Incorporating Nondestructive Evaluation Methods Into Bridge Deck Preservation Strategies

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Highway Research Center

FOREWORD

In its administration of the Federal-Aid Highway Program, the Federal Highway Administration has placed increasing focus on the use of data-driven decisionmaking. This process enables proactive and timely maintenance and preservation actions to ensure highway infrastructure remains in a state of good repair.

Nondestructive evaluation (NDE) technologies provide the opportunity to harness objective, repeatable measurements to supplement traditional visual inspection methods in assessing bridge deck conditions and to inform asset management decisions. This report summarizes the state-of-the-art for using NDE to determine conditions of highway bridge decks. The report outlines a framework to move the industry toward greater adoption of NDE into practice, which is expected to increase the safety and efficiency of condition assessment and improve the selection and timeliness of preservation actions.

This report serves as a resource for State highway agencies and decisionmakers striving to enhance their asset management strategies through the integration of NDE technologies with preservation practices.

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16. Abstract

The use of nondestructive evaluation (NDE) for the condition assessment of bridge decks is growing and has the potential to reduce operating costs and extend lifecycles by fostering cost-effective and timely interventions. Highway agencies recognize that preservation treatments can impact the lifecycle costs of bridges. Several NDE technologies identify and characterize deck configurations and deterioration caused by corrosion, cracking, delamination, and other forms of degradation. This study reviewed the current state of practice and provided a framework and recommendations for applying NDE to inform decisionmaking. Typical bridge preservation actions are synthesized for common highway bridge deck and wearing surface types, and applicability of various NDE technologies is summarized. The framework is introduced with real-life and hypothetical case studies, to demonstrate the viability of NDE to inform preservation treatment selection and prioritization. The framework covers three stages in the lifecycle of a typical bridge deck: new construction; early- to middle-aged structures in service; and planning for repair, rehabilitation, or replacement of the deck. Several NDE methods provide benefit based on the maturity of methods, level of acceptance, and relevance of data to assessing and predicting deck conditions. Lifecycle cost analysis explores savings in case studies by comparing the combined cost of NDE and intervention costs to the cost of not implementing NDE-informed actions. Generally, the cost of NDE was negligible versus benefits over the lifecycle of a bridge deck.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

3D	three dimensional
AADT	average annual daily traffic
AAR	alkali-aggregate reaction
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACS	automated concrete sounding
ADT	average daily traffic
AI	artificial intelligence
ASR	alkali-silica reaction
ASTM	ASTM International
BMS	bridge management system
BPM	bridge preventative maintenance
CA	compromised area
CASLE	corrosion and service life evaluation (model)
CDOT	Colorado Department of Transportation
CF	chloride front
CI	cracking index
Cl^-	chloride
CP	cathodic protection
CRF	capital recovery factor
CS	condition state
CSE	copper–copper sulfate electrode
DIC	digital image correlation
DMI	distance-measuring instrument
DOT	Department of Transportation
DRBA	Delaware River and Bay Authority
ECE	electromechanical chloride extraction
EIS	electrochemical impedance spectroscopy
ER	electrical resistivity
EUAC	equivalent uniform annual cost
FHWA	Federal Highway Administration
FRP	fiber-reinforced polymer
GCR	general condition rating
GPM	galvanostatic pulse method
GPR	ground-penetrating radar
GPS	global positioning system
HCP	half-cell potential
HMA	hot-mix asphalt
HMWM	high-molecular weight methacrylate
HMAWM	hot-mix asphalt with membrane
HPC	high-performance concrete
HRI	high-resolution imagery
HRV	high-resolution visual
HS	high speed

HSCD	hammer sounding, and chain drag
IDOT	Illinois Department of Transportation
Iowa DOT	Iowa Department of Transportation
IE	impact echo
INDOT	Indiana Department of Transportation
IRT	infrared thermography
IR-UTD	ultra-time domain infrared thermography
LCC	lifecycle cost
LCCA	lifecycle cost analysis
LiDAR	laser imaging, detection, and ranging
LMC	latex-modified concrete
LOS	line of sight
LPR	linear polarization resistance
LRFD	load and resistance factor design
LS	low speed
LSDC	low-slump dense concrete
MBE	AASHTO's *The Manual for Bridge Evaluation*
MBEI	AASHTO's *Manual for Bridge Element Inspection*
MDOT	Michigan Department of Transportation
MnDOT	Minnesota Department of Transportation
MFL	magnetic flux leakage
MM	magnetometer
MSC	microsilica concrete
NaCl	halite
NBE	national bridge element
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standards
NDE	nondestructive evaluation
NJDOT	New Jersey Department of Transportation
NPC	net present cost
NYSDOT	New York State Department of Transportation
ODOT	Oregon Department of Transportation
OMB	Office of Management and Budget
PC	portland cement
PCC	portland cement concrete
PCI	Precast/Prestressed Concrete Institute
PMA	polymer-modified asphalt
PPC	premixed polymer concrete or polyester polymer concrete
PSPA	portable seismic property analyzer
PV	present value
RH	relative humidity
RILEM	Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages [International Union of Laboratories and Experts in Construction Materials, Systems and Structures]
ROI	return on investment
SAFT-C	synthetic aperture focusing technique with combinational sounding

SASW	spectral analysis of surface waves
SBS	styrene-butadiene-styrene
SCM	supplementary cementitious material
SDDOT	South Dakota Department of Transportation
SFC	silica-fume concrete
SHA	State Highway Agency
SHRP	Strategic Highway Research Program
SHRP 2	Second Strategic Highway Research Program
SI	system identification; also susceptibility index
SIP/SIPMF	stay-in-place metal forms
SLAM	simultaneous location and mapping
SM	structural monitoring
SF	square ft
TPO/TBPO	thin(-bonded) polymer overlay
TIS	time in state
UAV	unmanned aerial vehicle
UDOT	Utah Department of Transportation
UHPC	ultra-high-performance concrete
UPV	ultrasonic pulse velocity
USW	ultrasonic surface waves
UT/UST	ultrasonic testing
VDOT	Virginia Department of Transportation
w/cm	water-to-cementitious materials ratio
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

The use of nondestructive evaluation (NDE) and structural monitoring (SM) technologies for condition assessment of bridge decks is growing and has the potential to reduce operating costs and extend lifecycles by fostering cost-effective and timely interventions. Highway agencies recognize that preservation treatments can impact the lifecycle costs of bridges. Several NDE technologies that identify and characterize deck configurations and deterioration caused by corrosion, cracking, delamination, and other forms of degradation have evolved. SM can monitor bridge deck conditions when combined with analytical models and empirical relationships to predict deck performance. Each of these technologies might be leveraged to support the selection and planning of preservation activities.

This study reviews the current state of practice and provides a framework and recommendations for applying NDE to inform decisionmaking for bridge deck preservation treatment selection and planning. Although SM is considered, SM has limited applicability for the evaluation and management of bridge decks, so it is not further explored. The current state of practice for NDE reported herein is based on a detailed literature review, a limited questionnaire, and interviews with select departments of transportation (DOTs). The range of typical bridge preservation actions is synthesized for the most common highway bridge deck and wearing surface types, and the applicability of various commercially available NDE technologies is summarized. In current practice, high-resolution imaging, ground-penetrating radar, acoustic wave methods, infrared thermography, and half-cell potential are the most common and applicable NDE methods for bridge decks.

The number of permutations of wearing surface types and potentially applicable NDE methods is large, and insufficient data on these methods are publicly available to develop specific trigger and selection criteria for each one. Therefore, a general framework is introduced, supported by specific real-life and hypothetical case studies, to demonstrate the viability of NDE to directly inform preservation treatment selection and prioritization. The framework covers three stages in the lifecycle of a typical bridge deck: new construction; early- to middle-aged structures in service; and planning for repair, rehabilitation, or replacement of the deck. Applications and associated case studies discuss corridor- or network-level applications for screening and prioritizing action and project-level applications for identifying projected or current deterioration and making bridge-specific decisions for preservation or rehabilitation. The potential economic benefit of the various applications is explored for the case studies.

This study finds many viable techniques for directly informing deck preservation decisions but highlights several techniques that appear to provide the clearest benefit based on the maturity of methods, level of acceptance, and relevance of data to assessing and predicting deck conditions. Some efforts have been made in research and practice to correlate NDE output with national bridge element condition states; however, the latter being based primarily on visual inspection leads to limitations and oversimplification of NDE data. Few agencies have progressed to using NDE as the direct input for bridge deck preservation or maintenance decisionmaking. Costs of NDE are variable and can be affected by the number and size of decks being evaluated. In this study, lifecycle cost analysis explores estimated savings from hypothetical and real-life case studies by comparing the combined cost of NDE and intervention cost to the cost of not

implementing actions that would be informed by NDE data. Generally, the cost of NDE was negligible compared to the potential benefits or savings over the lifecycle of a bridge deck.

CHAPTER 1. INTRODUCTION

The use of nondestructive evaluation (NDE) and structural monitoring (SM) technologies for condition assessment of bridge decks is growing and has the potential to reduce operating costs and extend lifecycles by fostering cost-effective and timely interventions. Highway agencies recognize preservation treatments can impact the lifecycle cost of bridges. Several NDE technologies that identify and characterize deck configurations and deterioration caused by corrosion, cracking, delamination, and other forms of degradation have evolved. SM can be used to monitor bridge deck conditions when combined with analytical models and empirical relationships to predict deck performance. Each of these technologies might be leveraged to support the selection and planning of preservation activities.

Traditionally, bridge engineers have assessed bridge decks' condition using visual and sounding surveys, supplemented by limited and focused destructive or nondestructive methods. Many agencies have established decision matrices that categorize decks for action based on condition ratings or condition state assessments based on these methods, and such matrices may generally prescribe courses of preservation treatments, repairs, rehabilitation, or replacement.

A wide array of NDE methods have evolved over recent decades that directly apply to highway structures. These technologies apply our understanding of physical principles (including physical stress and displacement concepts, mechanical or stress-wave propagation, electromagnetic properties of materials across the full frequency spectrum, and electrochemical and thermal principles) to indirectly obtain information about the configuration, condition, and performance of structural elements. Further, the ubiquity of digital data acquisition, the ease and low cost of storage, and rapid advancements in computer-based data processing are changing the landscape on condition assessment and asset decisionmaking for highway bridges and similar assets. NDE and SM technologies are making it more practical to obtain and analyze condition data that may indicate deterioration without waiting for such deterioration to manifest as spalling, delamination, cracking, or other visible forms of damage. Guidance is needed on when and how to use NDE and SM technologies for timely bridge deck condition assessment. Such guidance needs to consider not only the technical viability of the technologies but also their cost effectiveness and practicality for incorporation into production inspection and preservation decisionmaking processes.

The Federal Highway Administration (FHWA) has undertaken research to determine the feasibility and economics of incorporating NDE and SM methods into bridge deck preservation strategies for early detection and quantification of changes in bridge deck conditions. These methods can trigger timely preservation treatments that will prevent, delay, or reduce deterioration of existing bridge decks; restore their function; keep them in good condition; extend their life; and help determine the preservation treatment's quality. This report documents the state of practice regarding NDE methods and their application to deck preservation decisionmaking, followed by the identification of appropriate NDE methods for the range of common wearing surfaces and the associated inputs for the selection of preservation actions. A framework is then developed to guide the implementation and interpretation of NDE and the selection of treatment alternatives.

CHAPTER 2. METHODOLOGY

This study was executed by performing the following steps:

- Gathering background information from literature and departments of transportation (DOTs).
- Identifying deck and wearing surface types and their associated modes of deterioration.
- Compiling available NDE methods and associated applications for deck assessment.
- Developing effective decision framework for NDE-based preservation selection.
- Evaluating example case studies to show the economic benefits of NDE for deck preservation decisionmaking.

CURRENT STATE OF PRACTICE IN THE PRESERVATION ACTION DECISIONMAKING PROCESS

The first steps include the following actions:

- Identify the types of wearing surfaces or protective overlay systems. Applicable wearing surfaces include bare concrete decks, and thin bonded polymer overlays, asphalt overlays with or without membranes, latex-modified, and other cementitious rigid overlays on concrete decks. Considerations include concrete decks with stay-in-place forms and with partial-depth precast panels. Various types of deck reinforcing were also investigated for their service life and influence on applicable NDE methods.

- Identify common defects in decks that may influence the rate of moisture and deicer intrusion and their underlying causes. Applicable defects may include deck porosity, map cracking, spalling, and delamination.

- Determine the effective, appropriate, and proven NDE and SM technologies that may be used to identify changes in bridge deck conditions.

- The research team supplemented its expertise with the following activities: Conducting an extensive literature search.

- Distributing an electronic questionnaire to State and local agencies, accompanied by follow-up web-based interviews.

- Obtaining documented case studies in which different State highway agencies (SHA) have used NDE and SM technologies to make informed preservation-action decisions.

Where feasible, the team requested information about costs for procurement, deployment, operation, and maintenance of the technology. The result of these activities is a comprehensive review of the current state of practice, nationally and internationally, of proven NDE and SM technologies. Using this information, the research team developed guidance on how to effectively use NDE or SM methods when considering bridge preservation strategies.

THRESHOLDS FOR SPECIFIC PRESERVATION ACTIONS

Next, the researchers defined NDE and SM thresholds that can be used to trigger certain preservation actions for concrete bridge decks, which are by far the most used type of bridge decks in the United States. Based on a review of the current state of practice, SM methods are not widely used to assess the condition of bridge decks and, as such, preservation trigger thresholds will not be applicable for these methods. On the other hand, several NDE methods can be used to assess the condition of bridge decks, and several agencies are currently employing, or at least considering the implementation of, such methods to be conducted routinely to aid in better assessment of bridge deck conditions. This report includes a summary of the most common NDE methods used for condition assessment of bridge decks, and guidance on the appropriateness of different NDE techniques to detect certain defects.

DECISION MATRIX TO INCORPORATE NDE INTO BRIDGE PRESERVATION STRATEGIES

The researchers developed a decision matrix to indicate when certain conditions trigger specific preservation actions, with consideration for the accuracy and reliability of the various NDE methods deployed, as well as the environmental and external influences (e.g., chloride applications, level of chloride in the deck, air entrainment, freezing and thawing cycles, reinforcing bar coatings, traffic loads) that affect deck service life. This decision matrix and the costs associated with various intervention techniques provide a suite of economically advantageous deployment strategies. The researchers developed a decision framework in the form of a decision tree process through which one or more NDE methods can be implemented to inform specific preservation decisions through the life of the asset. The researchers then illustrated the application of NDE in this framework through the series of use cases and the discussion of economic impact from the previous task.

ECONOMICS OF INCORPORATING NDE INTO BRIDGE PRESERVATION STRATEGIES

Finally, the cost of NDE-informed intervention cost was compared to the cost of not collecting NDE data and enacting intervention based on traditional visual and sounding methods. Such a comparison can define potential “savings” associated with finding specific types of deterioration at an earlier stage. While we present cases for selected NDE technologies, the framework presented here can be applied to other technologies as well when quantifying the economics of incorporating NDE technologies to guide bridge deck preservation. The lifecycle cost analysis (LCCA) presented in this report illustrates the economic impact of using NDE and making bridge management decisions with the NDE information compared to making decisions based on traditional visual inspection or sounding methods. In conjunction with the decision framework developed, hypothetical cases or real-life case studies are presented to illustrate the value of NDE information in providing a more indepth condition assessment than traditional methods, which enables agencies to make more cost-effective decisions.

CHAPTER 3. LITERATURE REVIEW

OVERVIEW OF TYPES OF BRIDGE DECK SYSTEMS AND WEARING SURFACES

Highway bridge decks in the United States are commonly built using reinforced or prestressed concrete, steel, and timber. A recent snapshot from National Bridge Inventory (NBI) data shows that out of a total inventory of 618,456 bridges and culverts greater than 20 ft, 430,313 are bridges excluding bridge-sized culverts. Those records indicate that concrete bridge decks are the most widely used type of deck at 87.3 percent of bridge decks by number of structures. Steel and timber decks represent 3.2 percent and 6.8 percent, respectively.

Table 1 summarizes common defects associated with common deck types. The American Association of State Highway and Transportation Officials (AASHTO) *Manual for Bridge Element Inspection* (MBEI) specifically defines defects and associated condition states (CS) 1 through 4 as good, fair, poor, and severe, respectively, for Element 12—Reinforced Concrete Deck, as shown in table 2 (AASHTO 2022).

Table 1. Common deck and wearing surface defects (AASHTO 2022).

Reinforced Concrete Deck	Prestressed Concrete Deck	Steel Deck	Timber Deck	Wearing Surface
Delamination/spall/ patched area	Delamination/spall/ patched area	Corrosion	Decay or section loss	Delamination/ spall/patched area
Exposed rebar	Exposed rebar and exposed prestressing	Cracking	Checks and shakes	Cracking
Efflorescence/rust staining	Efflorescence/rust staining	Connection *	Cracks (timber)	Effectiveness
Cracking	Cracking	—	Split/ delamination	—
Abrasion/wear	Abrasion/wear	—	Abrasion/wear	—
—	—	—	Connection*	—

*Refers to absence or presence of loose or missing fasteners, rust, distortion, or fractures that may impact function.
—No data.

Table 2. Defects and condition states for Element 12—Reinforced Concrete Deck (AASHTO 2022).

Defects	CS 1 Good	CS 2 Fair	CS 3 Poor	CS 4 Severe
Delamination/spall/ patched area (1080)	None.	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area that is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on the strength or serviceability of the element or bridge, or a structural review has been completed, and the defects impact the strength or serviceability of the element or bridge.
Exposed rebar (1090)	None.	Present without measurable section loss.	Present with measurable section loss but does not warrant structural review.	
Efflorescence/rust Staining (1120)	None.	Surface is white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC) (1130)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Abrasion/wear (PSC/RC) (1190)	No abrasion or wearing.	Abrasion or wearing has exposed coarse aggregate, but the aggregate remains secure in the concrete.	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.	
Settlement (4000)	None.	Exists within tolerable limits or is arrested with no	Exceeds tolerable limits but does not warrant	

Defects	CS 1 Good	CS 2 Fair	CS 3 Poor	CS 4 Severe
		observed structural distress.	structural review.	
Scour (6000)	None.	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in CS 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in CS 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in CS 4 under the appropriate material defect entry.

CS = condition state; RC = reinforced concrete; PSC = prestressed concrete.
Note: The numbers in parentheses indicate the item number associated with the specific defect, as defined in AASHTO MBEI (2022).

WEARING SURFACES

The wearing surface of the bridge deck is the surface over which vehicles ride. The wearing surface may be the bare bridge deck or an overlay, such as a cementitious rigid, bituminous, or polymer overlay. that has been applied to the top of the bridge deck to address deck deterioration mechanisms. Concrete protective coatings for decks include sealers and membranes. Sealers are not typically considered a wearing surface because they are often quite thin (negligible thickness to less than 0.25 inches) or only present in local areas of the deck. However, they are discussed here because they are commonly observed on wearing surfaces. The AASHTO *MBEI* specifically defines defects and associated CS 1 through 4 as good, fair, poor, and severe, respectively, for Element 510—Wearing Surfaces (table 3) (AASHTO 2011, AASHTO 2022, FHWA 2014). Defects and condition states for Element 521—Concrete Protective Coating is presented in table 4.

Table 3. Defects and condition states for Element 510—Wearing Surfaces (AASHTO 2022).

Defects	CS 1 Good	CS 2 Fair	CS 3 Poor	CS 4 Severe
Delamination/spall/ patched area/pothole (wearing surfaces) (3210)	None.	Delaminated. Spall less than 1 in. deep or less than 6 in. diameter. Patched area that is sound. Partial-depth pothole.	Spall 1 in. deep or greater or 6 in. diameter or greater. Patched area that is unsound or showing distress. Full-depth pothole.	The wearing surface is no longer effective.
Crack (wearing surface) (3220)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy patterns (map) cracking	The wearing surface is no longer effective.
Effectiveness (wearing surface)(3230)	Fully effective. No evidence of leakage or further deterioration of the protected element.	Substantially effective. Deterioration of the protected element has slowed.	Limited effectiveness. Deterioration of the protected element has progressed.	The wearing surface is no longer effective.
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Table 4. Defects and condition states for Element 521—Concrete Protective Coating (AASHTO 2022).

Defects	CS 1 Good	CS 2 Fair	CS 3 Poor	CS 4 Severe
Wear (concrete protective coatings) (3510)	None.	Underlying concrete not exposed; coating showing wear from UV exposure; friction course missing.	Underlying concrete is not exposed; thickness of the coating is reduced.	Underlying concrete exposed. Protective coating no longer effective.
Effectiveness (concrete protective Coatings) (3540)	Fully effective.	Substantially effective.	Limited effectiveness.	The protective system has failed or is no longer effective.
Damage (7000)	Not applicable.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

UV = ultraviolet.

Bare Concrete

Bare concrete, referred to as simply concrete deck, does not have a wearing surface made of a second, distinct material. A bare concrete wearing surface may be referred to as a monolithic or integral wearing surface. Monolithic indicates that the wearing surface was placed concurrently with the structural deck, while integral indicates the wearing surface was placed after the structural deck (FHWA 1995). Two-course decks, where a wearing surface is placed after casting and curing of the structural deck but before initial opening of the deck to traffic, have been used successfully for decades. However, in these cases, the wearing surface concrete is the same material as the structural deck concrete. The AASHTO load and resistance factor design (LRFD) Bridge Design Specifications require that the minimum thickness of a concrete deck, excluding activities related to surface treatment (e.g., grinding, grooving), should not be less than 7 inches (AASHTO 2020). Prestressing in the span direction should be considered for slabs with thickness less than one-twentieth of the design span to control cracking. Most States require a minimum deck thickness of 8 inches, including a one-half inch integral wearing surface. The AASHTO requirement for reinforcement cover varies according to the reinforcement type (uncoated mild steel, epoxy-coated or galvanized steel, or corrosion-resistant chromium alloyed steel), the water-to-cementitious materials ratio (w/cm), and the exposure conditions (e.g., deicing, coastal, stud or chain wear) (AASHTO 2020). Epoxy-coated mild steel reinforcement in a 0.45 w/cm concrete deck subject to deicing would require minimum 2.0-inch cover if not subject to stud or chain wear.

Sealers

Sealers are typically used to reduce permeability and limit the ingress of water and deicing salts into reinforced concrete bridge decks. By doing so, sealers are intended to extend the service life of the deck by extending the time to initiation of corrosion of the reinforcing steel. By protecting the deck from water ingress, sealers can potentially reduce the deterioration rate from other types of concrete distress as well. While moisture itself is not a direct cause of damage, the presence of high moisture content helps accelerate different types of concrete degradation mechanisms such as freezing-and-thawing damage, alkali-silica reaction (ASR), and salt crystallization, and serves as a transport medium for chloride-induced and carbonation-induced corrosion. However, bridge deck sealers are not likely to prevent these various concrete degradation mechanisms, but only delay them. The most frequently used sealers for concrete bridge decks include penetrating sealers, healer-sealers, and crack sealers. Deck sealers, which refer to penetrating or healer-sealers, and crack sealers are generally reapplied to provide continuous protection for the bridge deck. Reapplication frequency varies depending on the type of deck sealer used (ElBatanouny et al. 2022).

Deck Penetrating Sealers

Deck penetrating sealers are typically silane- or siloxane-based materials with small molecules that penetrate and bond to the concrete. They protect the concrete by forming a hydrophobic layer in the treated area. Other commonly used penetrating sealers include silicone and linseed oil (Soriano 2003). Penetrating sealers do not produce a continuous membrane as a physical barrier to prevent water from penetrating the concrete. Instead, they allow the concrete to form a chemical repulsion of water (Aitken and Litvan 1989). Depending on the density, finish, and pore structure of the near surface of the concrete, penetrating sealers may achieve a depth of up to 0.25 inches.

