitation, or rebuild decisionmaking.	<ul style="list-style-type: none"> <li>• Investigate the data (e.g., UAV data and other remote-sensing or image data) need for post extreme-event bridge condition evaluation and repair, rehabilitation, or rebuild decisionmaking.</li> <li>• Investigate the data application approaches.</li> <li>• Evaluate the improvement (e.g., cost saving) by using the data.</li> <li>• Develop a decision tool that involve using the identified data.</li> </ul>



ID	Topic	Short Description
S1	Identify sustainable techniques for bridge and tunnel preservation and repair.	<ul style="list-style-type: none"> <li>• Investigate sustainable materials and techniques that can be used for bridge and tunnel preservation and repair.</li> <li>• Develop case studies and guidelines for applying identified materials and techniques.</li> <li>• Perform LCCA and lifecycle emission analysis.</li> </ul>
C2	Identify performance and preservation needs for bridge components and elements with duplex coating rebar.	<ul style="list-style-type: none"> <li>• Investigate the field performance of the coating systems of the 80 or so bridges in the United States known to have duplex coatings.</li> <li>• Identify potential maintenance needs.</li> <li>• Perform LCCA.</li> </ul>
B2	Evaluate the performance of fiber-reinforced concrete for bridge decks and deck overlays.	<ul style="list-style-type: none"> <li>• Evaluate fiber-reinforced concrete because it shows potential in solving the problem of deck cracking, a common problem of bridge decks.</li> <li>• Investigate the performance of fiber-reinforced concrete deck or overlay.</li> <li>• Investigate the possibility to use steel fiber to facilitate EV charging.</li> </ul>
B3	Develop guidelines for link slab design, construction, inspection, and preservation.	<ul style="list-style-type: none"> <li>• Link slab has shown advantages in extending deck service life. A national policy or guideline has not yet been developed.</li> <li>• Investigate the underused technology of link slab and its performance.</li> <li>• Perform LCCA to justify the value of the technology.</li> </ul>
B4	Assess UHPC shotcrete or other applications for bridge preservation.	<ul style="list-style-type: none"> <li>• Conduct a literature review for UHPC shotcrete applications and interview selected early adopters.</li> <li>• Evaluate UHPC shotcrete material characteristics and application procedures.</li> <li>• Evaluate the performance of UHPC shotcrete for preservation of bridge components.</li> </ul>
B5	Develop methods to monitor, report, repair, and prevent fire damage and vehicle and vessel collisions.	<ul style="list-style-type: none"> <li>• Develop the data framework and reporting procedure for fire and collision events.</li> <li>• Investigate sensing and prevention systems for fire and collision events.</li> <li>• Investigate fire damage repair and prevention technologies.</li> <li>• Investigate collision damage repair and prevention technologies.</li> </ul>

<b>ID</b>	<b>Topic</b>	<b>Short Description</b>
B7	Develop performance criteria, corrective actions, and optimization for bridge approach systems.	<ul style="list-style-type: none"> <li>• Investigate current bumps at bridge entrances/ends, which are common, especially for bridges with stub abutments. The bumps can cause larger live-load impact and discomfort for drivers and passengers.</li> <li>• Conduct a study for best design and construction practice to reduce bump formation.</li> <li>• Develop the specification of performance criteria for bridge approaches and how to achieve the desired performance through cost-effective design, construction, and maintenance practices.</li> <li>• Recommend early preservation intervention activities and their effects.</li> </ul>

\*Recently funded NCHRP synthesis topic 55-01 is similar to topic C1.<sup>(52)</sup> FHWA will follow up to avoid duplicate research and identify new needs.

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