Healer-Sealers

Healer-sealers are typically applied to concrete with fine cracks and a high crack density to prevent moisture and chlorides from penetrating the cracks to the underlying steel. This type of sealer consists of flooding the surface with a polymer and then broadcasting aggregate on top of the polymer for friction. The binders are typically high molecular weight methacrylate (HMWM), thin epoxy, or polyurethane. Healer-sealers can be applied on any concrete deck or a steel deck with a concrete-wearing surface and do not apply to bituminous overlays or wood or timber-wearing surfaces. Healer-sealers should only be considered when the deck is in good condition with little to no distress because they are less effective at mitigating deterioration when distress has already begun to manifest.

Crack Sealers for Crack-Chasing

Crack sealers are used to fill cracks in concrete decks to prevent the passage of moisture and deicing salts through the crack, thereby providing protection to the deck reinforcement from corrosion damage. Crack-chasing involves applying a sealer along individual cracks and is typically done when the concrete has a low crack density or wider cracks. Different materials can be used for sealing deck cracks, including HMWM, epoxy, and urethane resins. Typical methods for using these materials to fill and bond the cracks are through pressure injection or gravity feed. Correlation is often observed between cracking and deterioration in bridge decks because cracks have a higher transport rate for chlorides and oxygen than sound concrete (American Concrete Institute (ACI) Committee 201 2023). For long service life, cracks allowing chloride penetration to the reinforcement should be treated and adequately sealed soon after formation in areas subject to direct contact with deicers.

For major new bridge projects, there has been significant discussion about the minimum crack width required to be sealed for long-term (e.g., 100-yr) service life. As a starting point, some projects have referred to AASHTO LRFD Bridge Design Specifications, Section 5.7.3.4, which provides an equation to calculate crack width caused by flexure (AASHTO 2020). In that section, Class 2 exposure is defined as areas with an increased risk of corrosion and prescribes an upper bound of 0.013 inches for cracks. Other industry guidelines have lower values, including Section 6.6 of ACI 357.3R that states, “Although a direct correlation between concrete surface crack widths and corrosion of reinforcement has not been clearly established, control of crack widths is considered desirable for structures located in salt-water or brackish water” (ACI Committee 357 2014). ACI 224R, *Control of Cracking in Concrete Structures* recommends a maximum surface crack width under service loads in seawater and seawater-sprayed structures of 0.006 inches (0.15 mm) and provides guidance on calculating expected crack widths based on reinforcement distribution (ACI Committee 224 2001). The 0.006-inch (0.15-mm) crack limit is generally reasonable for decks subject to deicers but hairline through-deck cracks that have water staining and leakage on the deck underside have been seen during deck surveys. Preferably, all visible cracks should be filled soon after construction and as necessary afterward to achieve a long service life.

Rigid Cementitious Overlays

Cementitious overlays are overlays made of hydraulic cement concrete. Sometimes, typical structural concrete or the equivalent is used, in which case the overlay is referred to as a portland cement concrete (PCC) overlay. Often, concrete is modified in some way to make it less permeable so that chlorides from deicing chemicals or marine environments cannot penetrate the overlay concrete as easily as the deck concrete. These modified concrete overlays include low-slump dense concrete (LSDC) overlays, silica fume concrete (SFC) overlays, latex-modified concrete (LMC) overlays, and ultra-high-performance concrete (UHPC) overlays.

PCC Overlays

Conventional PCC overlays are commonly used. While advantageous because they use conventional concrete mixtures that all contractors are familiar with, one disadvantage of PCC overlays is the long curing time, which can cause substantial disruption to traffic. Using Type III portland cement (PC) accelerates setting time and early strength gain and can reduce the curing time; however, it also increases both shrinkage and cracking risk. Surface preparation consists of removing and repairing bituminous patches and unsound concrete and removing the deck concrete or existing wearing surface to a specified depth. The depth specified often depends on the elevations of the bridge joints and guardrails, the presence of a previously placed overlay, and the extent of chloride contamination.

LSDC Overlays

LSDC overlays typically have a maximum slump of 1 to 2 inches, which reduces the required w/cm ratio. LSDC is less permeable than typical concrete due to its low w/cm ratio, but LSDC is more susceptible to shrinkage cracking and delamination. When constructed and cured such that cracking is minimized, LSDC overlays are superior at preventing chloride ingress and moisture compared to conventional PCC overlays. Like PCC overlays, LSDC overlays have long curing times. LSDC overlays are expected to have a lifespan of approximately 15 to 35 yrs (Krauss, Lawler, and Steiner 2009).

SFC Overlays

To further reduce permeability and inhibit moisture and ion intrusion, supplementary cementitious materials (SCMs), such as fly ash, slag cement, and silica fume, can be added to the concrete. Concretes using these materials to improve performance characteristics, such as long-term durability, are generally called high-performance concrete (HPC). SFC, or microsilica concrete, is a specific type of HPC and a commonly used overlay material. SFC contains approximately 7 to 12 percent silica fume by weight of cement, which decreases permeability by packing into the pores of the cement paste and providing additional hydration products within these pores. However, concrete with such high amounts of silica fume are difficult to place and prone to cracking, often compromising the protection they can provide. SFC and other HPC overlays typically provide a deck service life extension of at least 15 yr (Krauss, Lawler, and Steiner 2009).

LMC Overlays

LMC overlays typically use PC or blended cements with an admixture of organic (styrene-butadiene latex) particles suspended in water (Lane 2013). This type of overlay has also been widely used with long-term durability expectations. The organic particles make the overlay less permeable and more resistant to chemical attacks. The polymer also improves adhesion to the original deck concrete and reduces shrinkage. Construction of LMC overlays requires specialized equipment and is sensitive to weather conditions. Plastic cracking and cyclic freezing damage can occur if overlays are not formulated properly. LMC overlays require similar curing times to conventional PCC overlays (Lane 2013). Some States noted that LMC overlays are more costly than SFC and LSDC, while Indiana DOT noted that LMC overlays have a lower cost than LSDC (Ramey and Oliver 1998). LMC overlays are generally expected to provide deck service life extensions between approximately 15 and 30 yr (Krauss, Lawler, and Steiner 2009).

UHPC Overlays

UHPC in the United States is still considered by many SHAs as an experimental overlay material for a bridge deck and is not specified in the standard specifications of most States. The Iowa Department of Transportation (Iowa DOT) performed its first trial of UHPC overlay in 2016 and completed a short-term field study on the trial in 2018 (Wibowo and Sritharan 2018). UHPC overlays contain high amounts of silica fume, steel fibers, and very low w/cm ratios, typically 0.26 or less. Conventional concretes typically have a w/cm ratio of at least 0.32. UHPC does not use coarse aggregates, but fillers (e.g., fly ash, slag, and lime) may be used. Due to the low w/cm ratios and high amounts of silica fume, UHPC has very low porosity, which makes it highly resistant to the ingress of both chloride and moisture. UHPC overlays are expensive but have shorter set times and curing times compared to conventional PPC overlays. UHPC overlays are believed to provide deck service life extensions of over 50 yr (Haber et al. 2023).

Bituminous Overlays

Bituminous overlays typically include hot-mix asphalt (HMA) or polymer-modified asphalt (PMA). HMA is relatively inexpensive compared to PMA, but it is more porous to moisture and deicing chemicals. To address this issue, HMA overlays may be constructed with a waterproofing membrane between the overlay and the bridge deck. The asphalt chosen and the decision of whether to use a waterproofing membrane depend on the type of bridge deck and the purpose of the overlay.

HMA Overlays

HMA overlays are typically preferred as a short-term solution to extend the deck's life in its final years until it can be replaced. For example, the Michigan DOT (MDOT), Minnesota (MnDOT), and Wisconsin DOT (WisDOT) suggest using asphalt overlays without a waterproofing membrane on decks that are planned to be replaced within less than 5 yr. HMA overlays require shorter traffic closures and generally cost less than conventional PCC overlays. The disadvantage of HMA overlays is the inability to visually inspect the concrete deck. Thus, ongoing corrosion in the deck may occur without being noticed, as well as the additional imposed dead load, and it does not contribute to the structural capacity of the deck. Asphalt overlays without a waterproofing membrane can also trap deicer-laden water between the overlay and concrete deck, accelerating chloride penetration into the deck or induce cyclic freezing damage.

When a longer-term overlay life is desired, HMA overlays may be constructed with a waterproofing membrane underneath to block moisture and aggressive ions that penetrate the HMA. An HMA overlay with a properly installed waterproofing membrane can achieve a service life of over 10 yr (Krauss, Lawler, and Steiner 2009). However, waterproofing membranes increase construction time and require experienced contractors for quality installation. Construction errors in the membrane can result in water leakage or entrapment underneath the membrane, leading to water and chloride ingress and corrosion of the deck reinforcement.

PMA Overlays

PMA overlays are relatively uncommon but useful in specific applications. Thermoplastic polymer-modified overlays and overlays that use mastic asphalt are examples of PMA overlays.

This type of overlay typically contains an increased content of asphalt binder and includes polymer modifiers such as styrene-butadiene-styrene (SBS) to make the overlay less permeable and perform better under cyclic loading. Thus, a waterproofing membrane is not required, and a longer overlay life may be achieved. PMA overlays are quick to construct but expensive, and their performance has been inconsistent (Sprinkel and Apeagyei 2013; Hunsucker et al. 2018). PMA overlays are expected to increase the deck service life by 10 to 15 yr (WisDOT 2021).

Polymer Overlays

Polymer overlays are relatively impermeable compared to cementitious and especially bituminous overlays, but their material costs are relatively expensive. Polymer overlays consist of a polymeric binder, typically epoxy, polyester, or urethane, and aggregates. Different aggregates may be used, either to fill volume and decrease the binder content of the material, which reduces material cost, or broadcast on top of the overlay to provide skid resistance. Skid resistance requires relatively hard, abrasion-resistant aggregates. Polymer overlays are generally classified by their thickness and their binder type (ElBatanouny et al. 2017).

Thin Polymer Overlays

Thin polymer overlays (TPO) are generally desirable because they prevent deicer salts from infiltrating the deck, can restore skid resistance for at least a short time, add minimal dead load due to their thinness, and do not require the elevations of the joints or parapets to be adjusted to accommodate new deck elevations. TPOs are typically constructed in multiple layers. The deck surface is flooded with resin binder, and aggregates are broadcast on top. The process is repeated until the desired thickness is achieved (typically one-quarter to one-half inch). Figure 1 shows an example of a multilayer TPO. Epoxy is a commonly used binder for TPOs, but polyester, methyl methacrylate, and epoxy urethane have also been used. TPOs are expected to extend the service life of a deck by 7 to 15 yr (WisDOT 2021). TPOs are generally not recommended on decks with existing delamination, patch repairs, or other signs that corrosion has initiated because TPOs are relatively susceptible to reflective cracking and distress due to their thin nature.

Figure 1. Photo. Top and side views of a TPO on a core from a concrete deck.

Premixed Polymer Concrete Overlays (PPC)

PPC overlays are constructed by premixing the resin and aggregates and placing and screeding the mixture on the deck surface. These overlays are typically three-quarters to 1 inch thick. Greater thickness has been used, but thickness is often kept as small as is practical due to the high material cost of polymer concrete. PPC overlays are almost exclusively made using polyester, although some States have started to investigate premixed epoxy concrete overlays in recent years. PPC overlays have been used successfully in California for over 30 yr, while their use in Midwest States has been relatively limited. PPC overlays are flexible, almost impermeable, and are expected to protect the deck for approximately 10 to 20 yr or even 25 yr or longer, depending on the condition of the underlying deck and the quality of the installation (Fowler and Whitney 2011; ElBatanouny et al. 2022; Krauss, Lawler, and Steiner 2009). This overlay option has a relatively short curing time. Traffic can be reopened as soon as 2 to 4 h after placement.

Permanent Deck Formwork

Stay-in-Place Metal Forms (SIPMF)

SIPMF are used by some States for the construction of bridge decks. These permanent forms offer some advantages over conventional plywood forms, including time savings in deck construction, lower labor costs, ease of installation, safety of laborers, and minimal interruption to the environment or traffic below (Nims and Grace 2006). However, a major concern associated with the use of SIPMF is the inability to perform underside deck visual inspections (or sounding) due to the presence of the forms, which is a major metric in assessing deck performance and identifying potential issues during service.

Partial-Depth Precast Decks

Partial-depth precast concrete deck panels are thin precast, prestressed panels that can be used as permanent forms for the cast-in-place deck. The panels are a minimum of 3.5 in in thickness and are designed to span between girders and to act compositely with the cast-in-place portion of the deck (Precast/Prestressed Concrete Institute (PCI) Northeast Bridge Technical Committee 2017). This method was introduced in the 1950s for bridges in Illinois. These panels have been used in at least 28 U.S. States and Canadian Provinces (Goldberg 1987). The most common durability problem with this construction method is cracking in the cast-in-place concrete portion of the deck at transverse joints between the panels and at locations where the panels bear on the girders (Hieber et al. 2005). Often, this type of bridge deck cracking is known as reflective cracking.

Reinforcement

Reinforced concrete decks and slabs have different types of reinforcement, ranging from deformed bars and welded wire mesh to prestressing strands and posttensioning tendons. Deformed black steel bars are the most common form of reinforcement used for bridge deck construction. A subset of these bars is epoxy-coated steel bars, but other types of corrosion-resistant steel bars have come into use (figure 2). The epoxy-coated steel bars and corrosion-resistant bars are used in areas where the bridge is exposed to aggressive environmental conditions, for example, in the northern regions of the United States. In recent years, fiber-reinforced polymer (FRP) bars have also been used in some bridges in Canada.

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Figure 2. Photo. Different types of reinforcing steel.

Understanding the limitations that reinforcement type may impose on various NDE methods is important. For example, half-cell potential (HCP) testing cannot be done for bridge decks with FRP or epoxy-coated reinforcement. Because of the zinc outer layer, HCP of galvanized bars will give different potentials. Magnetometers are ineffective for detecting certain grades of stainless steel and FRP reinforcement. Ground-penetrating radar (GPR) is less effective in detecting FRP versus steel. The various NDE methods and their applications are discussed in later sections.

Overview of Common Defects in Bridge Decks

Given their impact on service life and safety, four modes of deterioration are the most crucial for bridge deck condition assessment: vertical cracks, reinforcement corrosion, delamination, and concrete degradation (Gucunski et al. 2013). In addition to these four defects, other types of defects exist, e.g., carbonation, honeycombing, and overlay debonding.

Deterioration Modes

Vertical Cracking

Different mechanisms may create vertically oriented cracks in concrete. These cracks may occur at an early age in plastic concrete or later in hardened concrete (ACI Committee 224 2007).

Early-age cracks in plastic concrete are typically caused by the following:

- Plastic shrinkage from moisture evaporation and absorption of water by dry aggregates.
- Autogenous shrinkage, a change in paste volume that directly results from chemical reactions during cement hydration.
- Plastic settlement from subsidence of fresh concrete over reinforcing steel or load transfer devices.

Cracks in hardened concrete may result from several mechanisms, including the following:

- Restrained volume changes of concrete (triggered by drying shrinkage resulting from paste moisture content reduction through loss to the environment and by temperature changes) result in stresses that exceed the tensile strength of concrete—this type of cracks, most frequently observed as uniformly spaced cracks in the transverse direction, can develop in as little as 7 d, and continue growing at a decreasing rate as the concrete matures. This is the most common type of crack in reinforced concrete decks.
- Thermal gradients, such as from poor curing and protection during cold-weather concreting.
- Structural movements resulting in shear strains and stresses exceeding concrete capacity.
- Over- and under-stressing of posttensioned steel tendons
- Design and detailing of decks.
- Deleterious processes in concrete.

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Figure 3. Photo. Cracking observed at a core hole in a concrete bridge deck during a research study on crack influence on corrosion.

Chloride-Induced Corrosion

In 1993, the Strategic Highway Research Program (SHRP) reported that roughly 40 percent of expenditures on the repair and retrofit of highway bridges were ascribed to reinforcing steel corrosion (Weyers et al. 1993). Given its alkalinity, concrete is an ideal environment to protect embedded steel reinforcement,. In the absence of chloride ions, the naturally forming iron oxides, Fe_3O_4 and Fe_2O_3, or their hydroxides form a protective layer around the reinforcement steel called a passive film (ACI Committee 222 2001). However, given the porous nature of concrete, CO_2 penetration causes carbonation and neutralization of the paste, which reduces its protective properties. When chloride-bearing solutions from deicing salts and the environment reach the steel reinforcement, they damage the passive film and trigger corrosion.

In cold climates, such as in the northeast United States, chloride ions are present because of the heavy use of deicing salts. In an arid climate, corrosion could still be an issue due to high concentrations of chloride salts in the soil. In coastal areas, chloride-induced corrosion is especially prevalent in splash zones. Acidic rains and sea spray may be another source of chloride ions.

The process of metal corrosion in concrete is described in *Protection of Metals in Concrete Against Corrosion* and is schematically shown in figure 4 (ACI Committee 222 2001).

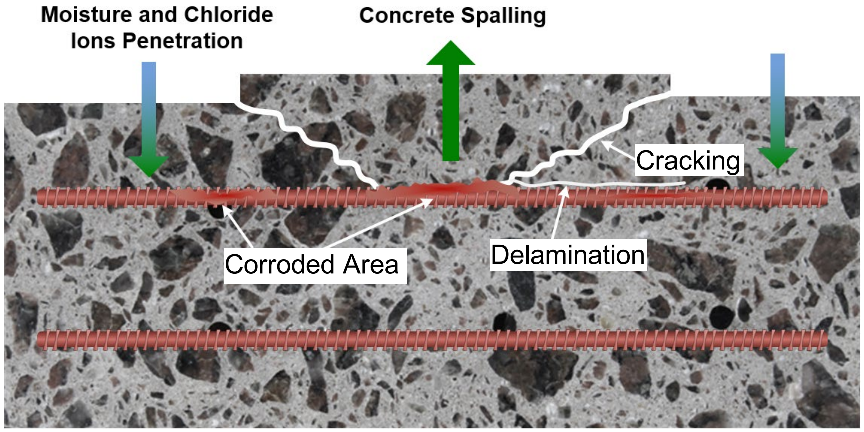

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Figure 4. Diagram. Schematic of concrete degradation due to corrosion.

ACI, in a previous version of *Cement and Concrete Terminology* (ACI 2000), points to corrosion of reinforcing steel as the primary cause of delamination. Because the corrosion products occupy a larger volume than the original steel, they create internal stresses in concrete, inducing cracking, delamination, and spalling, which combined with the loss of reinforcing steel cross-section, results in an eventual reduction of structural capacity as illustrated in figure 5.

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Figure 5. Photo. Extensive cracks caused by the corrosion of reinforcing steel.

Figure 6 illustrates the formation of growing clusters of halite (NaCl) and the accumulation of corrosion products around the surface of the reinforcing steel. Figure 7 depicts delamination caused by corrosion of reinforcing steel.

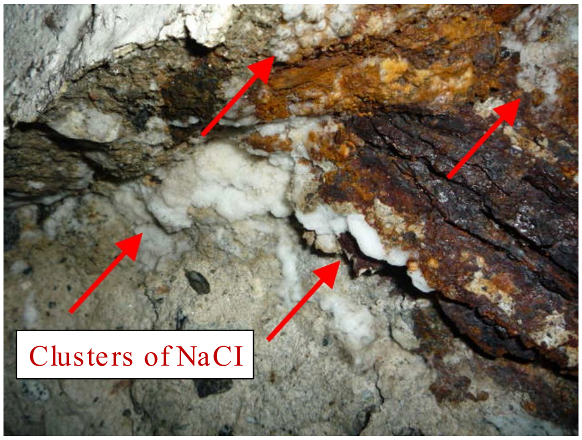

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Figure 6. Photo. Corrosion products.

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Figure 7. Photo. Spalls at edges of delamination caused by corrosion.

Often, delamination is not visible on the surface and, therefore, may suddenly turn into spalls with little to no warning. This result points squarely to the importance of preventive condition evaluation. Examples of delamination in cores extracted from a highway bridge deck are provided in figure 8.

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Figure 8. Photo. Delamination in a bridge deck visible after extracting a concrete core.

Carbonation

Concrete has a high pH value. This high alkalinity protects steel reinforcement against corrosion. Carbonation is the neutralization of the cement paste due to a chemical reaction with CO_2, which can result in corrosion. In carbonated concrete, the pH value is less than 10. When the pH level drops below 9, concrete loses its protective properties toward reinforcing steel, leading to corrosion. Carbonation depth can be determined in the field or laboratory by using phenolphthalein on freshly fractured concrete surfaces, as shown in figure 9. The pink and purple concrete correspond to pH values greater than 10, which means that no carbonation has occurred. Areas with no change in color are carbonated. Corrosion may be the result of carbonation, chloride exposure, or both. Carbonation-induced corrosion tends to be more uniform along the reinforcement surface and evolves more slowly than chloride-induced corrosion.

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Figure 9. Photo. Carbonation from top and bottom in a concrete deck core.

Concrete Degradation

Various physical and chemical mechanisms may cause degradation of concrete structural and functional performance; among them are corrosion, ASR, alternate freezing, and thawing, and alternate wetting and drying, among others (figure 10).

Investigation of concrete's condition often requires evaluating concrete at microscopic levels through petrographic examination, and electronic scanning microscopy.

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Figure 10. Photo. Degraded aggregate and cement paste loss on lightweight concrete deck.

Freezing and Thawing

Degradation due to cyclic freezing occurs when sufficiently saturated concrete is subjected to multiple freezing and thawing cycles, especially at an early age. These cycles result in progressive deterioration, including delamination and surface scaling of concrete (figure 11). For typical concrete mixtures, ACI 318-19 defines different freezing-and-thawing exposure classes and requirements to avoid concrete deterioration in terms of allowed air contents, which depend on the nominal maximum aggregate size (ACI Committee 318 2019).

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Figure 11. Photo. Freezing-and-thawing damage in a concrete bridge parapet.

Alkali-Aggregate Reaction

Alkali-aggregate reaction (AAR), and more specifically ASR, is a chemical reaction between reactive components (such as strained crystalline forms of silica) in the aggregates and alkalis in the cement paste pore solution of hardened concrete to produce a hygroscopic gel that expands when exposed to moisture. Expansive pressures are produced when the gel absorbs water, or if these pressures exceed the tensile strength of the concrete, they produce microcracking, and eventually macro-cracking (visible cracking), of the concrete as shown in figure 12. Water can infiltrate the concrete through the cracks and cause additional gel expansion, leading to more cracking and potentially spalling of the concrete. The gel can also stain or discolor the concrete surface when the gel flows or is carried to the surface (ACI Committee 201 2016).

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Figure 12. Photo. Cracking from AAR in a concrete deck-slab bridge.

The three essential factors for ASR to occur include the following:

1. Reactive silica-containing aggregates.
2. High alkali levels within the concrete pore solution.
3. Available moisture.

Removing any one of these factors will eliminate the risk of ASR. As such, in modern construction, it is customary to pre-screen aggregates for the risk of ASR so that either the reactive aggregates are not used or their reactivity is mitigated by using low-alkali concrete mixtures or incorporating SCMs to reduce the alkali content of the pore solution. However, because the mechanism of ASR was first identified in 1940, and test methods to prescreen aggregates for deleterious reactivity were not developed until the late 1950s, ASR is currently affecting numerous existing concrete structures where the use of potentially reactive aggregates without mitigation was not uncommon at the time of their construction (Thomas et al. 2006). Even in more modern structures, the desire for cheap, readily available aggregate may also have led to the use of marginal quality materials that may have some level of reactivity.

Honeycombs and Voids

The ACI defines honeycombs as “voids left in concrete between coarse aggregates due to inadequate consolidation.” (ACI 2021). To achieve its intended design properties, concrete must be properly consolidated. Inadequate consolidation stemming from mix design, improper mixing, heavy reinforcement without attention to the aggregate gradation, poor workmanship, or failure to use the right placement tools such as tremies can result in the formation of voids in between coarse aggregates or honeycombs. The size of the voids can be in the order of the largest aggregate size.

Honeycombs are important and common defects in concrete that can affect the structure's load-bearing capacity while increasing the susceptibility to corrosion due to increased concrete permeability. Honeycombs can occur in any concrete element, e.g., walls, slabs, beams, columns, or foundations. The honeycombs on the surfaces are readily visible after formwork removal (figure 13). On the other hand, the honeycombs inside the element can only be detected through destructive probing or NDE methods.

Related to honeycombs and voids are other forms of discontinuity within the bulk concrete element, such as horizontal cold joints or subsidence that may occur over shallow reinforcement while concrete is still plastic. These discontinuities or weak zones can result in delamination, which may be exacerbated by repeated traffic loading.

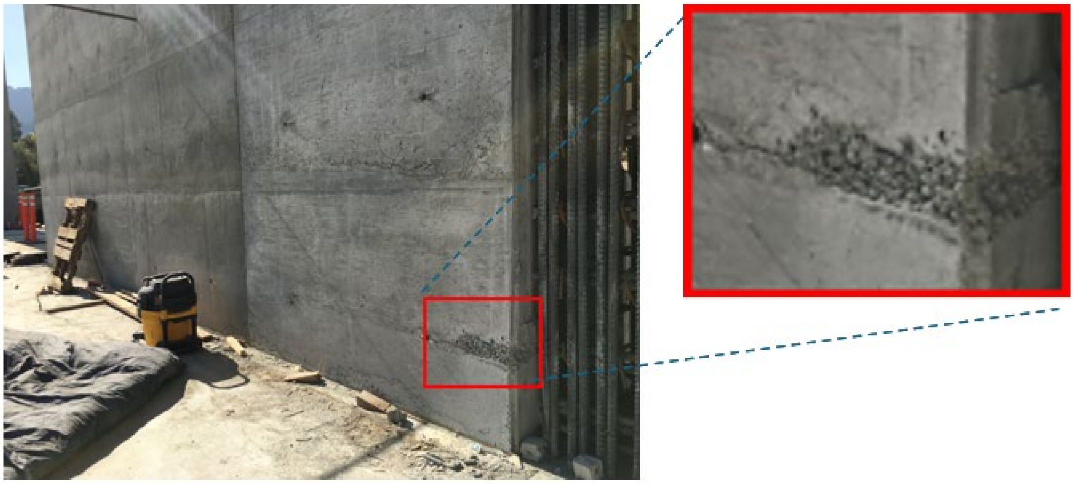

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Figure 13. Photo. Honeycomb in a concrete wall; honeycomb is not always externally visible.

Overlay Debonding

Overlay debonding can occur for various reasons, and while not the root cause of debonding, repeated loading and braking from heavy vehicles can contribute to the propagation of debonded areas. Inadequate surface preparation is the most common reason for early overlay debonding. Regardless of the overlay material, surface preparation of the concrete substrate to receive the overlay is crucial in ensuring a good bond between the overlay and existing concrete.

Material incompatibility also causes failure and debonding of the composite overlay material (e.g., polymer and bituminous overlay on concrete deck). One recent case indicates that HMWM primer caused severe delamination of the epoxy-based slurry overlay used on Panama's Bridge of the Americas (Fowler and Whitney 2011). Laboratory tests conducted on the material used on the bridge showed that a good bond was achieved initially, but that the bond deteriorated after several months where the concrete had been primed with methacrylate. Similar anecdotal observations have been made about the loss of bond strength with time when epoxy overlays are placed on HMWM resin-treated surfaces (Fowler and Whitney 2011). Patching should be completed well before surface preparation and cementitious patches should be wet cured to reduce shrinkage and debonding issues (Carter 1993).

Debonding issues can also occur in HMA with the waterproofing membrane (HMAWM). The HMAWM system tends to fail at the bond between the membrane and the deck substrate beneath, primarily due to poor-quality construction or traffic loads. The deck condition before the membrane placement can also affect the life of the system, and moisture or chlorides may become trapped under the membrane if the installation is poor, causing continued corrosion of the underlying deck. Nonetheless, for a well-performing membrane, if the asphalt overlay reaches end-of-life before the membrane, the overlay can be removed and reapplied, and the membrane can be left in place, provided it is not damaged.

Wear (Polishing and Rutting)

When concrete bridge decks contain soft aggregates that are not sufficiently abrasion-resistant and see high amounts of traffic, the service life of the deck may be controlled by abrasion or mechanical wear. Wear is one of the main deterioration mechanisms that directly affect the bridge deck riding surface used by the public. Wear can result in loss of cement paste, polishing of aggregates, and a commensurate loss of skid-resistance, which can become a safety concern (figure 14). Concrete decks and cementitious overlays are typically highly resistant to wear.

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Figure 14. Photo. Loss of cement paste and polishing of aggregate on a bridge deck.

In several studies, polymer overlays have demonstrated superior long-term skid resistance compared to concrete-wearing surfaces. However, using studded tires or snow chains produces high wear rates on polymer concrete overlays. Other types of polymer concrete degradation include the following:

- Polishing—If the aggregates have poor wear resistance, they and the resin may both become polished, compromising the skid resistance. Poor skid resistance can be prevented by selecting appropriate aggregates or by using premixed polymer concrete with low resin content.

- Aggregate pop-out—While polymer concrete is relatively impermeable, this property will degrade with time in part because of aggregate pop-out from tire abrasion and wear. When the aggregates are ripped out of the binder during service, they can leave behind cracks and holes through which moisture and chlorides can penetrate. Thicker premixed polymer overlays can better maintain their impermeability when experiencing this wear-related distress.

For HMA overlays, rutting or shoving can be an issue on high-traffic bridges. Rutting is the permanent deformation or depression of the surface that can affect the ride quality and safety of the road. Rutting in asphalt bridge deck overlays can occur due to a combination of factors, including the inherent properties of the materials used and environmental conditions. The causes of rutting in asphalt bridge deck overlays can include insufficient pavement thickness, inadequate mix design, poor compaction, heavy traffic loading, and elevated temperatures.

Shoving in asphalt bridge deck overlays is a pavement distress characterized by the development of a series of small, closely spaced waves or ridges on the surface of the asphalt. Shoving can negatively impact ride quality and safety. The causes of shoving in asphalt bridge deck overlays are similar to the causes of rutting and can include inadequate mix design, poor compaction, low shear strength, heavy traffic loads and tire pressures, and elevated temperatures.

NDE and SM Technologies Relevant to Deck Evaluation

Bridge owners and highway transportation infrastructure stakeholders are relying increasingly on NDE technologies to obtain comprehensive information about the condition of reinforced concrete bridge elements in a way with the least impact on mobility. Using reliable NDE technologies can help limit invasive sampling while providing the information needed for decisionmaking.

In its recommendations on strategies for developing repair procedures for reinforced concrete structures damaged by corrosion, The International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM) submits that the engineers need to first have a thorough understanding of the causation, extent of damage, an estimate of damage progression with time, and any adverse effect of the damage on structural integrity and serviceability (Elsener et al. 2003).

A comprehensive condition assessment of reinforced concrete bridge decks can be accomplished using various NDE technologies together with an informed and minimal destructive probing to gather ground truth information and for laboratory testing (table 5). These techniques include, but are not limited to, GPR, impact echo (IE), ultrasonic surface waves (USW), ultrasonic tomography (both shear wave and P-wave), HCP, electrical resistivity (ER), infrared thermography (IRT), and hammer sounding and chain drag (HSCD). These technologies differ in their principle and mechanism of operation and have specific strengths and limitations. The objective of a given investigation is the primary factor determining the appropriate set of tests. Table 6 summarizes which methods most apply to assessing a specific structural feature or defect.

Table 5. Summary of applicable NDE methods for reinforced concrete decks.

Category	NDE Method	Defect or Deterioration
General	Visual inspection	Identify cracks, spalls, and areas with visual degradation (such as corrosion staining, efflorescence).
	Scanners (photogrammetry, high-resolution image, video, 3D scanning)	Identify cracks, spalls, and areas with visual degradation (such as corrosion staining, efflorescence; identify structural features for location reference and filtering.
Acoustic and stress waves	HSCD	Deck delamination detection.
	IE	Deck delamination or deeper void detection and characterization.
	USW	Measurement of elastic moduli and associated degradation.

Category	NDE Method	Defect or Deterioration
	UST	Identify embedded reinforcement, detect and characterize cavities, flaws, cracks, honeycombing, and posttensioning grout defects.
	ACS	Deck delamination detection.
Electromagnetic	GPR	Locating and detecting internal reinforcement elements. Indirect detection of deterioration caused by corrosion, delamination, voids and honeycombing.
	IRT and IR-UTD	Identify cracks and areas of suspected water flow, debonded and delaminated concrete.
Electrochemical	HCP	Measurement of the probability of active steel corrosion.
	ER	Likelihood of corrosive environment in concrete.
	LPR	Measure corrosion rate.
	GPM	Measure corrosion rate.

3D = three dimensional; ACS = automated concrete sounding; IR-UTD = ultra-time domain infrared thermography; LPR = linear polarization resistance; GPM = galvanostatic pulse method.

Table 6. Summary of NDE methods by features characterized.

Structural Feature	Type of Issue	Corresponding NDE Tests
Deterioration	Cracking	USW, IE
	Corrosion	ER, GPM, GPR*, HCP, LPR, MFL
	Degradation	GPR*, USW
	Delamination	HSCD, IE, IRT, UST, ACS, GPR*
	Overlay debonding	HSCD, IE, IR, ACS, UST
	Void	IE, IRT, UST, GPR*
Dimensional or mechanical feature	Reinforcement cover depth	GPR, MM
	Reinforcement locating and mapping	GPR, MM
	Thickness measurement	GPR, MM, IE, UST

*Indirect measurement of these deterioration modes.
MFL = magnetic flux leakage; MM = magnetometer; UST = ultrasonic testing.

Visual Inspection

The first step in the inspection of a bridge deck is visual inspection. Visual inspection establishes the baseline conditions right after construction and is the first step in routine, special, and damage inspections. One of the advantages of visual inspection is that it does not require a high level of training. However, it is inherently limited to capturing surface defects and patches and can be impacted by various physical and environmental factors (Moore et al. 2001).

High-Resolution Imagery

High-resolution digital imagery has gained popularity over the past several years due to significant advancements in digital camera technology. The prevalence of inexpensive high-resolution cameras and improvements in computer processing and data storage have greatly reduced costs and increased efficiency in managing digital images. High-resolution images can be captured via smartphones and tablets or deployed via vehicle-mounted or aerial systems. The images can be geo-tagged and annotated in the field to document observations. The images can also be used to create a three-dimensional (3D) rendering of a structure during image postprocessing. Although an effective tool in providing additional information in the condition assessment of bridge decks, digital images were traditionally not as accurate as laser imaging, detection, and ranging (LiDAR) for spatial documentation. Recent enhancements in photo resolution and photogrammetric processing methods have changed the balance. High-resolution imagery can be impacted by lighting and shadows.

Digital images can be collected at traffic speed when using vehicle-mounted systems. Similarly, the data can be collected at a high rate when using unmanned aerial vehicles (UAVs), eliminating the need for traffic disruption. This efficiency also reduces the time needed for the personnel to be in the field compared to other NDE methods.

Recent advances in machine learning and artificial intelligence (AI) techniques for pattern recognition have increased the reliability of damage detection from high-resolution imagery (HRI) sources. Algorithms are being developed and improved to quantify and characterize visible defects such as spalls and cracks. (Spencer, Hoskere, and Narazaki 2019) Improvements in digital image resolution and data analysis now reportedly permit detecting cracks from vehicle-based HRI down to widths of 0.007 in or finer while gathering the data from within the normal traffic stream at posted speeds.

Laser Imaging

LiDAR is an active remote sensing technology to compute the distances or ranges of an object. Active remote sensing systems like LiDAR and radar emit pulses and record reflections. The difference between radar and LiDAR is that radar uses electromagnetic waves, whereas LiDAR uses light (ACI Committee 444 2021).

LiDAR systems can be deployed in the following three configurations, depending on the objective of the investigation, the accuracy needed, and the time allotment:

- Stationary, i.e., ground-based.
- Mobile terrestrial, i.e., while mounted on a vehicle or person.
- Airborne, i.e., attached to a UAV.

Each of these deployment methods has certain strengths and limitations. For example, airborne systems can collect data over different terrains, but they provide lower accuracy. Similarly, mobile systems can acquire data faster but provide lower accuracy than stationary systems. Most systems are equipped with global positioning system (GPS) integration, and methods such as simultaneous location and mapping (SLAM) enable spatial data capture in GPS-denied environments.

A typical LiDAR scan involves placing scanner-specific targets in known locations within the scanner's range. The targets must be within visible range since LiDAR can only map the line of sight (LOS). The highly reflective targets must be spread out at known locations to establish the coordinates. (Hiremagalur et al. 2007). Standing water can interfere with other reflections and need to be removed.

The high-resolution 3D maps generated by LiDAR can be used to detect the location and extent of surface defects, such as cracks and spalling (Hoensheid 2012). When enhanced by integrating with photo imaging, they can also highlight staining and patches on the surface of bridge decks. They can also be used to measure deflections.

Infrared Thermography

IRT can detect delamination and debonding in reinforced concrete bridge decks. The *Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography* governs the application of infrared technology for bridge deck evaluation (D4788 (ASTM International 2013)). The standard applies to both bare and overlaid concrete bridge decks. The appearance of delaminated areas differs for the data collected during the daytime and the nighttime. During daytime testing, delaminated areas appear warmer because the air heats up faster than the surrounding solid materials. On the other hand, during nighttime testing, delamination appears colder because the air cools down faster. This is shown in figure 15. Delamination may cause a measurable difference in surface temperature of 1°C to 3°C compared to sound areas (Gucunski et al. 2013). Like most NDE methods, the infrared findings must be validated using exploratory probing or other NDE methods.

The ASTM standard limits the speed of data collection. Currently, the survey speed should not exceed 10 mph. However, this speed is expected to change as the quality and processing speed of infrared cameras keep improving. Many companies now offer high-speed, high-resolution IR imaging of decks and pavements from vehicle-based platforms that travel and collect data at posted traffic speeds.

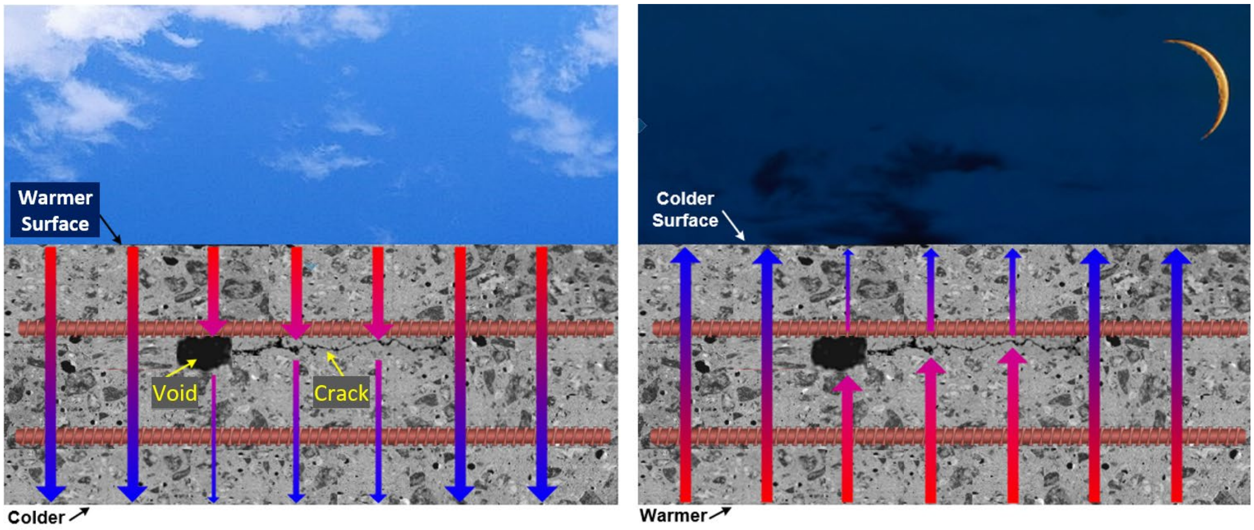

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Figure 15. Diagram. Passive IR.

The IR method is only valid for asphalt-overlaid bridge decks with overlays up to 4 inches thick. Additionally, the discontinuities captured by the IR method may only reflect debonding between the overlay and the concrete, as opposed to delamination in concrete.

Ground-Penetrating Radar

GPR is a rapid, nondestructive technique used in a wide range of applications, including evaluation of transportation infrastructure, geophysical investigations, mine detection, location of utilities, and archaeological investigations. GPR has been used for highway investigation since 1985 when FHWA developed the first vehicle-mounted GPR (Jol 2009).

A typical GPR system consists of five components: an antenna, a data acquisition unit, a graphical user interface, for example, a laptop or a tablet, a survey wheel, and a distance measuring instrument (DMI). The antenna comprises two types of transducers: a signal transmitter and a receiver. Based on the transmitter and receiver configuration, GPR systems are classified as monostatic, bistatic, or multistatic. In a monostatic system, one antenna works as both transmitter and receiver. A bistatic system is one in which transmitting and receiving units are set up at a known distance from one another, even though they may be housed together in the same enclosure. This is the typical configuration used for commercial GPRs. Finally, when a radar system consists of at least three transmitters and receivers, it is called a multistatic radar. A multistatic GPR has several receivers and at least one transmitter unit.

Based on the distance between the antenna and the ground at the time of deployment, GPR systems are classified as either ground-coupled or air-coupled. Ground-coupled systems are operated while in direct contact with the ground. For optimal results, the antenna must be located within one-tenth of the wavelength (Geophysical Survey Systems, Inc. 2009). Air-coupled systems are suspended several inches above the ground and allow for a higher speed of data collection. Air-coupled systems can be operated at the normal speed of traffic without the common wear and tear associated with dragging the ground-coupled antennas on the ground.

In addition to determining reinforcement layout and concrete cover thickness, GPR is one of the most popular NDE methods for condition assessment of reinforced concrete bridge decks when the deterioration is due to chloride-indued corrosion. The presence of moisture, chloride ions, iron oxide, cracks, and water-filled delamination increases the attenuation of electromagnetic waves, which will be reflected in GPR condition maps.

Figure 16 illustrates using a ground-coupled GPR system to survey a reinforced concrete bridge deck.

Figure 16. Photo. Ground-coupled single antenna GPR.

The traditional approach for condition assessment of reinforced concrete bridge decks using GPR involves analyzing the amplitudes of electromagnetic waves reflected from top reinforcing bars in the time domain. Certain deterioration threshold levels are defined based on the provisions of the *Standard Test Method for Evaluating Asphalt-Covered Concrete Bridge Decks Using Ground Penetrating Radar* to detect deteriorated areas ((D6087 (ASTM 2008)). Traditional GPR data analysis involves selecting a single electromagnetic wave velocity for the entire bridge. This can result in erroneous data interpretation for bridges in poor condition with many patches and different repair materials. Figure 17 illustrates a representative GPR condition map. In recent years, other processing techniques combining time-domain and frequency-domain information, along with AI applications, have gained popularity.

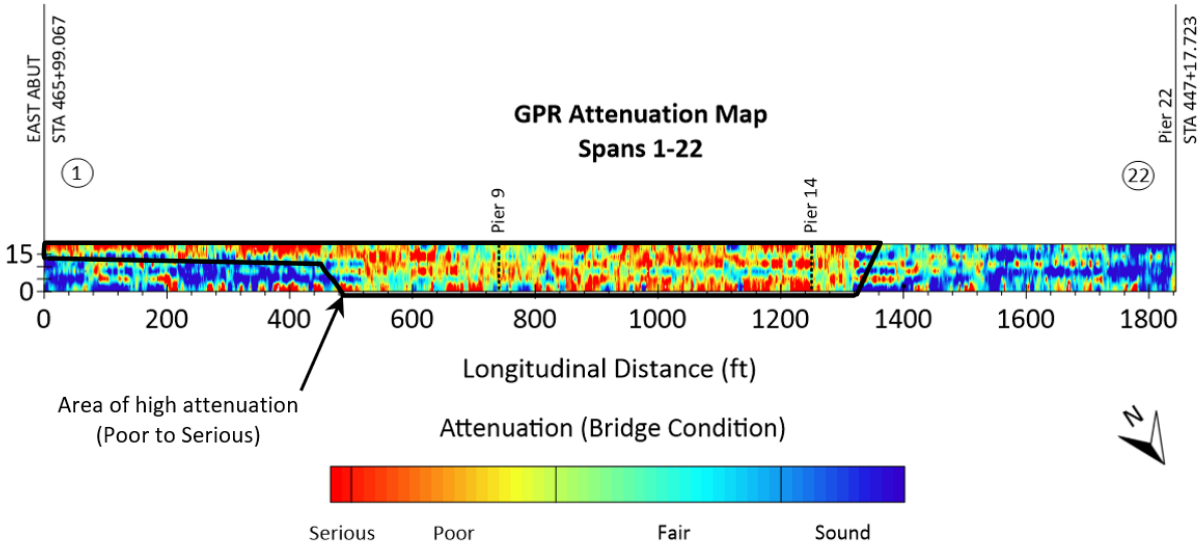

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Figure 17. Plan. Representative GPR attenuation contour map.

Like other NDE methods, GPR has certain limitations. For example, it cannot be used on bridges with UHPC overlay due to the presence of steel fibers. Similarly, GPR is not suitable when conductive aggregates such as slag and steel fibers are used in the concrete.

Magnetometer

Magnetometers, or cover meters or pachometers, rely on electromagnetic principles to detect steel, such as reinforcing bars and conduits, and other conductive metals embedded inside concrete. The eddy current method works by inducing a magnetic field that generates an eddy current on the surface of conductive material within the field, imparting measurable changes to impedance in the sensing coil.

Magnetometers are useful for locating embedded reinforcement and determining the depth of concrete cover. Some models also allow the estimation of bar size with limited accuracy. Some units include mapping capabilities through measurement along a predetermined pattern or using embedded distance-measuring instrumentation. Since the strength of a magnetic field decreases at a rate of approximately the cube of the distance from the source, the depth to which a magnetometer can measure is limited to a few inches in practice. Magnetometers can only detect the nearest layer of reinforcement, and close bar spacing (<1.5 times cover depth) decreases effectiveness. Magnetometers would not be effective for detecting nonconductive materials (e.g., FRP) and can be influenced by metallic fibers or aggregates. Older versions of the technology were based on magnetic reluctance rather than electrical conductivity, making them less sensitive overall and unable to detect nonmagnetic metals.

Hammer Sounding, and Chain Drag

HSCD are the most rudimentary NDE methods for locating areas with shallow delamination in a bridge deck. Despite their significant limitations and subjectivity, they are the most common

NDE methods used by various SHAs. In chain dragging, a steel chain is dragged along the deck's surface. In hammer sounding, the surface is struck using a steel rod or hammer. Good quality concrete generates a ringing sound, whereas testing over a delaminated area produces a dull and hollow sound.

This testing is performed according to procedure C of “Standard Practice for Measuring Delamination in Concrete Bridge Decks by Sounding ” (D4580 (ASTM 2018)).

Impact Echo

IE is a popular NDE method for thickness verification. It is also widely used for locating potential delamination and discontinuities within reinforced concrete elements. The IE survey is typically conducted over a 2-ft by 2-ft grid for bridge deck evaluation. The test surface is impacted at each grid location using an impactor (steel ball, ball pein hammer, or solenoid) to generate stress waves. The impactor's size is determined by the depth and size of the anomaly. The smaller the impactor, the higher the frequency and, therefore, better near-surface resolution, although this will be at the cost of penetration depth.

When stress waves propagating in a concrete bridge deck reach an interface with a material with different acoustic impedance (for example, air or steel), a portion of the incident wave is transmitted through the second layer, while another portion of the signal is reflected to the surface. The IE waveforms are processed in the frequency domain using a fast Fourier transform. The frequency spectrum consists of a range of frequencies associated with the deck thickness and other reflectors, such as reinforcement or delamination. Figure 18 illustrates a simplified representation of IE testing. The figure shows a typical IE response for a solid concrete section away from reinforcing steel or defects. The graph on the left is the response in the time domain, also known as the waveform, while the graph on the right is the same signal in the frequency domain or the signal spectrum. The waveform is dominated by a decaying periodic equation. For this example, there is a single large amplitude peak in the spectrum known as the thickness frequency, corresponding to the deck's thickness.

Although IE is more common for bare concrete bridge decks, it can also be used on asphalt-overlaid bridges if the testing is conducted in colder months when asphalt is less viscous. Conducting IE in warmer months may result in erroneous data interpretation due to the asphalt layer quickly dissipating the stress wave.

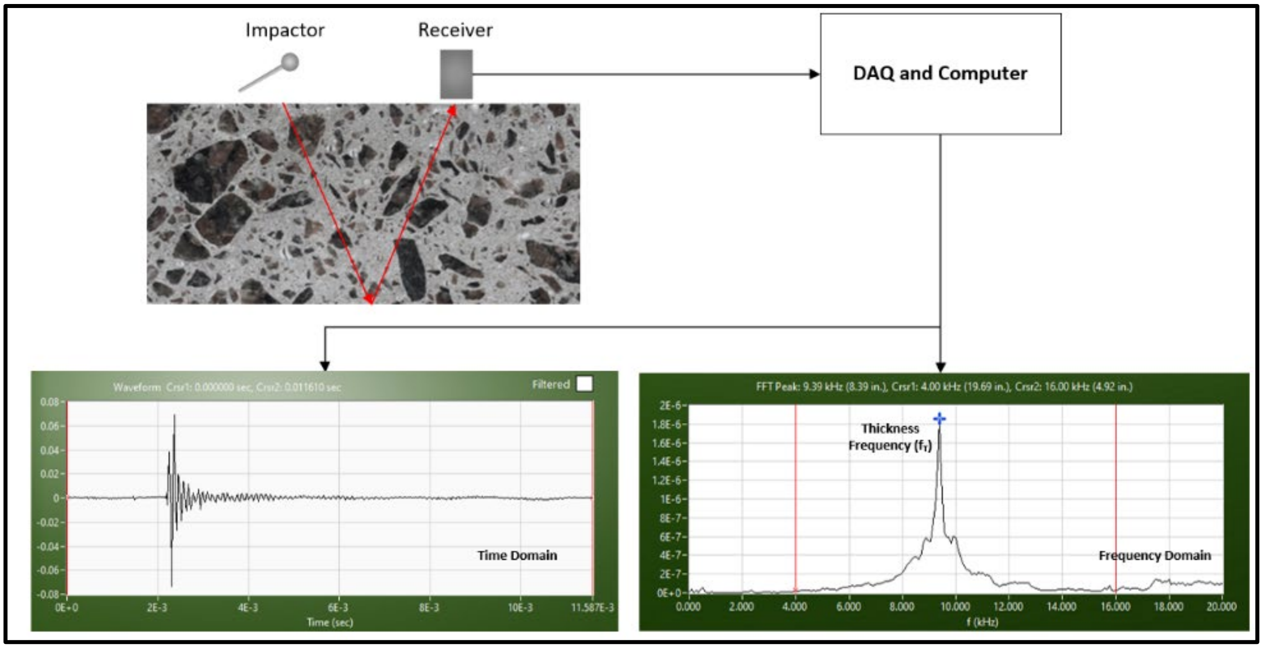

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Figure 18. Illustration. IE schematic.

Figure 19 illustrates four different conditions and the corresponding frequency spectrum. Each scenario is explained. Figure 19-A corresponds to a solid concrete section with no reinforcement or defect and represents the p-wave traveling from the surface through the element thickness, being reflected at the back wall, and traveling back. The single peak, called the thickness frequency, can be calculated from equation 1 as follows:

$$f_h = \frac{\beta C_p}{2h} \tag{1}$$

Where β is the shape factor, C_p is the p-wave velocity in concrete, and h is the thickness.

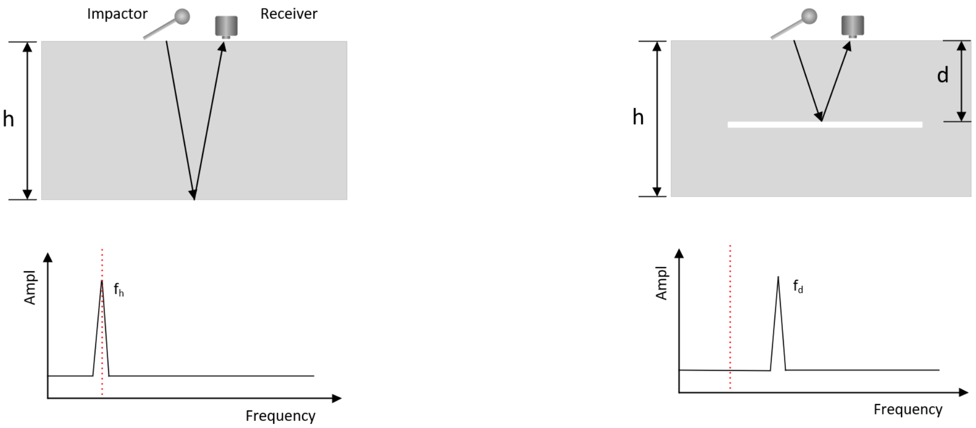
Figure 19-B corresponds to a large delamination with length L, where the L/d is greater than 1.5. In this case, the dominant frequency response is calculated using the same equation for a plate with a thickness equal to the delamination depth. Therefore, there is a single dominant peak in the spectrum, higher than the nominal thickness frequency, because the travel path is shorter. The shorter travel path results in increased frequency.

Figure 19-C corresponds to delamination with smaller lateral expansion. In this case, two sets of oscillations are detected: the refractions from the edge of the defect reflecting from the back wall and the reflections from the delamination. Therefore, there are two peaks in the spectrum as follows:

- The smaller peak is called the shifted frequency, which is lower than the thickness frequency and corresponds to the reflections from the back wall.

- The higher frequency component corresponds to the reflections from the surface of the delamination.

Figure 19-D corresponds to shallow delamination (above top reinforcement or <2.5 inches deep). In this case, the frequency response is much lower than the thickness frequency. This frequency is the flexural frequency of the thin layer above the delamination and represents the vibration of the shallow delamination. Figure 20 illustrates impact echo application on a bridge deck. Figure 21 illustrates the impact echo findings for three spans of a bridge superimposed on the aerial view of the deck.



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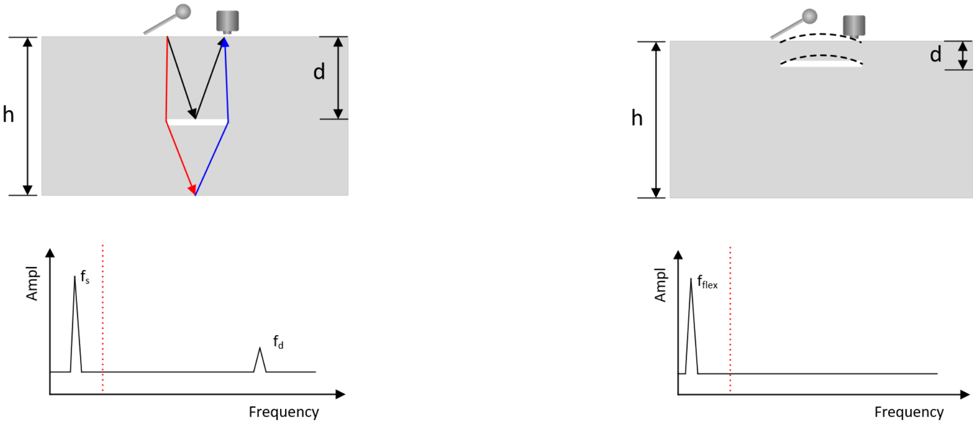
A. Intact.

B. Wide deep discontinuity.



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C. Narrow deep discontinuity.

D. Shallow discontinuity.

Figure 19. Diagrams. Representative IE response for various conditions.

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Figure 20. Photo. IE system and data collection.

Original Photo © 2020 Google® Earth. Modified by FHWA. (See Acknowledgments section.)

Figure 21. Photo. IE findings on spans 1 through 3 of a bridge deck (Google® Earth 2020).

In addition to the traditional impact echo systems, which collect data at a slower rate, there are some custom-made systems that can collect data at walking or slow driving speeds. Different consultants use these systems, but they are not commercially available for purchase.

Ultrasonic Surface Waves

The USW method, also known as spectral analysis of surface waves (SASW), measures the average elastic modulus of pavements and concrete bridge decks. Since the USW method provides modulus, it is well suited to evaluate potential deterioration and modulus reduction caused by corrosion, delamination, cracks, and other causes.

A USW system consists of an impactor and two receivers. One receiver is closer to the impact source (near receiver), and one is farther away from the impact source (far receiver). Unlike IE and ultrasonic, which operate based on elastic body waves, a USW system uses the passing

Rayleigh waves (Gucunski et al. 2013). Figure 22 shows a USW system known as PSPA (Portable Seismic Property Analyzer). The average elastic modulus across the deck thickness is then calculated as follows (Nazarian, Baker, and Crain 1993):

$$E = 2(1+\nu)\left[\rho(1.13 - .16\nu)V_R^{\,2}\right] \tag{2}$$

Where ν is the concrete Poisson's ratio, V_R, is the surface wave phase velocity, and ρ is the density. The term in the bracket on the right side of the equation is the shear modulus.

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Figure 22. Photo. Cart-based ultrasonic surface wave test device.

Custom-made systems exist that combine impact echo and SASW test into one piece of equipment in a rolling configuration, which would permit faster data acquisition, but the system still cannot move faster than walking speeds at this time.

Currently, the USW method is not governed by an ASTM standard. However, SASW is one of the NDE methods discussed in ACI PRC-228.2, *Report on Nondestructive Test Methods for Evaluation of Concrete in Structures* (ACI Committee 228 2013).

Ultrasonic Tomography

Despite the strength and advantages of IE for locating horizontal discontinuities, the resolution is inherently limited to the grid size. For example, smaller delamination between the test points may not be detected on a 2-ft × 2-ft grid. This limitation can be addressed through ultrasonic tomography. With this technique, ultrasonic waves can be evaluated through arrays of transducers sending and receiving stress waves in sequence and interpreted to produce 3D dimensional interpretations (tomography) of the results. Ultrasonic shear and p-wave (compression waves) can be measured and interpreted through commercially available tomographic devices.

Shear Wave

Ultrasonic tomography can be used for thickness verification, detection of delamination and voids, detection of voids in grouted ducts for posttensioned tendons, etc. Ultrasonic tomography traditionally involves the propagation of shear stress waves (s-waves) through the concrete. The stress waves are transmitted and received by an array of dry point transducers. The transducers are spring-loaded, allowing for the testing of uneven surfaces. Depending on the mode of data collection, the data can be postprocessed to allow for a 3D representation of embedded features.

For 3D reconstruction, the data are collected as a series of step-by-step shots on a grid. The images are postprocessed using the focusing technique of synthetic aperture with combinational sounding (SAFT-C). The results can be viewed in a 3D volume format and on three orthogonal planes, which can be placed at any cross-section within the test section. Figure 23 depicts a commercially available ultrasonic system using shear wave transducers.

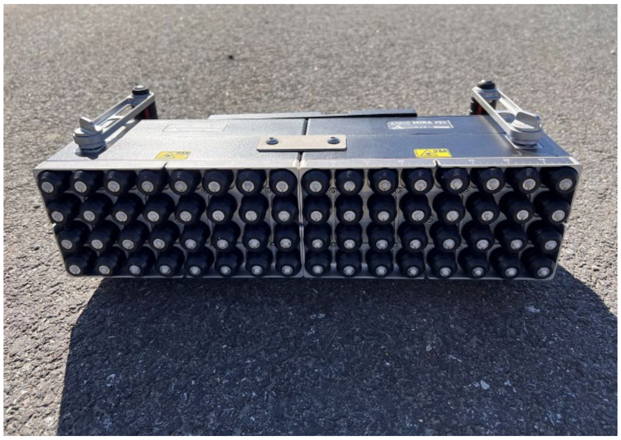

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Figure 23. Photo. Array of transducers on an ultrasonic tomographer.

P-Wave

In addition to ultrasonic shear wave tomography, there have been recent advances in using p-waves for subsurface imaging in recent years. A new emerging technology is using rolling ultrasonic scanning instead of discrete deployment using a shear wave tomographer (figure 24).


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A. Close up.

B. Overview.

Figure 24. Photo. Rolling ultrasonic system.

Using rolling ultrasonics significantly improves the rate of data collection. A large area can be scanned at a high speed, although at the cost of resolution. After identifying areas of concern, the survey speed can be adjusted for optimal resolution and higher accuracy. One of the benefits of using the rolling ultrasonic system is quickly locating reinforcement in UHPC-overlaid bridges. Because of the presence of steel fibers, GPR cannot be used.

Electrical Surface Resistivity

Electrical resistivity measurements provide insight into whether reinforcing steel in concrete is susceptible to corrosion. The decrease in surface electrical resistivity of concrete is known to be consistent with the degrading of protective properties of concrete toward reinforcing steel, which increases the potential for corrosion. With increased permeability and volume of interconnected pores, the saturation of concrete subject to water intrusion increases, and its electrical resistivity decreases accordingly. The presence of dissolved chloride (Cl^-) increases electrical conductivity as well.

ASTM does not have any standards geared specifically toward measuring the electrical surface resistivity of reinforced concrete elements. ASTM G57, *Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method*, prescribes how to measure the electrical resistivity of soil using a four-electrode Wenner probe (ASTM 2020b). AASHTO T358-19, *Standard Method of Test for Surface Resistivity Indication of Concretes Ability to Resist Chloride Ion Penetration* prescribes the use of a Wenner probe to measure the resistivity of concrete samples in the laboratory (AASHTO 2019). Additional provisions for ER measurements in concrete are prescribed in ACI 228.2R, *Report on Nondestructive Test Methods for Evaluation of Concrete in Structures* (ACI Committee 228 2013).

The Wenner probe described in ASTM G57 and ACI 228.2R has four equally spaced electrodes (figure 25) (ASTM 2020b; ACI Committee 228 2013). An alternating current is applied to the two outer electrodes, and the voltage is measured between the two inner probes. Using the applied current and measured voltage, the resistivity is then calculated as in equation 3:

$$\rho = \frac{2\pi dV}{I} \tag{3}$$

Where ρ is resistivity in Ω·m, d is electrode separation in m, V is voltage in V, and I is current in A. The inverse of the electrical resistivity is the electrical conductivity σ [S/m], which is one of the material properties affecting electromagnetic wave propagation.

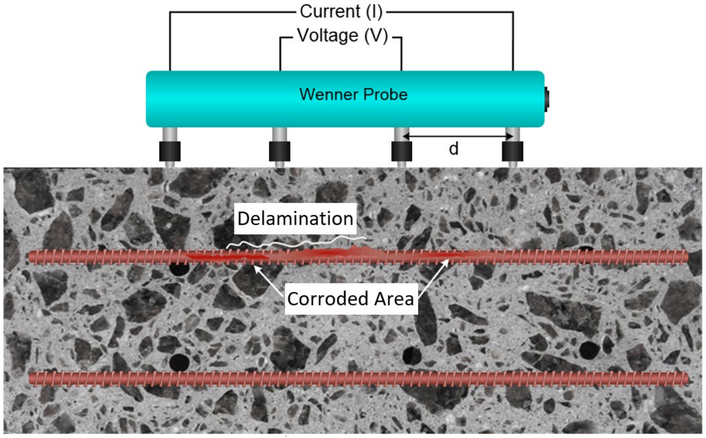

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Figure 25. Diagram. Electrical resistivity measurement of concrete.

ACI 222R and RILEM TC-154 provide additional information about the relationship between ER and the expected corrosion rate, as shown in table 7 from ACI 222R, *Protection of Metals in Concrete Against Corrosion*, (ACI Committee 222 2001).

Table 7. Relationship of concrete surface resistivity to corrosion rate (ACI Committee 222R-2001).

Resistivity [kΩ·cm]	Corrosion Rate
<5	Very high
5–10	High
10–20	Moderate–low
>20	Low

Contour maps based on ER do not contain information about whether the reinforcing steel is actively corroding (Polder 2001). The deteriorated areas as detected by GPR attenuation and surface resistivity are both characterized by the corrosive environment. However, the GPR attenuation is a function of corrosiveness within the bulk of concrete in which the electromagnetic waves travel, while the Wenner probe measures the resistivity above the top reinforcing bar.

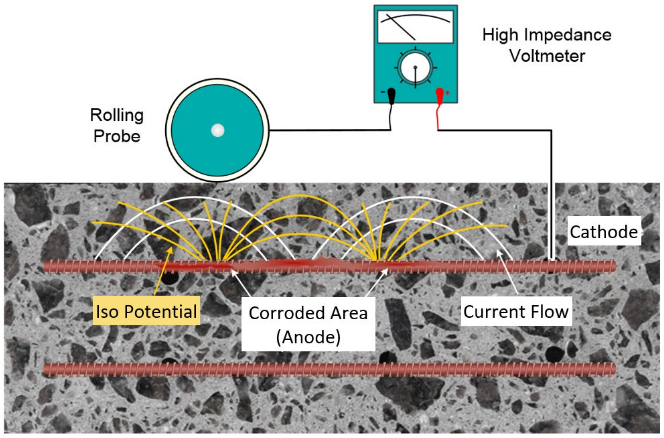
Half-Cell Potential

HCP is a popular NDE method used to determine the extent of corrosion experienced by reinforcement in reinforced concrete elements. It does not provide quantitative information regarding the corrosion rate, nor does it detect the degree of corrosion or section loss. Rather, it detects areas with a high probability of active corrosion occurring in reinforcement close to the point of testing as illustrated in figure 26.

Figure 26. Photo. HCP testing using a roller probe.

The testing requires drilling into the deck to connect to the reinforcing steel. A high-impedance voltmeter is then used to measure the electrical potential between a standard reference electrode, usually copper-copper sulfate (Cu-CuSO$_4$, also known as CSE), and the reinforcing steel. The standard reference CSE electrode is a copper rod immersed in saturated copper sulfate solution, forming half of the electrochemical cell. The embedded reinforcement forms the other half of the electrochemical cell.

A prewetted sponge soaked in a liquid detergent solution is used to bridge between the reference electrode and the surface of the concrete. The results serve as an indication of the probability of active corrosion. The schematic of the HCP testing is illustrated in figure 27.



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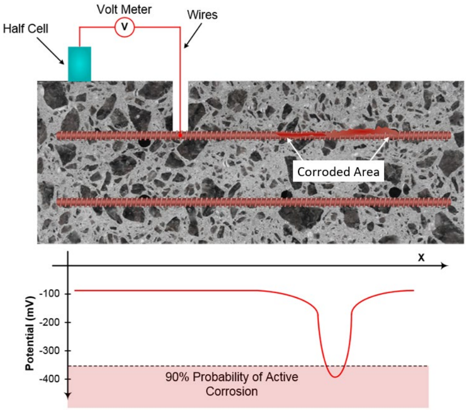
A. HCP measurement.



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B. HCP interpretation.

Figure 27. Illustration. HCP schematic showing test device, connection to concrete reinforcement, and interpretation of corrosion probability.

HCP testing is performed according to the ASTM C876, *Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete* (ASTM 2015). Based on this standard, three threshold values need to be considered when analyzing the HCP measurements, although these limits may change due to various factors. These thresholds are as follows:

- Potentials less than -350 mV CSE (more negative) indicate a greater than 90 percent probability of active corrosion.
- Potentials within the range of -200 mV CSE and -350 mV CSE indicate that corrosion activity in that area is uncertain.
- Potentials greater than -200 mV CSE (more positive) indicate a greater than 90 percent probability of no active corrosion.

RILEM suggests that these limits need to be treated with caution. Other influencing factors are overlooked by the ASTM, and therefore, these threshold values may need to be adjusted on a case-by-case basis. Similarly, the German Society for Nondestructive Testing advises against using fixed thresholds.

A good practice for adjusting ASTM C876 limits is to determine acid-soluble chlorides content in concrete under the *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete* (C1152 (ASTM 2020b). Comparing the content of acid-soluble chlorides in concrete with the threshold values triggering corrosion suggested by ACI 222R is a valuable tool for adjusting the ASTM limits for HCP measurements (ACI Committee 222 2001).

Structural Monitoring Technologies

Structural monitoring approaches commonly identify and quantify structural performance and changes in that performance through system and component levels. Such structural characteristics most commonly include tracing the global load path, the distribution of component actions (e.g., displacement), and the distribution of stresses within critical cross-sections, though other instrumentation may track the progression of temperature, humidity, corrosion, and other parameters. ACI PRC-444.1-21, *Structural Health Monitoring Technologies for Concrete Structures—Report* provides a useful overview of relevant technologies and their common applications for SM of reinforced and prestressed concrete elements (ACI Committee 444 2021).

Currently, the most common approach for assessing the structural performance of a bridge is by performing load rating, whereby the expected demands are compared to an estimated capacity. *The AASHTO Manual for Bridge Evaluation* (MBE) is the current authority on structural evaluation and load rating of highway bridges and culverts (AASHTO 2018). When an analytical rating is insufficient to ensure capacity meets demand, physical load testing or longer-term monitoring of the structure may be warranted. SM systems can range from basic monitoring (e.g., measuring crack widths, deflections, and joint widths) to more advanced monitoring (e.g., corrosion rate monitoring or vibration and deflection monitoring) combined with manual data collection, automated data logging, and data transfer.

Bridge decks receive more direct impact from traffic loads; therefore, deck slab condition data are desired in some cases. SM methodologies can be applied to assess and monitor the behaviors of a deck slab as an element within the structural system. However, the current use of SM technologies to directly assess the condition of bridge decks on a practical basis appears limited.

The selection and configuration of appropriate SM technology will vary depending on the type of bridge deck to be evaluated. The following sections discuss the general types of monitoring that may be relevant to bridge decks.

Vibration Monitoring

Vibration monitoring as an SM methodology is concerned with changes in global bridge behavior that may reflect changes in the condition of component members of the bridge. Using vibration monitoring to capture modal frequencies and mode shape characteristics can indicate damage in members, including decks, by investigating changes in modal responses through the time of service. Bridge vibration can be induced by ambient excitation sources such as dynamic loading induced by traffic, wind, seismic activity, or evaluators by excite the bridge, in what is known as forced vibration testing, with a heavy shaker or dropped weight. The principle is to compare the actual behavior measured on-site with a theoretical model representing the designer's concept. The fundamental tools are system identification (SI), damage determination, and localization. The analysis determines the modal parameters, namely the structure's natural frequencies, mode shapes, and damping coefficients. These parameters, which are gained from the measurements, represent the real condition of a structure and are used to update mathematical models of the structure or are compared to reference data from earlier measurements. Structural changes, such as damage leading to decreased load-carrying capacity, affect the dynamic response. The notion is that measurement and monitoring of the dynamic response characteristics can be used to evaluate structural integrity, though researchers and practitioners have reported significant differences in the sensitivity levels to localized damage, particularly in bridge decks versus primary structural load-carrying members. Therefore, vibration monitoring may or may not be suitable for deck condition assessment, depending on the structure type and the nature of the damage.

Strain and Displacement Monitoring

The most common type of structural monitoring is the measurement of localized changes in strain at critical sections of a structure under ambient or induced loading to verify that behavior matches design assumptions. Similarly, displacement at critical locations (e.g., midspan of flexural members, spacing at structural joints, or movement at bearings) can be used to monitor behavior under both gravity and thermal loading and, in some cases, seismic loading. These types of measurements are useful in characterizing the load paths and distribution of forces among structural members but are less directly useful for evaluation condition of bridge decks, other than to assess potential contributing factors to the occurrence of deck cracking (such as restrained shrinkage, thermally induced or flexural cracking).

Temperature and Environmental Monitoring

Capturing external environmental influences on a bridge, often as part of a more comprehensive monitoring system, is also useful. Changes and distributions of temperature profiles through a structure and rates of change can cause significant stresses in structural components, the influence of which may often be greater than superimposed lives load. The temperature gradient between the bottom and top of a structure may be crucial, particularly in deeper or stiffer, more complex structures such as boxes or trusses. Similarly, particularly for concrete elements, relative humidity, and precipitation can influence several mechanisms ranging from drying shrinkage to reinforcement corrosion. These measurements are generally not suitable for deck condition assessment.

Corrosion and Moisture Monitoring

There are commercial and experimental devices in concrete, such as a bridge deck, to monitor parameters related to corrosion or potential for corrosion. The most common devices of this nature may be embedded probes that directly monitor the corrosion (half-cell) potential of reinforcement bars in specific areas of a structure based on electrochemical principles. These would generally represent embedded probe variants of HCP or corrosion rate measurements, such as LPR, GPM, electrochemical impedance spectroscopy (EIS), or microcell current techniques (ACI Committee 444 2021). The type and stability of the reference electrodes in a high-pH, moist environment is a critical factor in the robustness of these systems, and it is important to adjust results with respect to temperature when making comparisons. These devices are frequently used in association with applications of cathodic protection of reinforced concrete elements. Currently, there is very little evidence of routine use in highway bridge decks.

Some "sacrificial" sensors involve embedding a surrogate material adjacent to reinforcement that is monitored to determine the arrival of chloride and the associated onset of corrosion in a wire of known chemistry based on its change in resistivity. There are also fiber-optic, reflection- and absorption-based sensors wherein a compound, such as silver chloride, AgCl, reacts directly with chloride in concrete, and the development of precipitate or changes in color related to chemical reaction changes the transmission of light, thereby indicating chloride concentration (ACI Committee 444 2021). Both sensors represent "trigger" indications that reflect one-time, irreversible reactions. The corrosion rate cannot be indicated by these sensors.

Devices are used to monitor relative humidity (RH) and measure temperature. Types include capacitive or resistive polymer sensors or fiber-optic sensors based on Fabry-Perot hygroscopic filtering or fiber Bragg grating methods (ACI Committee 444 2021). The RH sensors have limitations in the range of RH for which they are accurate, and they lose accuracy as RH approaches 100 percent. Some sensors are sensitive to moisture vapor but may be rendered inoperative by contact with liquid water.

CHAPTER 4. AGENCY QUESTIONNAIRE

SUMMARY OF AGENCIES INTERVIEWED

The research team prepared a questionnaire with 17 questions to obtain input from SHAs with known experience in using NDE and SM technologies. The questionnaire is provided as appendix A. The questionnaire was sent to nine SHAs (table 8). Ten responses were received because the Oregon DOT (ODOT) provided two responses. The research team interviewed six SHAs (Oregon, Wisconsin, Minnesota, Indiana, Iowa, and Virginia) to clarify their questionnaire responses. The findings in the next sections are a compilation of questionnaire responses and notes from the follow-up interviews.

Table 8. List of agency contacts that responded to the questionnaire.

State	Agency
Oregon	ODOT
Wisconsin	WisDOT
Minnesota	MnDOT
New York	NYSDOT
Indiana	INDOT
Washington	WSDOT
Iowa	Iowa DOT
Virginia	VDOT
Utah	UDOT

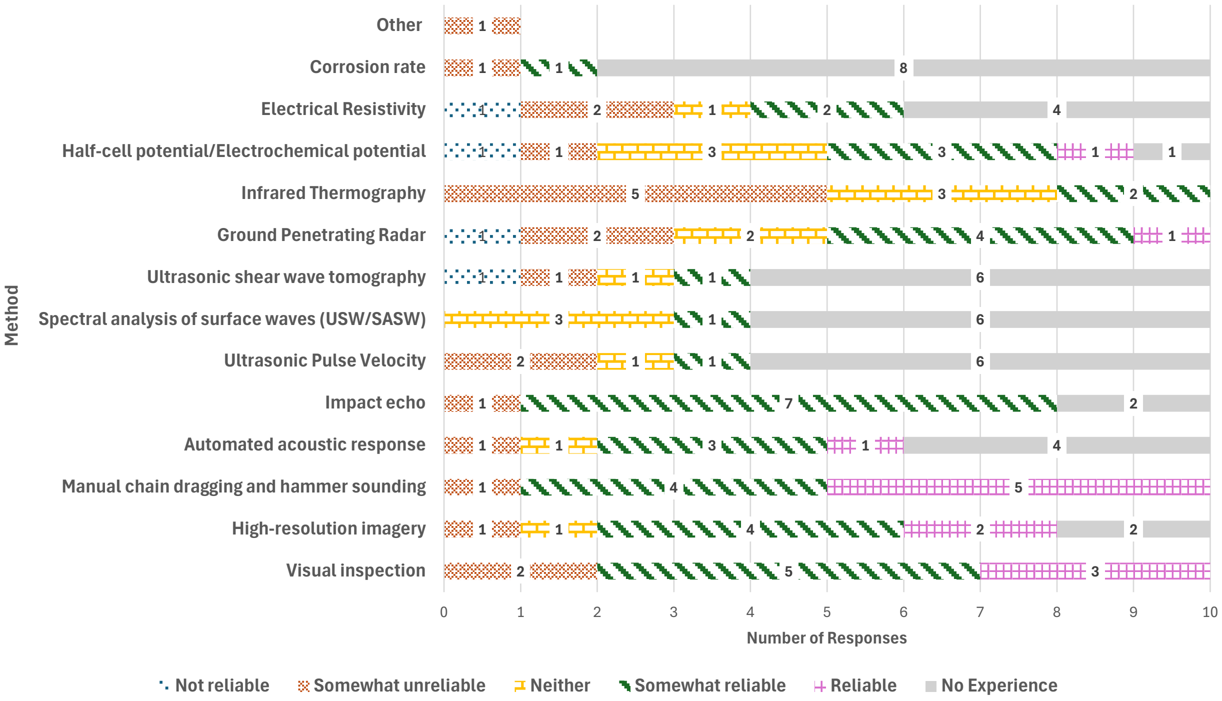
UDOT = Utah Department of Transportation; NYSDOT = New York State Department of Transportation; INDOT = Indiana Department of Transportation.

Questionnaire

The questionnaire was prepared on a web-based platform and distributed to the SHAs by email. The first two questions listed NDE methods used for concrete deck and steel deck evaluation, respectively, and asked responders to assess their level of confidence in these methods on a scale of one to six (1-No Experience, 2-Not Reliable, 3-Somewhat Unreliable, 4-Neither, 5-Somewhat Reliable, and 6-Reliable). Questions 3 through 5 asked whether different NDE methods were used for bare decks versus various overlay types and if agencies used any innovative or developmental NDE methods they experimented with for their evaluation. Question 6 asked about the purposes of NDE applications at the agency and the relative proportions of these purposes. In Question 7, agencies were asked whether in-house forces or contractors are used for NDE testing. Agencies were also asked what potential benefits they see currently or in the future from NDE methods (Question 8). Questions 9 through 12 asked about agency thresholds for NDE tests, spatial frequency for certain NDE tests, and cost estimates or records for NDE tests. In Question 13, agencies were asked to rate the maturity of the adoption of NDE for bridge decks by their agency. Agencies were also asked whether they validated the results that they are getting from NDE methods and if there are specific NDE methods that they have stopped using (Questions 14 and 15). Question 16 asked whether agencies have experience using SM for bridge deck evaluation, preservation planning, or condition tracking. The last question asked for any clarification or questions from the responders.

Summary of Compiled Responses

The questionnaire responses are presented with a summary of agency responses and graphics. The responders will be referred to as "agencies" in the text, and the term does not indicate a generalization for all SHAs. Figure 28 presents the reported agency confidence level in NDE methods for concrete deck evaluation. The agency feedback on the reliability of the NDE methodologies varies. The exact input for a specific technology and reliability level can be seen on figure 28 for concrete decks and figure 29 for steel decks. A perceived average reliability level is discussed based on the responses and feedback from the follow-up interviews.



Source: FHWA.

Figure 28. Chart. Reported level of confidence in NDE methods for concrete deck evaluation.

On average, agencies find visual inspection somewhat reliable and note that it is the method that they have used for the longest time, most often, and are most familiar with. HRI is reported as somewhat reliable. The Iowa DOT found HRI to be good quality, but unsuitable for broad application because using it for the full inventory would be expensive. ODOT has used high-speed line scanning and HRI 360° imaging on a few structures, mostly for measuring curb heights, widths, parapet configurations, and laser profilers to look at rutting. ODOT found it to be reliable. VDOT found HRI to be reliable for what it does, considering that HRI will not give input on anything underneath the subsurface. INDOT found HRI somewhat unreliable, not because of the feedback from HRI but rather the unreliability of the technologies it is paired with.

Manual HSCD were the most reliable method compared. Most methods had one response as "reliable," if any, while manual HSCD were "reliable" by five responders. ODOT does chain dragging on about 70 percent of deck projects. ODOT has seen better results with automated concrete sounding (ACS) (rapid chain data) than other NDE methods. INDOT found chain dragging somewhat subjective and more suitable for low-noise environments (not ideal for interstate). MnDOT has done ACS on two bridges and found it to be reliable. MnDOT has not yet completed any repairs to these bridges to validate the findings. The Iowa DOT has done ACS half of the time for project quantities (partial depth or full depth repairs) and half of the time for condition assessment to avoid having to do manual chain drag on high-volume roadways.

IE is reported as somewhat reliable. VDOT has had success on smooth surfaces, which is probably the best experience among all NDE for concrete decks with IE. Experience from other agencies was limited to a few trials. The experiences with ultrasonic pulse velocity (UPV), USW/SASW, and ultrasonic Shear Wave Tomography were also limited. The assessment for UPV was somewhat unreliable, for USW/SASW neutral, and for ultrasonic shear wave tomography somewhat unreliable.

GPR is reported to be somewhat reliable. MnDOT reported that they are not getting a good correlation from GPR on quantities but are tracking data in a spreadsheet. MnDOT usually takes half the amount of GPR damage projected for project quantities. The Iowa DOT did not find GPR reliable in finding damage because chlorides interfere. ODOT defined their experience with GPR as "hit or miss" since people do not always understand what they are looking at. Although GPR is starting to get better communicated, it is still not assessed as a great tool for finding concrete defects. ODOT has had consultants on projects just to locate reinforcing bar for strengthening. It has been "hit or miss" not just for damage quantities but for simply locating the reinforcing bar. WisDOT also has limited confidence in GPR and is working on a process to understand the results. Miscommunication between contractors and regional bridge maintenance personnel has been an issue. GPR gives predicted deterioration, not present damage. WisDOT reduced the use of GPR due to their limited ability to identify delamination and hope to use GPR results to predict faster than typical deterioration (e.g., some new decks show high levels, wondering if it is correlated to accelerated deterioration in service). INDOT also reports that GPR has not been useful in finding delamination but is great for finding steel or areas of high moisture.

Agencies have some experience with IR and assess it as somewhat unreliable. WisDOT plans to combine GPR and IR with overlaid decks to assess the defect depth and see how the two methods correlate. MnDOT finds IR unsuccessful due to constraints (clean deck, shallow depth limitation, hard to distinguish) and prefers technology that crews can perform. In Iowa DOT's experience, IR did not pick up damage in wheel lanes and was not efficient enough. ODOT found IR somewhat reliable or unreliable and not suitable for concrete decks. One high-speed application seemed to work (east Oregon during summer with good temperature gradient and no shading from vegetation), while other deployments did not have enough thermal contrast. MnDOT found IR somewhat reliable. Fixed-wing applications were the least reliable, and MnDOT achieved better results from vehicle-based applications. INDOT had inconsistent results with IR and found it subject to weather conditions and shading.

With HCP, agency experience is broadly variable. In Iowa DOT's experience, HCP does not correlate well with delaminations and damage detection. ODOT has limited experience and found HCP somewhat reliable for the probability of corrosion (not damage detection). INDOT has been using HCP for a while and reports it as somewhat reliable. Overall, experience with ER is also limited by different agency assessments of its reliability. ODOT found ER somewhat unreliable based on limited experience but considered it a great test on new concrete for quality assurance. Once in place, the local environment plays a big role and leads to qualitative data since the moisture content of concrete may influence the results too much. Only two agencies reported experience with corrosion rate: Washington State DOT (WSDOT) (somewhat unreliable) and VDOT (somewhat reliable). VDOT has mostly used corrosion rate and ER for research purposes but multiple technologies may be needed to obtain a good picture of what is happening in the structure.

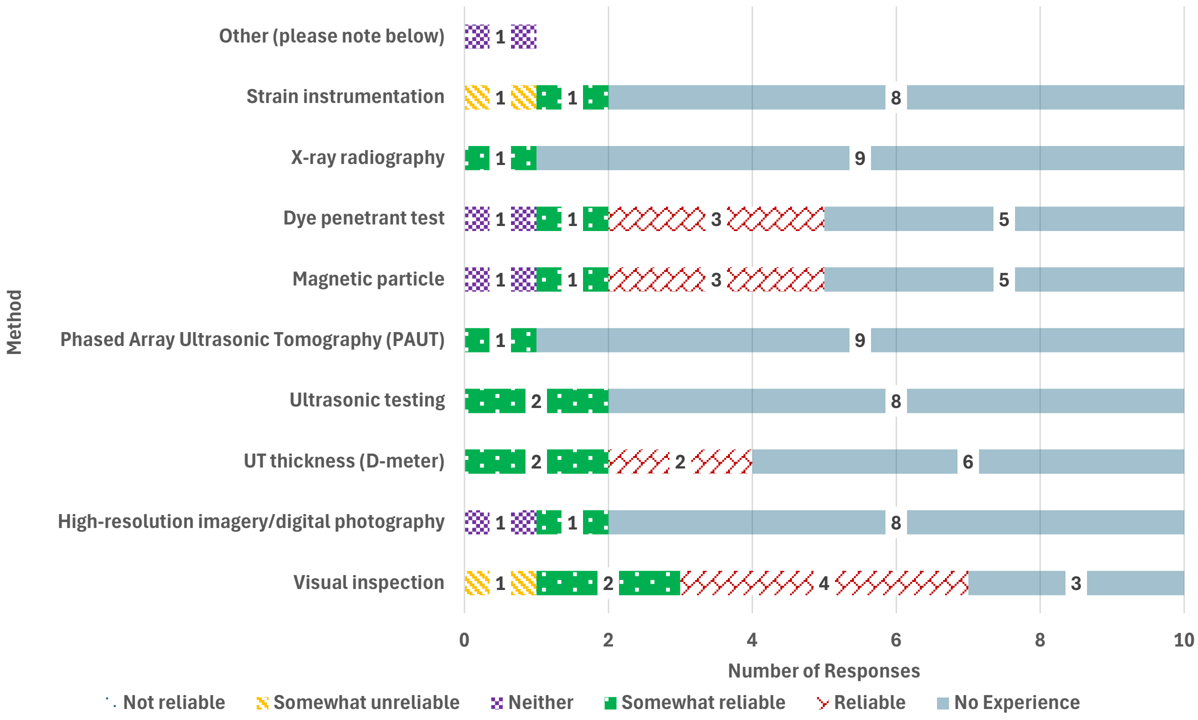
Figure 29 presents the reported agency confidence level in NDE methods for steel deck evaluation. NDE and related experience for steel decks are limited compared to concrete decks, driven by the smaller percentage of steel decks in SHA inventories. Agencies have had positive experiences with ultrasonic testing (UT) thickness, magnetic particle, and dye penetrant tests.

The choice of NDE typically varies with bare deck versus various overlay types. The choice of NDE changes based on the existence and type of overlay according to 80 percent of the responses. With polymer overlays, MnDOT noted chain dragging is not as conclusive on the underlying substrate, and other methods might be needed, such as coring and hammer sounding. GPR is used for general reinforcing steel condition but not for contract quantities by MNDOT. According to NYSDOT, overlays and SIP forms impair visual, infrared, and sounding inspection of concrete decks, and thus, they consider overlay existence and types for NDE choice. INDOT is currently doing a research project with Purdue University, evaluating multiple NDE methods. Current research findings have led INDOT to question the use of IR with overlaid decks. UDOT typically uses sounding and visual as a primary indicator if the deck is bare or has a thin or rigid overlay (thin bonded polymer, polyester polymer concrete, etc.). For decks with an asphalt overlay, UDOT is using other methods, including GPR and IR, as options for evaluating the deck condition and visual inspection of the underside of the deck. The Iowa DOT changed NDE methods for decks with overlays because, for bridge decks with PC overlays, deck sounding will not differentiate between a debonded overlay or delamination due to corrosion. WisDOT is more likely to use the aerial IR method for bare decks (especially when lower quantities of delamination are expected). When any overlay is present, thermal anomalies from IR are more likely to need verification with sounding or coring. GPR may be used to determine actual overlay thickness and reinforcing bar depth. WisDOT may also use GPR to assist with IR mapping for bituminous overlays. According to Virginia DOT, asphalt overlays make IR and some ultrasonic methods ineffective, but the same methods would work fine for concrete overlays. For ODOT, asphalt concrete wearing surface is almost always only a visual inspection. Thin bonded polymer and polyester overlays are typically evaluated by visual and HSCD methods, as are bare decks and those decks with structural concrete overlays and inlays.

Agencies reported on innovative or developmental NDE methods that they have experimented with for the evaluation of bare decks in response to a question. VDOT has experimented with time-lapse IR thermography and stepwise GPR. UDOT is evaluating several methods of NDE on a corridor of bridge decks, including infrared thermography (truck-mounted and ultra-time domain), GPR, and ACS. ODOT has experimented with automated concrete sounding, high-speed IR, IR-UTD, and multisuite arrays that include USW, ER, IE, and GPR, multisuite high-speed, high-definition line-scan imaging, high-resolution image/360-degree imaging, IR, LiDAR, and laser profilers. WisDOT has been experimenting with fixed-wing aerial IR. Air-coupled, vehicle-mounted GPR is being experimented with for bare deck evaluation by NYSDOT. Ground-coupled GPR and soundings are also used for bare deck evaluation. MNDOT has experimented with ACS, GPR, and mobile infrared.

Innovative or developmental NDE methods that ODOT has experimented with for evaluating decks with overlays include IR and GPR, and VDOT has used time-lapse IR thermography and stepwise GPR. WisDOT has been experimenting with fixed-wing aerial IR (similar to the methods for bare decks). ODOT has experimented with the same methods described for bare decks on decks with structural concrete overlays and inlays, thin bonded polymer overlays, and polyester concrete overlays. UDOT is experimenting with IR (truck-mounted and ultra-time domain), GPR, and HCP, and NYSDOT is experimenting with GPR to evaluate decks with overlays. MNDOT reported using chloride modeling as an overlay prediction tool for decks with overlays.

Agencies were also asked to report on the percentage of NDE applications used by the purposes listed in table 9. While some agencies allocated percentages of overall NDE use to the specified purposes (VDOT, UDOT, Iowa DOT, NYSDOT, and MNDOT), others reported their estimates of how much of the NDE they would use for these purposes. For example, WSDOT reported that 90 percent of their NDE would be used for screening condition assessment, 20 percent for project-specific decisions and coming up with repair quantities, and all NDE would be used for assigning NBI general condition ratings (GCRs) or National Bridge Element (NBE) condition state quantities. WSDOT, WisDOT, and ODOT have a more pronounced use of NDEs in assigning NBI GCRs and NBE condition state quantities; Utah, Oregon, New York, and Minnesota DOTs appear to use NDE heavily for project-specific decisions to estimate repair quantities; and Virginia, Wisconsin, and Washington DOT use NDE for prioritizing among a group of structures or preservation action decisionmaking to a greater extent. Percentages here reflect the proportion of NDE use that is applied to the respective purposes but do not reflect the overall frequency at which NDE is used by the agencies when performing these activities. For example, the VDOT uses 30 percent of the NDE input for project-specific decisions, but they do not use NDE 30 percent of the time when making project-specific decisions for their overall bridge program.



Source: FHWA.

Figure 29. Chart. Reported level of confidence in NDE methods for steel deck evaluation.

Table 9. Agency purpose of NDE use.

Agency	Screening condition assessment (prioritizing among a group of structures or preservation action decisionmaking) (percent)	Project-specific decisions (repair quantities) (percent)	Inspection NBI condition ratings or NBE condition state assignments (percent)	Other (percent)
VDOT	70	30	—	—
UDOT	25	70	5	—
INDOT	20	40	20	20
Iowa DOT	0	50	50	—

Agency	Screening condition assessment (prioritizing among a group of structures or preservation action decisionmaking) (percent)	Project-specific decisions (repair quantities) (percent)	Inspection NBI condition ratings or NBE condition state assignments (percent)	Other (percent)
ODOT	5 percent initial screening is based on NBI/NBE data. However, chain drag is used in some instances in low-traffic volume areas.	70 percent typically is chain drag. 100 percent of deck area is chain dragged for quantities during construction.	100	—
WisDOT	75 percent by count of structures.	25 percent by count of structures.	95 percent (most) results are directly incorporated into inspection data.	5 percent research and contractor question and answer.
NYSDOT	15	84	1	—
WSDOT	90	20	100	—
MNDOT	30	65	5	—

—No data.

Agencies perform some of the NDE by in-house forces and equipment (40 percent) and some by hired consultants or contractors (40 percent), which typically varies based on the specific NDE technology. For example, MNDOT only hires out GPR and has some drones that use IR and have been used for trials only and not mapping. The ODOT does some in-house work, and some contracted NDEs, but will move more toward contractors in the future. WisDOT contracts the GPR work, and their choice of contractor heavily relies on the location of the NDE consultant, which significantly impacts the cost (mobilization and remobilization costs). INDOT has mostly done in-house NDEs (IE, IR, HCP, GPR) so far.

The most common benefit that agencies currently see, or foresee as potential benefit in the future, from NDE methods for bridge decks is assessing current condition (table 10). Agencies see some potential for all the listed benefits. In addition, ODOT believes that NDE can help provide quantities of defects for construction purposes but requires experience and knowledge to do so. Depending on the deterioration mode (chlorides, impact loading, overlay versus substrate deterioration, structural detailing), quantities can grow between design and construction, or unknown quantities can exist beneath overlays. Based on the experience of ODOT, NDE may not always accurately determine these depending on the type deployed. WisDOT reported assessing new technologies or methods to maximize efficiency as another potential benefit. INDOT lists construction quality assessment (i.e., reinforcing bar placement) as another potential benefit of NDE use for bridge decks.

Table 10. Current and potential benefits from NDE for bridge decks.

Current and Potential Benefits From NDE for Bridge Decks	Percent
To assess current condition.	100
To assess future condition, rate of deterioration.	50
To trigger specific preservation actions.	70
To differentiate between potential preservation actions.	90
To determine accurate defect quantities for contract and construction purposes.	70
Other (please elaborate):	30

Agencies were also asked how often they prescribe NDE tests of decks to be performed. Here, the interest was on thresholds they use to trigger NDE use, such as age, condition, roadway. The Iowa DOT does soundings every 6 yr by the internal staff and automated acoustic sounding on corridors as needed annually. ODOT typically tries to HSCD all decks for quantities before construction. However, many lower-risk preservation projects and maintenance activities may not receive chain drag before construction. Other deployed NDEs have been experimental and discrete in nature to date for ODOT. WisDOT has developed a deck-scanning policy, which is part of their *Structure Inspection Manual* (WisDOT 2020). The policy document specifies when to use a specific technology and what deliverables, at a minimum, should be provided. |The policy is necessary to determine the accurate scope of deliverable projects, certify structure work concepts for various funding programs, and refine deterioration models used in the Wisconsin Structures Asset Management System. UDOT currently selects NDE on a case-by-case basis, typically when work is needed and to differentiate between different treatments. NYSDOT conducts soundings as needed and GPR for project or network-level evaluation as needed. MNDOT currently uses NDE on box girders or bridges when a high quantity of repair may be expected.

Regarding spatial frequency, ODOT typically scans all deck areas when possible. The entire structure may not get sounded on interstates due to traffic control and mobility considerations. The VDOT has specified minimum image resolutions for both methods involving visible and infrared spectra at 1080 p and 320×240 pixels, respectively. For vehicle-mounted GPR scanning at speeds 45 mph or greater, the following spatial resolution was specified: individual line scans shall have a lateral spacing of no more than 3 ft, and the longitudinal distance between GPR individual scans shall be six inches maximum, with three inches preferred. NYSDOT typically conducts GPR scans using longitudinal scans at 2 ft lateral spacing. According to WisDOT, aerial imagery will need minimum overlap to create mosaic images and results. Most vehicle-based IR is taken with video. Specifications vary based on contractor equipment. Other agencies either do not have spatial frequency guidelines yet or are working on them.

Only five agencies reported on cost estimates for specific NDE methods, and a few noted that they would follow up by providing documentation (e.g., INDOT and Iowa DOT). Table 11 lists these costs as worded by the agencies to provide context. GPR cost provides a reference because it was commonly reported but also varies depending on the agency.

Table 11. Cost estimates for specific NDE tests.

Agency	Cost estimates and records for specific NDE techniques
VDOT	For scanning 76,488 SF of bridge deck area, unit costs of \$0.079/SF for vehicle-mounted IR, and \$0.079/SF for vehicle-mounted air-coupled GPR were observed for the winning bid, excluding mobilization and traffic control costs. For scanning 251,953 SF. of bridge deck area, the unit costs of \$0.06/SF for vehicle-mounted IR and \$0.065/SF for vehicle-mounted air-coupled GPR, were observed for the winning bid, excluding mobilization and traffic control costs.
UDOT	Our latest contract had high quantities, so the unit costs may be lower than typical: High-resolution imagery: \$0.06/SF mobile infrared: \$0.06/sq ft ACS: \$0.17/SF 3D GPR: \$0.14/SF IR-UTD: \$4000 per setup location.
INDOT	INDOT will provide costs separately as a follow-up.
Iowa DOT	For automated acoustic ACS \$0.28/SF.
ODOT	Most are done in-house and tied to traffic control costs, which vary greatly by site. Since the other methods deployed were small-quantity contracts or experimental in nature, they would likely not provide accurate unit costs.
WisDOT	IR Level 0 is \$0.06/SF to \$0.08/SF IR Level 1 is \$0.08/SF to \$0.20/SF IR Level 2 is \$0.13/SF to \$0.25/SF IR Level 3 is \$0.25/SF to \$0.33/SF Additional GPR with IR is around \$0.10/SF. Cost varies based on method, traffic control, contractor, and quantity.
NYSDOT	GPR is expected to cost approximately \$0.20/SF of deck area, excluding traffic control.

SF = square feet.

Agencies were also asked how they would rate the maturity of adoption of NDE for bridge decks by their agencies and what they consider strengths or impediments to adoption. Table 12 presents the agency responses. Aside from WisDOT, most states define themselves at an early adoption or experimental stage. WisDOT's approach is network-level data collection with a select method that is recorded in the agency asset management system for data-driven decisionmaking.

On varying scales, either for different contractors or methods, agencies have all done some form of validation for the results that they are getting from NDE. The Iowa DOT has compared NDE with chain dragging and known defects. NYSDOT has some level of validation of NDE results after the demolition of the existing deck and construction of a new deck, coring concrete, chloride testing, and cross-validation of various NDE results. GPR has been reviewed against spot field contract repairs and found to not correlate well with the MNDOT. Chaining correlates best, according to MNDOT, but can underestimate if there is an existing concrete-wearing course. Infrared is not used often to generate field quantities, and no direct comparison has been made because they often have thicker concrete cover than infrared is effective at. VDOT and

INDOT both have continuing research projects for validation. INDOT is comparing different methods, contractors, and used coring. At ODOT, in many cases, HCSD results and destructive testing (e.g., coring, chloride, and compressive strength), were compared to automated collection methods. The reliability of results varied greatly by consultant and NDE technology deployed.

Table 12. Self-assessment of maturity of NDE technologies' adoption.

VDOT	The internal research group has a lot of experience with multiple NDE technologies. They have not yet developed policies for production level.
UDOT	We are still at the experimental level of adoption. We have tried several different NDE methods, but we are still trying to get a level of confidence as to how the test results relate to treatment options and levels of actual degradation. The biggest challenge appears to be that each method has different ways to interpret the data, and they do not appear to be able to validate each other or correlate well. Most of the methods appear to give very conservative evaluations of bridge decks that may lead to premature extreme treatments that may not yet be warranted. This is not sustainable with constrained budgets that DOTs are faced with.
INDOT	We are still at an early stage. We have been working with a State university to evaluate different methods and the study has highlighted concerns with accuracy and consistency between methods and contractors. GPR is good for locating reinforcing bar, but not accurate for condition assessment and is affected by weather conditions. Aerial IR may be good for network assessment (identify candidates for further assessment), but not sure about the accuracy, IR is affected by shading of the deck. IE consistency between contractors seems to be an issue Pole mounted IR, which seems to be accurate but very expensive.
Iowa DOT	Moderate level of maturity.
ODOT	ODOT does not have a mature NDE program beyond extensive experience with chain dragging and hammer sounding. Costs and the sentiment that the benefit of additional NDE methods does not outweigh the additional costs appear to impede the widespread adoption of other NDE methods.
WisDOT	Lead adopter. Using an automated Bridge Maintenance System (BMS) and documenting data-driven programming decisions requires bridge deck NDE.
WSDOT	Not adopted.
Minnesota DOT	They have experimented with a few NDE technologies. However, they are not yet at production level.

Agencies reported that they stopped using some NDE technologies. The Iowa DOT has stopped using GPR, IR, and HCP. ODOT did not have the best success with GPR, although it has been useful when looking for reinforcing bar or shear connectors in a few instances. Initial testing of IR in the western portion of Oregon did not respond well due to a lack of thermal loading and high humidity and rainfall and vegetation shading solar radiation at several bridges. ODOT, however, has not stopped using or experimenting with them. WisDOT has drastically reduced the use of GPR due to its relative inability to quantify delaminations (areas that require deck repair during rehabilitation projects). They are evaluating GPR for the predictive ability of future delamination. Otherwise, WisDOT finds GPR to be good for determining overlay thickness and reinforcing bar depth, but these needs do not often arise. For NYSDOT, experience with rehabilitation quantity determination using both NDE and limited destructive testing suggests that older decks can appear visually (and with other NDE techniques) to be good candidates for rehabilitation, but when in construction, quantities increase to make that determination invalid. According to NYSDOT, it is possible that either the decks are deteriorating in a nonlinear fashion (accelerating after testing and before construction) or that tests, regardless of type, cannot accurately scope deterioration because of high latent chloride content.

The use of SM or some form of in-place instrumentation was very limited. VDOT has experience with monitoring structural behavior mostly during load-testing and for evaluating posttensioned tendons. VDOT has conducted short-term monitoring of bridge decks. The Iowa DOT has done some in-place instrumentation but not for preservation planning or condition tracking. WisDOT had a few research applications. NYSDOT has experimented with using accelerometers to evaluate bridge deck vibration and strain gages on girders to assess deck composite action.

Summary of State of Practice in NDE and SM Use for Bridge Decks

Most Used Technologies

Visual inspection is the age-old method for NDE of a structure, and combined with hands-on evaluation, it forms the basis for the National Bridge Inspections Standards (NBIS)-mandated inspection of highway bridges. The focus of this study is enhanced methods that give insight into the nonvisible portions of a structure, but it is recognized that visual assessment is and will remain an indispensable tool for informing bridge condition assessment. To the extent that digital photography has revolutionized the ease with which visual information can be captured, stored, organized, and even analyzed, high-resolution imagery provides a strong enhancement of the conventional value of visual inspection. The most common use is targeted photography of details of interest captured into an inspection report or bridge database, but technology is quickly evolving to leverage geo-positioning tied with digital photography to create 3D referencing and renderings, a more common application.

HSCD are most common for damage detection but are slow, require lane closures, are subjective, and are subject to noise interference from the surrounding environment. Also, location recordings are manual and, therefore, more time-consuming, less accurate, and less repeatable. Due to their long use and ease of application, HSCD are still considered by most agencies the standard against which other methods are compared.

GPR is a very common method that has evolved over the past few decades. It is most useful for identifying and locating embedded objects, such as reinforcement. It is also useful in identifying areas of relatively high moisture and ion content in concrete or timber. Early applications over-emphasized its usefulness in identifying delaminations, and many agencies have noted poor correlation with chain drag or actual damage quantities during construction, undermining their confidence in the method.

HCP is a common electrochemical method for measuring the probability of corrosion damage in reinforcing bars. While the method cannot be used to determine the extent of corrosion, it is highly useful in identifying areas with a high probability of corrosion damage (i.e., areas where delaminations are likely to form in the future). Several States indicated poor correlation when using the method to estimate delamination/spall quantities for repairs. HCP is mostly ineffective when used with epoxy-coated bars.

Most Promising Innovative Technologies

Technologies that are less common but for which users see promise were inferred from the written and verbal responses from SHAs on their NDE practices.

High-resolution imagery is gaining broader use as a stand-alone or complementary technique for rapid condition surveys. It can readily be deployed in manual, vehicle, and aerial configurations, and the quality and ease of data acquisition and storage make it a powerful tool for documenting existing visible conditions.

ACS is a more recent automated adaptation of HSCD that processes digitized sound waves, which has permitted the sounding of large areas under relatively short lane closures. Damage detection occurs through filtering of the acoustic response of an excited concrete surface. Filtering has become more sophisticated with recent applications, such that the subjectivity of manual methods is largely removed, and detection can extend to the measurement of frequencies beyond the range of human hearing. Rapid digital processing and automated location measurement (through distance measurement and GPS positioning) make the measurement inexpensive and repeatable.

Ultrasonic tomography is particularly useful in the case of steel fiber reinforced concrete or UHPC overlays because electromagnetic methods do not work due to the interference of the ferromagnetic materials. Ultrasonic tomography is a reflective UT method capable of detecting the presence of internal voids or defects within concrete elements. Like IE, the method can detect potential delaminations, including very deep ones, and estimate the depth with high reliability. However, the method is not commonly used for condition assessment of bridge decks because data collection will be very slow if used on a large area. The method also requires specially trained personnel to collect and process the data.

IE is a somewhat common method for measuring the thickness of concrete elements. It is mostly used to detect potential delaminations and discontinuities and estimate the depth of defects within concrete elements. While a reliable method, IE is not a popular method in bridge deck applications as measurements are collected on a point-by-point basis, which can take a very long time in large areas. The method also requires specially trained personnel to collect and process the data.

Main Impediments to Implementing NDE by SHAs

Misconception about different NDE limitations and capabilities—a common theme among discussions with SHA personnel is that several methods do not correlate well with HSCD quantities. Many end users have expressed frustration with GPR results when interpreted in this way. However, many acknowledged GPR to be very effective at locating embedded reinforcement and other features.

Impractical constraints on production use—IR is an example of a technology considered reliable by some but not by others. A chief limitation is that thermal conditions (not just temperature, but temperature change, and solar radiation and shading at the time of measurement) must meet carefully prescribed criteria to obtain acceptable results.

Inconsistent method applications within the industry—a common concern among agencies is that the application and interpretation of many methods are not uniform within the industry, even with methods for which industry standards exist. Therefore, it is difficult to determine the quality of the end product and the associated reliability and repeatability that can be expected when procuring from a range of vendors or in-house providers.

Lack of in-house expertise in selecting, applying, and interpreting NDE technologies—NDE technologies cover a wide range of physical principles and practical application methods. It is difficult for SHA decisionmakers to have a strong working knowledge of each method and its respective limitations, on top of the requirements of their daily roles.

The expense of applying NDE and SM on top of existing inspection requirements—although NDE and SM methods can provide very valuable supplemental information to understand bridge conditions, none can fully replace the conventional biennial hands-on visual inspection that is federally mandated for highway bridges. There is a need to demonstrate where NDE and SM methods can reduce the burden of inspection.

Conclusions From Agency Questionnaire

The perceived reliability of the same method varies greatly from agency to agency. Potential causes may be false expectations on what information the method can provide, application under a nonideal environment for the method, contractor issues, or limitations. NDE evaluation of steel decks by SHAs does not appear to be common or a priority so far, driven likely by the limited portion of steel decks in their bridge networks.

CHAPTER 5. NDE AND SM INFORMED PRESERVATION ACTIONS

Several NDE methods can be used to assess the condition of bridge decks, and several agencies are currently employing, or at least considering the implementation, of such methods to be conducted routinely to aid in better assessment of bridge deck conditions. This chapter includes a summary of the most common NDE methods used for condition assessment of bridge decks as well as guidance on the appropriateness of different NDE techniques to detect certain defects. SM methods are not widely used to assess the condition of bridge decks and, as such, preservation trigger thresholds will not be applicable for these methods.

The current state-of-practice does not rely on NDE methods to trigger actions for the preservation or maintenance of bridge decks. This result is mainly due to the absence of documented research that can aid in developing such thresholds, although numerous research and practical applications have shown that NDE methods can provide data that can ultimately be used for this purpose. To alleviate this gap, two approaches were explored to show how NDE data can be used to trigger bridge deck preservation and maintenance actions:

Approach 1: Focus on using NDE methods to define different element-level condition states for bridge decks. These condition states can then be used to guide the selection of bridge deck preservation strategies based on the input of NDE, among other factors.

Approach 2: Focus on using NDE methods to directly guide the selection of bridge deck preservation strategies. Due to the complexity of this approach, the lack of available literature and supporting data to fully develop NDE thresholds for all the available NDE techniques, and scope limitations, the main focus was to develop a framework that can be used to develop NDE thresholds for the different methods. Examples of the potential use of NDE methods to guide the selection of bridge deck preservation strategies are provided.

The results of the two approaches on NDE-based thresholds for bridge preservation and maintenance are presented. In addition, a discussion on how various NDE methods can be strategically deployed to accomplish specific bridge management and preservation objectives over the lifecycle of a single bridge or inventory of bridges is provided. This information will help agencies determine when and how certain NDE techniques are applied based on the bridge deck age, exposure, and condition.

CONDITION RATING-BASED PRESERVATION THRESHOLDS

This section describes the work performed to complete approach 1 to develop condition rating-based NDE thresholds to trigger bridge deck preservation and maintenance actions. Different SHAs are already employing thresholds based on general condition ratings and condition state (element-level) data to select appropriate preservation or maintenance actions for bridge decks. The idea behind Approach 1 is that a deck of a given condition can be characterized by its general condition rating, its element-level data, or its NDE data, but all three methods of characterization should provide a similar conclusion as to the condition of the deck and the appropriate preservation or maintenance action(s). To fulfill Approach 1, the thresholds used to trigger preservation and maintenance actions currently expressed in terms of the general condition rating of the deck or its element-level data need to be translated and expressed in terms of the data provided by NDE techniques. For element-level data, this method is a relatively simple task because the visual inspections and sounding surveys currently conducted to generate element-level data and the NDE techniques identified in this report as most common or suitable for deck evaluation have high overlap in the types of deck conditions that they characterize, e.g., delaminations, spalls, and cracks.

Translating NDE data into GCRs is less intuitive because general condition ratings communicate the aggregate condition of the deck and do not provide details as to the extent, severity, or type of defects present. However, because of the lack of information provided by the GCR, many SHAs use both GCR and element-level condition data to select appropriate preservation and maintenance, thereby expressing the range of element-level conditions expected to be observed at the different general condition ratings. Therefore, NDE data can be tied to GCR through element-level data. This relationship, in turn, enables NDE data to be used as input in existing decisionmaking aids, such as flowcharts and matrices currently used by the SHAs to trigger preservation or maintenance actions.

The first step to developing condition rating-based NDE thresholds was to compile the thresholds and decisionmaking tools currently used across the United States to guide preservation and maintenance decisions. While the focus of this project is preservation, the majority of these SHAs' thresholds consider bridge decks in fair or poor condition, which will mainly require corrective maintenance, rehabilitation, or replacement, and the thresholds for these actions were included in the review. Any current use of NDE techniques or testing to inform preservation and maintenance decisions was also noted during the review.

The manuals and published guidance on bridge design, maintenance, preservation, and repair of 10 SHAs were reviewed, and the *AASHTO Guide to Preservation of Highway Bridge Decks* (AASHTO 2023). The 10 States were Colorado, Florida, Illinois, Indiana, Michigan, Minnesota, New Jersey, New York, Virginia, and Wisconsin. This review found that each SHA had a unique approach to collecting and using condition data to select preservation or maintenance actions and as a result, the methodology, maintenance triggers, and decisionmaking aids used by each of the ten SHAs are summarized individually. A summary table listing key element-level condition scenarios, the GCRs expected to correspond to the selected element-level condition scenarios, and appropriate preservation or maintenance actions that may be triggered in each scenario was developed based on a synthesis of the SHAs' thresholds and is presented at the end of this section.

Colorado DOT Preservation Practice

When considering a bridge deck for preservation or maintenance, the Colorado DOT relies on a "Susceptibility Index" (SI) to technically inform the choice of maintenance action. The SI is not determined based on the GCR, element-level condition data, or NDE or SM techniques but instead relies on chloride testing. Calculation of SI is as follows:

$$SI = {\left(\sum_{1}^{n}(Cl_{th} - X_i)\right)}\Big/{(n * Cl_{th})} * 10 \tag{4}$$

Where n is the number of locations where chlorides were measured; Cl_{th} is the threshold chloride concentration required to initiate corrosion; and X_i is the chloride concentration at the depth of the top mat of reinforcing steel at the i^{th} measurement location.

The greatest SI that can be achieved is 10, representing a deck with no chloride ions at the reinforcing depth (at any test location). Lower SI values indicate a greater risk of active chloride-induced corrosion. An SI value of 0 corresponds to the scenario where the chloride concentration at the depth of the top mat of reinforcing steel equals the threshold chloride concentration at all tested locations, on average. Negative SI values typically indicate that corrosion has initiated at most tested locations. Obtaining a representative SI depends on good sampling practices, and as a result, the Colorado DOT provides guidance for chloride testing. A minimum of five cores or at least one core per 3,000 square ft (SF) of deck, evenly distributed across the travel lanes, must be collected and tested. The SI was developed as part of the work completed in National Cooperative Highway Research Program (NCHRP) Report 558, Manual on Service Life of Corrosion-Damaged Reinforced Concrete Bridge Superstructure Elements, to which Colorado DOT refers readers (Sohanghpurwala 2006).

The Colorado DOT (CDOT) subsequently uses the SI to determine which types of maintenance actions are appropriate for the deck, as shown in figure 30, which reproduces figure 33-2 from the *CDOT Bridge Design Manual* (CDOT 2023). Figure 33-2 of the *CDOT Bridge Design Manua*l is very similar to figure 3 of NCHRP Report 558 but tailored to the maintenance actions used in Colorado (Sohanghpurwala 2006). CDOT considers "sealers" to be penetrating sealers and commonly uses alkyl-alkoxy silane sealers. While thin-bonded epoxy overlays are categorized as "membranes," CDOT considers them to have a high lifecycle cost, and where membranes are deemed appropriate by NCHRP Report 558, CDOT only lists HMA overlays with waterproofing membranes. CDOT clarifies in the accompanying text that "overlays" refer to cementitious and polyester concrete overlays and do not include asphalt-wearing surfaces. Corrosion inhibitors may be surface-applied or admixed with repair materials and are not commonly used in Colorado, nor is electrochemical chloride extraction (ECE). Lastly, CDOT notes that galvanic anodes in patch areas are acceptable for cathodic protection (CP). All the corrosion control strategies are intended to be used in conjunction with repairing any unsound concrete, and CDOT recommends considering the replacement of chloride-contaminated concrete as well.

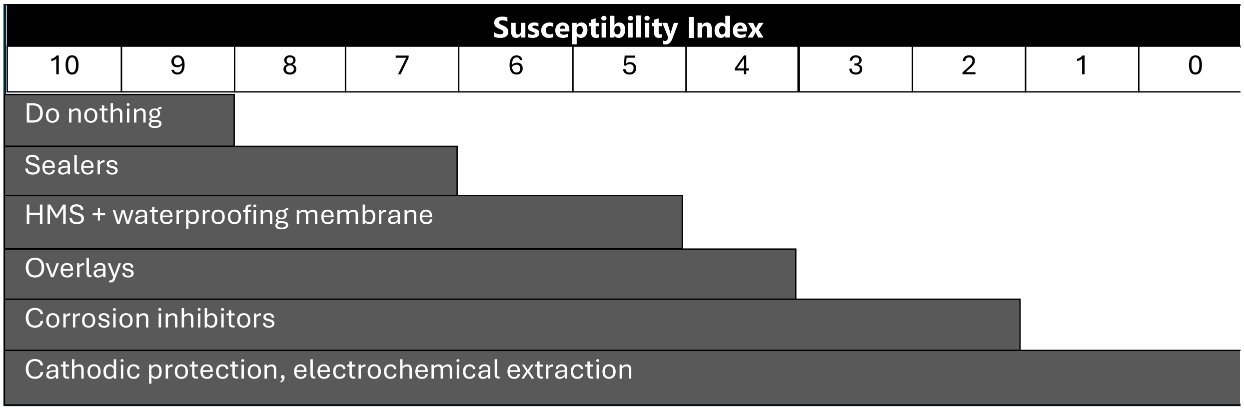


Figure 30. Chart. Optimal corrosion control strategies based on the Susceptibility Index, adapted from CDOT *Bridge Design Manual* (CDOT 2023).

CDOT recommends that the desired service life extension and bridge replacement schedules be considered in addition to the SI when selecting a maintenance action. For example, CDOT considers CP the most cost-effective when the desired service life extension is over 15 yr (CDOT 2023). Additionally, CDOT acknowledges that not all of the corrosion control strategies identified may be compatible with epoxy-coated reinforcing. If the deck has epoxy-coated reinforcing bar, CDOT refers to NCHRP Web Document 50, *Repair and Rehabilitation of Bridge Components Containing Epoxy-Coated Reinforcement* (Sohanghpurwala, Scannell, and Hartt 2002). Otherwise, the systematic process is widely applicable regardless of whether the maintenance is intended to be preventative, corrective, or rehabilitative.

According to CDOT, a primary goal of bridge preventive maintenance (BPM) projects is to seal concrete decks. Three permissible deck protection systems include the following: asphalt overlays with waterproofing membranes, three-quarter-inch polyester concrete overlays, and three-eighths inch thin-bonded epoxy overlays. CDOT does not present a process for identifying bridge decks suitable for BPM projects other than acknowledging that structures in “good condition” have greater priority for BPM projects. “Good condition” is not explicitly defined and is assumed to refer to the Federal definition of GCR 7 or better. CDOT also does not present a decisionmaking process for choosing between the three deck protection systems identified, but it does discuss the practical considerations that may drive the choice and informs the user that chloride testing may be required to verify that the preservation option under consideration is suitable based on the SI and figure 33-2 of the CDOT *Bridge Design Manual* (CDOT 2023).

In summary, CDOT does not have condition-based thresholds that automatically trigger consideration of specific bridge decks for specific preservation or maintenance actions. Based on the *CDOT Bridge Design Manual*, when a deck has been selected for project work, often based on deficiencies noted from NBI inspections or based on prioritizing funds for BPM projects, the CDOT uses the Susceptibility Index of the deck, which is based exclusively on chloride testing results, to trigger the removal of maintenance actions expected to be ineffective or perform poorly from consideration (CDOT 2023).

Florida DOT Preservation Practice

The Florida DOT (FDOT) relies on a series of "decision aid matrices" in the Bridge Maintenance Reference Manual to guide users through the process of selecting a preservation or maintenance action for a bridge deck (FHWA 2015). FDOT is concerned with both corrosion-related deterioration due to chloride ingress or carbonation and the risk of ASR and uses decision aid matrices for each of these deterioration mechanisms.

Starting with maintenance actions to address corrosion, tables 20.7 through 20.9 in the *Bridge Maintenance Reference Manual* identify suitable types of maintenance based on the deck's condition. Table 20.7 is reproduced in table 13 as an example and shows that the type of maintenance selected depends on the crack width, crack spacing, and percentage of the deck area that is spalled or delaminated. The specific table to be used for guidance is based on the "corrosion potential" of the deck, with table 20.7 used for a "low" corrosion potential, table 20.8 for a "moderate" corrosion potential, and table 20.9 for a "high" corrosion potential. The corrosion potential is determined based on chloride concentrations, the risk of active corrosion based on HCP survey data, the concrete cover, and the concrete pH following table 20.5 (for decks with uncoated reinforcing bar) or table 20.6 (for decks with coated reinforcing bar). Table 20.5 is shown in table 14 for reference. The manual states that the corrosion potential can be determined even if not all the conditions listed in tables 20.5 and 20.6 are known, but it encourages users to assess all four attributes when selecting maintenance based on condition.

Users rely on table 20.12 of the Bridge Maintenance Reference Manual when addressing ASR in a bridge deck. The table bases the maintenance decision on the concrete compressive strength measured from deck cores and whether ASR is present based on petrography or other destructive testing methods.

Table 13. Low corrosion potential actions, table 20.7 from the *Bridge Maintenance Reference Manual* used by FDOT (FHWA 2015).

Selection Criteria	**Percent Spalls and Delaminated Deck Area 0 percent < Distress <2 percent**	**Percent Spalls and Delaminated Deck Area 2 percent < Distress <5 percent**	**Percent Spalls and Delaminated Deck Area 5 percent< Distress <10 percent**	**Percent Spalls and Delaminated Deck Area Distress >10 percent**
Deck cracking width <0.02 inches and spacing >3 ft	Do nothing or repair	Repair	Repair	Rehabilitation or replace deck
Deck cracking width <0.02 inches and 1 ft < spacing <3 ft	Do nothing or repair	Repair	Repair	Rehabilitation or replace deck

Selection Criteria	Percent Spalls and Delaminated Deck Area 0 percent < Distress <2 percent	Percent Spalls and Delaminated Deck Area 2 percent < Distress <5 percent	Percent Spalls and Delaminated Deck Area 5 percent< Distress <10 percent	Percent Spalls and Delaminated Deck Area Distress >10 percent
Deck cracking width ≥0.02 inches and 1 ft< spacing <3 ft	Do nothing or repair	Repair and seal deck	Repair and overlay	Rehabilitation or replace deck
Deck cracking width ≥0.02 inches and spacing <1 ft	Repair and seal deck	Repair and overlay	Repair and overlay	Rehabilitation or replace deck

Table 14. Uncoated deck reinforcing corrosion potential classification, table 20.5 from the *Bridge Maintenance Reference Manu*al used by FDOT (FHWA 2015).

Test Result	Low Potential	Moderate Potential	High Potential
Chloride levels (pounds per cubic yard)	<2	2.0 to 2.5	>2.5
HCP (volts)	More positive than -0.2	-0.2 to -0.35	More negative than -0.35
Cover concrete depth (inches)	>1.9	1.0 to 1.9	<1.0
Concrete pH	>9.0	7.0 to 9.0	<7.0

The specific maintenance action for a given bridge deck is selected based on various data collection techniques. However, deck maintenance needs are generally identified, i.e., maintenance is triggered based on visual inspection during the NBI inspection. Delamination surveys, for which sounding or NDE techniques are recognized, are only sometimes conducted during the NBI inspection. Any further NDE techniques or destructive tests needed to navigate the decision aid matrices are only executed if the visual inspection and delamination survey have already indicated a maintenance need.

Separate from the decision aid matrices presented in tables 13 and 14, the *Bridge Maintenance Reference Manual* also provides a table (table 22.2) identifying typical frequencies for common cyclical preventive maintenance activities (FHWA 2015). This table highlights that preservation and maintenance can be triggered by deteriorated conditions or the time because the previous maintenance was completed. In the latter case, the time because the previous maintenance was completed is intended to represent the time at which the maintenance is no longer effective, which more directly corresponds to the condition of the repair or treatment rather than the deck itself. However, relatively little work has been done on describing when the condition of a repair or treatment warrants its replacement compared to when the condition of a deck warrants deck repair or treatment, and this is an area for future work.

In summary, the Florida DOT relies on a systematic and data-based process for selecting a maintenance action for a given bridge deck. When addressing deteriorated conditions due to bridge deck corrosion, the decision as to which type of maintenance is suitable depends on crack width and spacing, the percent of the deck area that is spalled or delaminated, the chloride concentrations within the deck, the risk of active corrosion as shown by HCP, the concrete cover, and the concrete pH. When addressing deterioration caused by the ASR of the bridge deck, the decision as to which type of maintenance is suitable depends on destructive testing to assess compressive strength and the presence or potential of ASR gel. The Florida DOT leverages some NDE techniques, such as HCP, IE, and GPR, when selecting maintenance actions, but currently relies primarily on visual inspection and occasionally on delamination surveys, which may or may not use NDE techniques, to identify when a bridge deck's condition makes it a candidate for maintenance.

Illinois DOT (IDOT) Preservation Practice

IDOT bases preservation and maintenance decisions on the structure's existing condition and a recommended maintenance schedule. When the bridge deck area is entirely classified as CS 1 or CS 2, the IDOT relies on maintenance triggered by schedule rather than maintenance triggered by condition. Condition-based maintenance typically addresses elements with CS 3 or CS 4 quantities (IDOT 2019).

The following preservation maintenance schedule is recommended for bridge decks with no CS 3 or CS 4 quantities and a general condition rating of at least 5 as follows (IDOT 2019):

- Sweeping, power washing, and cleaning of the deck and drains every 1 to 2 yr.
- Sealing of the deck and cracks using a penetrating sealer every 4 yr.

Additionally, newly built bridge decks are recommended to be sealed within 1 yr, and bridge decks with a general condition rating of 4 are not considered candidates for preservation maintenance. However, they may remain in the deck sealing program on a discretionary basis. Other preservation activities, such as the application of overlays, are not explicitly discussed in the *Bridge Preservation Guide* (IDOT 2019). However, preservation projects may include some repair work in their scope and the deck condition, material, age, and anticipated service life should be considered when selecting a maintenance action for a bridge deck. Other considerations referenced by IDOT include deck size, design, functional class, average daily traffic (ADT), detour lengths, and corridor plans.

In the previous version of the *Bridge Condition Report Procedures and Practices*, IDOT referenced a B-SMART Program, which allowed for quick approval of low-cost bridge deck preservation projects that would extend bridge life through the application of an overlay (IDOT 2011). To qualify for the B-SMART program, decks were required to have a general condition rating of at least 5, their partial-depth repair needs could not exceed 15 percent of the total deck area, and their full-depth repair needs could not exceed 5 percent of the total deck area (excluding those associated with joint and deck drain work). For speed, compliance with the B-SMART criteria only needed to be assessed based on the element-level visual inspection associated with NBI inspections, and indepth inspection methods, such as a delamination survey, were not required.

IDOT provided a recommended maintenance schedule to consider as the bridge deck ages and deteriorates such that it is no longer a candidate for preservation (IDOT 2019). Patching and applying a hard overlay are recommended every 25 yr until bridge replacement, which is anticipated to be scheduled when the bridge is 100 yr old. Alternatively, the deck may be replaced when the bridge is 50 yr old. These recommendations for overlay installation or deck replacement are recognized as either schedule- or condition-based by IDOT, indicating that deck condition is anticipated to justify patching and overlay installation approximately every 25 yr, but if it does not, the deck should be considered a candidate for an overlay anyway.

While IDOT recognizes the need for condition-based maintenance once CS 3 or CS 4 quantities are present or the deck general condition rating decreases to 4, specific condition-based triggers for specific maintenance actions are not provided. Instead, IDOT generally relies on an indepth investigation of the bridge’s condition and a cost analysis to choose between potential maintenance actions on a case-by-case basis. In some instances, the action to be taken is apparent without indepth condition data beyond the available NBI inspection data, e.g., when the work is required to correct functional deficiencies or structural insufficiency or when the structure is in good condition (general condition rating of at least 5, CS 4 quantity not more than 5 percent, and CS 3 quantity no more than 15 percent). An indepth inspection that may leverage NDE techniques is required if the general condition rating is less than 5, the CS 4 quantity is greater than 5 percent, or the CS 3 quantity is greater than 15 percent (IDOT 2023).

The purpose of the indepth inspection of a bridge deck is to conduct a delamination survey to quantify the partial-depth and full-depth repair needs of the deck. Table 3.5-1 of the current *Bridge Condition Report Procedures and Practices*, shown in table 15, provides general guidance on whether deck repair or deck replacement is anticipated to be cost-effective based on the estimated repair area from the indepth inspection (IDOT 2023). Additionally, in the previous version of the *Bridge Condition Report Procedures and Practices*, IDOT recommended that replacement be considered if the quantity of full-depth deck repairs (including those associated with joint work) exceeded 13 percent of the deck area (IDOT 2011). If the estimated repair area falls between 15 percent and 35 percent, IDOT advises that other factors, such as joint and drainage work needs, previous deck repairs, and other deck issues, such as substandard cross-slopes, be considered (IDOT 2023).

Table 15. Table 3.5-1 of the Bridge Condition Report Procedures and Practices (IDOT 2023).

Estimated Repair Area (percent)	Scope of Work
<15	Deck repair.
15–35	Deck repair may be cost-effective.
>35	Deck replacement.

In summary, IDOT relies on schedule-based maintenance plans consisting of deck cleaning and sealing for bridge decks that are in good condition. While bridge deck condition is considered when selecting other preservation or maintenance actions, particularly actions that include repairs in their scope, the IDOT does not define condition-based triggers and relies on case-by-case analysis to identify the most appropriate work scope. However, bridge deck condition is used to trigger indepth inspections and inform decisionmakers when deck replacement is likely justified.

INDOT Preservation Practice

INDOT does not use condition data to trigger preservation or maintenance actions for a bridge deck. Instead, when a bridge deck is considered for work, its condition data are used to determine which type of work or specific maintenance actions it is eligible for.

INDOT classifies work as preventive maintenance, further broken down into condition-driven preventive maintenance and scheduled preventive maintenance, rehabilitation, or replacement. Condition-driven preventive maintenance and the conditions under which a bridge is eligible for those maintenance actions are presented in *Bridge Preservation* (INDOT 2013). Condition-driven preventive maintenance actions pertinent to bridge decks and their eligibility criteria are shown in table 16. These actions include crack sealing, patching, and various types of overlays. Due to their performance history in Indiana, asphalt overlays with waterproofing membranes are not included in INDOT's repertoire of condition-driven preventive maintenance actions. However, INDOT acknowledged that these systems can be successful repair methods and is open to their use, provided that the user coordinates with the Bridge Rehabilitation Department.

The preservation or maintenance actions considered to be scheduled preventive maintenance by INDOT are presented in the *Design Manual*, and those pertinent to bridge decks and their eligibility criteria are reproduced in table 17 and include deck washing and sealing (INDOT 2013).

Table 16. Condition-driven preventive maintenance and eligibility criteria used by INDOT (INDOT 2013).

Condition-Driven Preventive Maintenance Actions	General Condition Rating-Based Criteria		Other Criteria
	Bridge Component	Component Rating	
Bridge deck patching (partial- or full-depth)	Wearing surface	>4	Deck patching cannot exceed 10 percent.
	Deck	>4	
	Superstructure	>4	
	Substructure	>4	
Bridge deck overlays—flexible (Polymeric or thin overlays)	Wearing surface	>4	Deck patching cannot exceed 10 percent.
	Deck	>4	
	Superstructure	>4	
	Substructure	>4	
Bridge Deck Overlays—rigid (Typically, latex-modified concrete) overlays, or alternatively a silica fume concrete overlay	Wearing surface	>3	Deck patching cannot exceed 15 percent.+
	Deck	>4	
	Superstructure	>4	
	Substructure	>4	
Deck crack sealing	Wearing surface	>5	none
	Deck	>5	
	Superstructure	>5	
	Substructure	>5	

+While rigid bridge deck overlays are permitted under these conditions, when partial-depth and full-depth patching exceeds 10 percent of the deck area, the treatment is considered rehabilitation.

Table 17. Scheduled preventive maintenance and eligibility criteria used by INDOT (INDOT 2013).

Schedule-Driven Preventive Maintenance Actions	Bridge Component	Component Rating	Frequency
Cleaning and flushing bridge decks	Deck	>4	1 yr
Deck sealing	Wearing surface	>5	5 yr

The eligibility criteria are typically based on the general condition ratings of the major bridge components or their wearing surfaces. As shown in table 16, the overlay options have secondary criteria related to the percentage of the deck area that requires patching. In the accompanying discussion, INDOT clarifies the following thresholds:

- Remediation for decks delaminated across 5 percent of their area.
- Rehabilitation instead of preventive maintenance for decks if more than 10 percent of the deck area requires patching.
- Replacement for decks delaminated across 30 to 40 percent of their area.
- Replacement of decks if more than 35 percent of the deck area requires patching.

Other factors considered when choosing between rehabilitation and replacement include the age of the structure, average annual daily traffic (AADT), structure type and slab depth, and timing of the repair. For example, INDOT recommends that if a deck already has two rigid overlays, replacement should typically be chosen over a third rigid overlay.

When a deck is a candidate for work, particularly rehabilitation, an indepth inspection is conducted to quantify the extent of the distress and patching needs. The Indiana DOT primarily relies on visual inspection and sounding in these inspections. HCP surveys are recognized as an inspection tool, but the conditions under which their use is "warranted" are not discussed. Destructive testing, i.e., coring and chloride analysis, are presented as options, but due to sampling and data interpretation challenges, the Indiana DOT does not typically recommend their use.

Most of the previous discussion assumes that maintenance addresses chloride-induced corrosion. INDOT acknowledges that their bridge decks may also experience other degradation mechanisms, including:

- Freeze-thaw deterioration, in which case replacement is deemed the only remedy.
- Impact loading, in which case surface grinding, application of an overlay, rebuilding deck joints, or deck replacement are feasible options.
- Abrasion, in which case the maintenance options are surface grinding or application of an overlay.

In summary, INDOT relies on bridge deck condition data to determine if bridge decks are eligible for specific maintenance actions or precluded because their deterioration is too great, such that the maintenance action would be cost-prohibitive or ineffective. The eligibility criteria rely on the general condition ratings of the bridge components and the percentage of the deck area that requires patching, the latter is typically determined by visual inspection and sounding with minimal use of more advanced NDE techniques.

Michigan DOT Preservation Practice

The Michigan DOT (MDOT) maintains two Bridge Deck Preservation Matrices to guide users through the process of choosing work scopes for bridge decks that need or are candidates for maintenance. The matrices identify the range of deck conditions for which the repair options used by MDOT are deemed economical and provide supplementary information pertaining to deck condition improvement offered by the repair and the anticipated life of the repair. The first matrix is specific to decks with uncoated or "black" reinforcing bar and the second is specific to decks with epoxy-coated reinforcing bar (MDOT 2021a and MDOT 2021b). The most recent matrices are accessible on their "Management and Scoping" web page; a portion of the Bridge Deck Preservation Matrix for decks with black reinforcing bar is reproduced in table 18 to facilitate the discussion (MDOT 2024).

Table 18. Repair options considered economical for various deck condition states according to the MDOT's Bridge Deck Preservation Matrix for Decks with Uncoated Reinforcing bar (MDOT 2021a).

Deck Condition State				**Repair Options**
Top Surface		**Bottom Surface**		
BSIR No. 58a	**Deficiencies (percent)[1]**	**BSIR No. 58b**	**Deficiencies (percent)[2]**	
≥5	N/A	N/A	N/A	Hold or seal cracks.
				Silane.
				Healer-sealer.
	≤10	≥6	≤2	Epoxy overlay.
		≥4	≤25	Deck patch.
4 or 5	10–25	≥5	≤10	Deep concrete overlay.[3]
		4	10–25	Shallow concrete overlay.
				HMA overlay with waterproofing membrane.
		or 3	>25	HMA cap.
≤3	>25	≥6	<2	Deep concrete overlay.[3]
		4 or 5	2–25	Shallow concrete overlay.
				HMA overlay with waterproofing membrane.
		2 or 3	>25	HMA cap.
				Replacement with epoxy coated or stainless reinforcing bar deck.

BSIR = Bridge Safety Inspection Report.

[1] Top surface deficiencies defined as the percent of the concrete deck surface area (not thin epoxy overlays or other wearing surfaces) that is spalled, delaminated, or patched with a temporary patch material.

[2] Bottom surface deficiencies defined as the percent of the deck underside area that is spalled, delaminated, or has map cracking.

[3] The Bridge Deck Preservation Matrix for decks with epoxy-coated reinforcing bar provides the same repair options for the deck condition states shown in this table except for the following: if the BSIR No. 58a is 4 or 5, the BSIR No. 58b is not expected to be 5 or greater. If the BSIR No. 58a is 3 or less, the BSIR No. 58b is not expected to be 6 or greater. As a result, deep concrete overlays are not presented as options for decks with epoxy-coated reinforcing bar.

As shown in table 18, MDOT relies on GCRs of the top and bottom surfaces of the deck and the percentage of the top and bottom surfaces deemed deficient to identify repair options. The general condition ratings listed, BSIR No. 58a and BSIR No. 58b, may or may not describe the condition of the structural deck surface; if the top surface is covered by a protective wearing surface or coating, then the wearing surface is rated in BSIR No. 58a instead of the structural deck top surface and likewise for BSIR No. 59b if the bottom surface is covered by stay-in-place forms (MDOT 2016). MDOT has a distinct GCR, BSIR No. 58, which corresponds to the deck GCR reported from the NBI inspection and considers the overall condition of the structural deck alone without consideration for the condition of any protective coatings, wearing surfaces, or stay-in-place forms that may be present, but this general condition rating is not used in the Bridge Deck Preservation Matrices.

However, the footnotes of the matrices clarify that the percent deficient areas for the top and bottom surfaces pertain only to the structural deck surfaces, and distress of any protective coatings, wearing surfaces, or stay-in-place forms should not be considered in the quantities. “Deficient areas” are considered areas with delaminations, spalls, temporary patch materials (in the case of the top surface), or map cracking (in the case of the bottom surface). To get an accurate quantity of the deficient areas, a delamination survey and a visual inspection must be completed. Sounding may or may not be conducted with routine inspections but is required when conducting an indepth inspection, at least over areas of interest. The full surface area(s) of the top and bottom surfaces of the deck may not be inspected in full due to the desire to minimize traffic control and interruptions. A one-time indepth inspection of the top surface, bottom surface, or overall deck is recommended when its general condition rating deteriorates to a 6. It should be done regularly at 48-mo intervals when the GCR deteriorates to a 4. These condition-based triggers for indepth inspection help provide users of the Bridge Deck Preservation Matrices with the element-level condition information necessary to use the matrices.

The footnotes of the matrices and the discussion of their implementation in the *Project Scoping Manual* provide additional qualifying criteria to help users determine if maintenance is required or if bridge decks are eligible for the repair option under consideration (MDOT 2022). These additional criteria are listed in table 19. MDOT further recommends that users consider the conditions of the superstructure and substructure, any functional deficiencies of the bridge, such as bridge width, and work being done in the same corridor when choosing bridge deck maintenance.

In summary, MDOT relies on GCRs and element-level condition data describing the deck's top and bottom surfaces to determine which maintenance action(s) is appropriate and economical. The choice of maintenance action is further informed based on other factors, including but not limited to the structure type, types of deck materials present, and ongoing or planned maintenance for the bridge or its corridor. As observed in the policies of several other SHAs, MDOT does not use deck conditions to trigger maintenance actions but instead identifies the range of conditions for which each maintenance action is considered an appropriate option. The condition data needed to inform the maintenance choice can be determined by visual inspection and sounding, the latter of which is typically conducted in indepth inspections. An indepth inspection is triggered when any of the deck general condition ratings decrease to a 6, and indepth inspection at regular intervals is triggered when any of the deck GCRs decrease to a 4 such that users have the data needed to select an economical maintenance action based on MDOT’s two Bridge Deck Preservation Matrices.

Table 19. Additional recommended criteria (MDOT 2021a; MDOT 2021b; MDOT 2022).

Repair Option	Additional Recommended Criteria for Consideration
Hold.	Considered only if maintenance to sustain the current ratings is ongoing.
Seal cracks or healer-sealer.	Concrete must be more than 28 d old before sealing. Recommended when cracks are easily visible (greater than 0.010 inches wide or can be seen from a standing position). Recommended when unsealed cracks with narrow widths and less than 0.125 inches wide and a spacing greater than 8 ft is present. Healer-sealers should be applied when the crack density is too great to seal individually by hand.
Epoxy overlays.	Deck should have moderate to extensive cracking with multiple thin cracks but minimal delaminations or spalls.
HMA overlay with waterproofing membrane.	Considered when full depth precast deck panels are used. Used as an HMA cap if the deck is not scheduled for replacement.
HMA cap (overlay with no waterproofing membrane)	Used to address ride quality; deck should be scheduled for replacement in the 5-yr plan.
Deep concrete overlay	Considered when joint or railing replacement will remove most deficiencies on the bottom surface. Not allowed on tee-beam structures.
Deck replacement	When deck contains slag aggregate and qualifies for a concrete overlay, especially if bridge crosses over travelled lanes.

MnDOT Preservation Practice

MnDOT categorizes bridge preservation as either maintenance, typically conducted by in-house forces, or major preservation, typically conducted under contract. For the latter, MnDOT maintains a priority matrix that identifies how the bridges in the list of candidates for contracted work are prioritized for funding and the recommended scope of work. MnDOT's Bridge Replacement and Improvement Management system and input from district staff developed the list of candidate bridges for which the priority matrix is used. The Bridge Replacement and Improvement Management system does not apply condition-based thresholds; instead, it predicts each bridge's replacement and improvement needs based on condition data and expected deterioration and identifies candidate bridges for work based on the risk of service interruption.

At a high level, MnDOT recommends considering major preservation for a bridge when more than 15 percent of the area of its deck or wearing surface is in condition state 3 or 4. Table 20 shows MnDOT's priority matrix, which contains more detailed guidelines specific to bridge decks and some additional guidance included in the accompanying text of their *Bridge Preservation and Improvement Guidelines* (MnDOT 2015). The matrix relies primarily on the percent of unsound deck area, which is not explicitly defined in the guidelines but likely refers to patched, spalled, and delaminated areas since HCP surveys are not generally used by MnDOT (MnDOT 2019). Deck evaluations typically rely on visual inspection, sounding surveys, and occasionally GPR in special circumstances. In addition to the percent of unsound deck area, the maintenance actions recommended for the deck and the priority level depend on the concrete cover to the top mat of reinforcing steel, the current ADT, whether the deck is part of the structural system of the bridge, and the depth of unsound concrete with respect to the top mat of reinforcing steel. The condition of the deck soffit is also considered when selecting deck maintenance, although no specific guidance on condition-based thresholds tied to the deck soffit is given. While the priority matrix presents MnDOT's strategies for maintenance investments, MnDOT cautions users that the criteria are not absolute, and each project should be evaluated on a case-by-case basis to consider its unique circumstances and constraints.

Table 20. Priority matrix used by MnDOT to select and prioritize work scopes for bridge decks (MnDOT 2015)[1,2]

Condition Category	**Percent of Unsound Deck Area[3]**	**Concrete Cover ≥2 inches**			**Concrete Cover < 2 inches[4]**
		Current ADT:			
		<2,000	**2,000 to 10,000**	**>10,000 and Interstates**	
I (Slight deterioration)	0 to 2 percent SIMS deck CS 2.	**Priority 11** Do nothing, or spot repairs.	**Priority 9** Do nothing, or spot repairs.	**Priority 8** Do nothing, or spot repairs.	Deck repairs and protective overlay.
II (Moderate deterioration)	2 to 10 percent SIMS deck CS 3.	**Priority 10** Mill and patch.	**Priority 7** Mill and patch.	**Priority 6** Mill and patch or reoverlay.	Deck repairs and protective overlay.
III (Severe deterioration)	10 to 25 percent[5] SIMS deck CS 4.	**Priority 5** Deck repairs, 100 percent scarify, and add overlay.	**Priority 4** Deck repairs, 100 percent scarify, and add overlay.	**Priority 3** Deck repairs, 100 percent scarify, and add overlay.	Limited-service overlay; consider deck replacement.
IV (Critical deterioration)	>25 percent SIMS deck CS 5.	**Priority 4** Deck repairs, 100 percent scarify, and add overlay.[6]	**Priority 2** Schedule new deck.[5]	**Priority 1** Schedule new deck.[5]	Schedule for deck replacement after usable life has been expended.

SIMS = structure information management system.

[1] Alternative repair procedures may apply depending on the condition of the deck soffit.

[2] If a bridge has a deck that is a main structural support member, or part of one, then it is prioritized over other bridges in the same category. This criterion includes concrete box girder, concrete slab span, and concrete deck-girder bridges.

[3] MnDOT does not provide a definition of "unsound" areas or the SIMS deck CSs referred to in this column.

[4] This column is not part of the priority matrix and priority levels for each set of deck conditions are not identified.

[5] If the deck is a main structural support member or is part of one, then it is classified under Category III "Severe Deterioration" if 10 to 60 percent of the deck area is unsound. Deck replacement should only be considered if the percent unsound area exceeds 60 percent.

[6] Only overlay if there is minimal unsound concrete below the top mat of reinforcing steel.

Pertaining to overlays, the priority matrix typically recommends considering overlays when more than 10 percent of the deck area is unsound, i.e., when isolated repairs are required, and a new concrete cover is needed, or a protective layer is desired. However, according to MnDOT, the decision to overlay or reoverlay a bridge deck needs to consider lifecycle costs and benefits, and the decisionmaker needs to be informed not only of the condition of the top and underside of the deck, but also the chloride levels, cracking width and locations, deck age, type of reinforcement and concrete cover, expansion joint and barrier conditions, ability of in-house forces to maintain the existing overlay effectively, expected overlay life, and expected service life of the deck. Chloride levels in existing concrete overlays or decks that are cost-prohibitive or difficult to replace due to construction challenges (e.g., monolithic decks on box girder bridges) are specifically required to be measured at least every 5 yr. A new overlay is to be scheduled before the chloride concentration reaches half the chloride threshold for corrosion at the depth of the top mat of reinforcing steel and defines the chloride threshold as 750 ppm if the water-soluble chloride concentration is measured or 175 ppm if the acid-soluble chloride concentration is measured.

MnDOT also uses overlays as protective treatments before deck deterioration occurs. MnDOT places special emphasis on applying overlays to decks that have high traffic volumes (ADT > 2,000) and frequent deicing chemical exposure but no current protective system. Polymer overlays may be considered as alternatives to concrete overlays if accelerated construction or minimal additional dead load is necessary or if the deck has large amounts of cracking, high deicing chemical exposure, and accident-prone conditions; however, no condition-based thresholds are used to select between different types of overlays.

Decks that are not under contract rely on maintenance done by in-house forces. These maintenance activities include both cyclical preventive maintenance, including deck flushing, crack sealing, and deck sealing, and minor condition-based reactive maintenance, such as partial-depth or full-depth repairs of spalled or delaminated areas, deck sealing to inhibit scaling, and bituminous overlay repairs to address ride quality. MnDOT provides target frequencies for cyclical preventive maintenance actions, but condition-based thresholds that qualify bridge decks for such maintenance actions are not presented.

In summary, MnDOT identifies bridge deck maintenance needs using a risk analysis of future conditions instead of condition-based thresholds triggered by current deck conditions. When a bridge deck is selected, a priority matrix is used to identify the recommended maintenance action; however, the priority matrix has limited applicability, and MnDOT provides additional guidance and requirements for selecting deck maintenance outside the matrix. The deck maintenance action selected depends partly on deck condition data, for which condition-based thresholds are provided in terms of the percent of unsound area. However, other factors, particularly deck design, traffic volumes, and replacement cost, greatly impact the selected maintenance action. Additional deck condition data, such as underside condition, crack characteristics, and chloride contamination, should also be considered but does not provide condition-based thresholds using these data, except for a chloride-based threshold for reoverlaying. MnDOT primarily relies on visual inspection, sounding surveys, and regular chloride testing to inform maintenance decisions and generally does not use NDE techniques. Bridge decks not identified for contracted maintenance in the risk analysis are maintained by state in-house forces, which conduct cyclical and condition-based preventive maintenance.

MnDOT does not currently have condition-based thresholds qualifying or disqualifying these bridge decks for such maintenance.

New Jersey DOT (NJDOT) Preservation Practice

NJDOT relies on a combination of bridge deck condition, practical considerations such as available funding and cost efficiencies, and engineering judgment to choose bridge maintenance actions. NJDOT relies extensively on system-level modeling to identify candidate bridges for maintenance or other work. The modeling holistically quantifies the net benefits to, and costs of, the bridge system to optimize the maintenance plan. As a result, NJDOT does not have a fixed set of condition-based thresholds that automatically trigger maintenance on a bridge level. Instead, condition-based "treatment triggers" are varied in the models to help optimize the system-wide maintenance plan (NJDOT 2022).

NJDOT selects candidate bridges by first identifying a geographic region, typically a highway corridor. The bridges within the region must have a general condition rating of at least 5 (presumably for all three major components, although this is not explicitly stated) to be considered for preventive maintenance. For preventive maintenance actions specific to the deck, the element-level condition state requirements that must be met and anticipated implementation frequency are presented in table 21. The use of element-level condition data as treatment triggers in the system-level modeling is reportedly a new and developing practice at the New Jersey DOT (NJDOT 2022). When selecting the appropriate preventive maintenance actions for the bridges in the highway corridor, both their condition reports and their maintenance history are reviewed and a field visit, which may include a deck condition survey, is conducted to finalize the maintenance decisions.

Table 21. Deck condition requirements used by NJDOT to qualify bridge decks for preventive maintenance (NJDOT 2016a).

Deck Maintenance Action	Deck General Condition Rating	Deck Condition State	Frequency
Bridge cleaning, washing, sweeping.[1]	No requirement.	No requirement.	2 yr
Repair concrete deck and sidewalk.	≥5	CS 3 or lower.	10 yr
Seal concrete deck.	≥5	CS 2 or lower.	5 yr
Seal cracks on wearing surface (asphalt overlay).	≥5	CS 2 or lower.	2 yr
Seal cracks on deck.	≥	CS 2 or lower.	2 yr
Corrosion inhibitor.[2]	No requirement.	No requirement	5 yr

[1] These maintenance actions are considered for all "functional structures." Highway-over-highway bridges are given priority.

In the context of more costly maintenance such as rehabilitation, deck evaluation surveys using NDE methods are commonly conducted to finalize the maintenance scope for candidate bridges selected based on system-level modeling. Deck evaluation surveys may include a visual inspection of cracking, spalling, and scaling, a delamination survey, chloride testing, an HCP survey to identify areas of active corrosion, and pachometer (or magenetometer) testing to characterize the concrete cover over reinforcement. Bridge decks may be classified as having light to no, moderate, or extensive active corrosion based on the results, as shown in table 22.

If NJDOT plans to conduct rehabilitation, i.e., extend bridge deck life by 10 to 15 yr, as described in table 9.1 of the *Design Manual for Bridges and Structures*, then visual inspection is to be done across the entire deck(s), and chloride testing, an HCP survey, and pachometer testing are to be done on the first five spans and decks as well as 10 percent of the remaining deck area (NJDOT 2016b). All deteriorated concrete must be removed and repaired, and suggested protective systems include either an HMA overlay with a waterproofing membrane or a thin concrete overlay (less than one inch). If NJDOT plans to do "permanent" restoration, then the evaluation survey procedures and work vary based on the corrosion category, as shown in table 23. If the bridge deck has "light to no active corrosion," NJDOT recommends implementing "permanent restoration" instead of rehabilitation. Generally, NJDOT recommends rehabilitation if up to 60 percent of the deck area is deteriorated, and replacement if more than 50 percent of the deck area is deteriorated. In the overlapping range, other considerations may control the decision to rehabilitate or replace.

Table 22. NJDOT definitions for corrosion categories (NJDOT 2016b).

Corrosion Category	Definition
Light to no active corrosion	No spalls, or 0–5 percent of deck area is deteriorated (based on delamination and HCP surveys), or 0–5 percent of deck area has chloride levels in excess of chloride threshold at depth of rebar (based on chloride testing).
Moderate active corrosion	0–5 percent of deck area is spalled, or 5–40 percent of deck area is deteriorated (based on spalls, delaminations, and areas of active corrosion based on HCP survey), or 5–40 percent of deck area has chloride levels more than chloride threshold at depth of rebar (based on chloride testing).
Extensive active corrosion	At least 5 percent of deck area is spalled, or At least 40 percent of deck area is deteriorated (based on spalls, delaminations, and areas of active corrosion based on HCP survey), or 40 percent. of deck area has chloride levels more than chloride threshold at depth of rebar (based on chloride testing).

Table 23. Permanent restoration of bridge decks depending on corrosion category (NJDOT 2016b).

Corrosion Category	Testing Procedures	Required Restoration Work	Suggested Protective Systems
Extensive active corrosion	VI, CL, HCP, and PT used as necessary (likely only VI is necessary).	Complete deck replacement.	Membrane with HMA overlay, or Thin concrete overlay protective system (<1 inch).
Moderate active corrosion	Same as for either "extensive active corrosion" or "light to no active corrosion," as determined by the State.	Same as for either "extensive active corrosion" or "light to no active corrosion," as determined by the State.	Same as for either "extensive active corrosion" or "light to no active corrosion," as determined by the State.
Light to no active corrosion	VI, CL, HCP, and PT used.	Remove and replace all deteriorated areas and areas with active corrosion based on HCP and chloride testing.	Membrane with HMA overlay, or thin concrete overlay protective system (<1 inch)

VI = visual inspection; CL =chloride testing; PT = pachometer testing.

In summary, the NJDOT uses a holistic and systematic process to select bridge decks for maintenance. NJDOT does not have fixed condition thresholds that trigger maintenance and instead explores condition-based triggers as a variable in system-level modeling. However, based on their general condition rating and element-level condition data, bridge decks may be precluded from preventive maintenance actions. When assessing the condition of a bridge deck, NJDOT may rely on existing deck condition reports or require a deck evaluation survey that relies on a combination of VI, NDE methods (specifically HCP and concrete cover surveys), and destructive testing methods (specifically CL) to inform the scope of work. The data are used to classify the bridge deck as having extensive, moderate, or light-to-no active corrosion and select a rehabilitation or replacement strategy.

NYSDOT Preservation Practice

NYSDOT does not maintain a decision matrix or similar decisionmaking aid to help engineers select maintenance but provides guidance in multiple manuals (NYSDOT 2021, NYSDOT 2008, NYSDOT 1992). The guidance includes qualifying and disqualifying criteria describing when a bridge deck is and is not a candidate for various maintenance actions based on its condition and other considerations. However, the guidance is generally framed as an informative resource to aid engineers in selecting practical and technically appropriate maintenance actions to compare in a cost analysis rather than criteria used to arrive at a final decision.

Table 24 summarizes the guidance the three manuals offer for the various deck maintenance actions considered by the NYSDOT. The deck general condition rating is referenced only three times, and element-level condition state quantities are not used, although some criteria are related to the percent deteriorated area of the deck. The NYSDOT commonly relies on condition data that would be obtained from more detailed or indepth inspections, such as type of distress and crack widths, neither of which is required to be reported to the FHWA as part of the element-level portion of NBI inspections. Other factors considered include the physical characteristics of the deck, such as its materials, the service conditions of the deck, such as the AADT, and the history of, and future plans for, the deck.

In addition to the criteria listed in table 24, full removal of the top surface of the deck to a depth at least 1 inch below the top mat of reinforcing steel may be justified, according to NYSDOT, for decks in urban areas with high traffic volumes when any of the following conditions are met:

- The spalled area exceeds 2 percent of the deck area.
- The delaminated area exceeds 30 percent of the deck area.
- The deck area that is likely to be actively corroding exceeds 40 percent.
- The total damaged area exceeds 50 percent of the deck area.

These criteria do not explicitly qualify or disqualify specific maintenance actions, but if the top surface of the concrete is removed, as described previously, a concrete overlay is the only option.

Table 24. Summary of guidance for selecting bridge deck maintenance provided in NYSDOT documents (NYSDOT 2008; NYSDOT 1992; NYSDOT 2021).[1]

Maintenance Action	Appropriate Applications	Disqualifying Conditions
Cyclical Preventive Maintenance		
Bridge Cleaning	All bridges except culverts.	—
Concrete deck sealing	Priority given to decks that include the following: • Do not have epoxy-coated steel. • Do not use high-performance concrete. • Are new. • Have less than the current standard design concrete cover. To address scaling at early stages and to address the following cracking: • Working cracks between 0.004 and 0.007 inches wide. • Dormant cracks between 0.007 and 0.012 inches wide.	—

Maintenance Action	Appropriate Applications	Disqualifying Conditions
	• Cracks between 0.004 and 0.007 inches wide and exposed to deicing chemicals.	
Crack sealing of PCC decks	For sealing longitudinal cracks above and in line with underlying precast box beam segments.	—
Crack sealing of wearing surfaces using Bituminous sealer	Decks with concrete or asphalt surfaces.	—
Crack sealing of wearing surfaces using Polymeric sealer	To address the following cracking: • Working cracks greater than 0.007 inches wide • Dormant cracks greater than 0.012 inches wide • Cracks wider than 0.007 inches and exposed to deicing chemicals.	Decks with asphalt surfaces
Replacing the asphalt wearing surface[2]	• Bare decks with deteriorated area[3] no more than 15–18 percent of deck area. • Bare decks with insufficient concrete cover.	—
Corrective Preventive Maintenance		
Concrete deck repair	Any deck with a deck general condition rating less than 5.	—
Full-depth deck repair	When there is a clear and present danger to the travelling public.	—
Placing a thin polymer overlay	When deck meets following criteria: • Deck general condition rating is 5. • Concrete wearing surface in good condition (based on visual inspection). • Delaminated area does not exceed 15 to 18 percent of deck area.[4] • Bridge will remain in service and will not require significant work over lifespan of overlay.	—

Maintenance Action	Appropriate Applications	Disqualifying Conditions
Nonprotective Treatments		
Placing a HMA overlay (no waterproofing membrane)	Short-term applications, i.e., to keep deck in service until replacement.	—
Maintaining existing wearing surface (i.e., repair of potholes)	Short-term applications, i.e., to keep deck in service until replacement.	—
Protective Treatments		
Placing a HMA overlay with a waterproofing membrane	Rural, through-traffic structures.	• High-traffic roadways (>5,000 AADT) • Steep grades (>4 percent) • Sharp curves (ramps and major interchanges with on and off ramps).
Placing a concrete overlay (class E concrete)	When a HMA overlay with a waterproofing membrane is inappropriate. To address deterioration due to freeze-thaw, scaling, or AAR.	When the deck cannot support the dead load (minimum overlay thickness greater than 3 inches)
Placing a high-density concrete overlay	When neither of the following overlays can be used: • HMA overlay with a waterproofing membrane. • Concrete overlay more than 3 inches thick. • To address deterioration due to freeze-thaw, scaling, or AAR.	When the deck cannot support the dead load (minimum overlay thickness of 2 inches)
Placing a LMC or MSC overlay	When neither of the following overlays can be used: • HMA overlay with a waterproofing membrane. • Concrete overlay more than 3 inches thick. • To address deterioration due to freeze-thaw, scaling, or AAR.	When the deck cannot support the dead load (minimum overlay thickness of 1.5 inches)
Replacement		
Deck replacement	When deck has noticeable deterioration[5] and meets any of the following:	—

Maintenance Action	Appropriate Applications	Disqualifying Conditions
	• Is at least 40 yr old. • Has an existing overlay that was placed to address condition issues. • Has had a deck general condition rating of 4 or less over at least 10 yr. • To address severe and advanced scaling or AAR.	

—No discussion was provided.

[1] Information is compiled from *Fundamentals of Bridge Maintenance and Inspection*, *Bridge Deck Evaluation Manual*, and *NYSDOT Bridge Manual* (NYSDOT 2008; NYSDOT 1992; NYSDOT 2021).

[2] Includes placement of a waterproofing membrane.

[3] A definition is not provided for "deteriorated area" in this instance.

[4] Chloride levels are recommended to be tested as well, although no selection criteria based on chloride measurements are provided in the discussion.

[5] Noticeable deterioration is described as widespread cracking, spalling, or deterioration on the top surface and efflorescence, rust staining, or dampness on the underside.

Indepth deck condition inspections for collecting the condition data needed to make an informed maintenance choice may rely on a combination of visual inspection, NDE techniques, and destructive testing. If the visible distress present is insufficient to identify the most suitable maintenance actions that should be considered, then delamination and HCP surveys are conducted. The *Bridge Deck Evaluation Manual*, which remains the current version of the manual, noted that delaminations could be detected with thermography and that GPR or IE were experimental methods of detecting delaminations at the time of its publication (NYSDOT 1992). Coring is commonly conducted to verify the presence of delaminations and active corrosion or to visibly observe distress at deeper levels in the deck. Cores may also undergo laboratory testing if the deck's soundness or freeze-thaw resistance is in question, although this is relatively uncommon. The NYSDOT has also found chloride testing useful for determining the depth of concrete removal that should be specified when treating a two-course deck. The data collected from the indepth inspection helps the engineer select maintenance options to compare and is used to identify the specific scopes of work and quantities that should be assumed in the cost analysis.

In summary, NYSDOT relies minimally on the deck's general condition rating to identify the maintenance actions suitable for a bridge deck and does not express any condition-based thresholds in terms of element-level condition state quantities. However, NYSDOT already has condition-based thresholds that directly relate to the output of NDE techniques, such as crack widths and percent deteriorated area based on spalled, delaminated, or actively corroding areas, in place for a limited number of maintenance actions. The condition-based thresholds, whether expressed in terms of the deck's general condition rating or indepth distress information, are not intended to trigger a maintenance decision but to provide maintenance options to the engineer for a cost-comparative analysis, which is used to make the final maintenance decision.

VDOT Preservation Practice

VDOT maintains several decisionmaking aids to help bridge and maintenance engineers select technically appropriate and cost-effective bridge deck treatments. These include a Deck Decision Matrix, used to select condition-based maintenance, and a table titled Evaluation Requirements and Recommendations for Concrete Decks, which identifies the testing recommended or required to be performed to use the Deck Decision Matrix. The engineer must follow these tables as a minimum requirement unless waived by the district structure and bridge engineer.

Table 25 presents the VDOT's high-level rules for which bridges are candidates for the various types of bridge maintenance based on the general condition rating or element-level condition states of the major bridge components. Examples of each type of maintenance that pertain to bridge decks specifically are listed.

Table 25. General condition-based thresholds used by VDOT to qualify bridges for maintenance (VDOT 2022).

Bridge Condition		Type of Bridge Maintenance	Maintenance Examples
Good (min. GCR ≥7)		No action or preventive maintenance.	Bridge cleaning, deck sealing, thin polymer overlays.
Fair (min. GCR = 5 or 6)	Satisfactory (min. GCR = 6)	Preventive maintenance or restorative maintenance.	Bridge cleaning, deck sealing, thin polymer overlays, rigid deck overlays, cathodic protection.
	Cusp (min. GCR = 5)	Restorative maintenance.	Rigid deck overlays, cathodic protection.
Poor (min. GCR ≤4)		Bridge rehabilitation or replacement.	Deck replacement.
CS 1 or CS 2		No action or preventive maintenance.	Bridge cleaning, deck sealing, thin polymer overlays.
CS 3 or CS 4		Restorative maintenance or rehabilitation.	Rigid deck overlays, cathodic protection, deck replacement.

Table 26 presents part of the more detailed Deck Decision Matrix, which relies not only on the general condition rating but also on the following deck condition information, some of which relies on the following NDE techniques or destructive testing:

- **Compromised area (CA).** The CA is defined as the greater of the total area of the deck in CS 2, CS 3, or CS 4, as determined by visual inspection, or the total deck area identified as delaminated, spalled, or patched plus additional deck areas in CS 1 but identified as likely having active corrosion per an HCP survey.

- **Depth of chloride front (CF).** The CF is used to identify the depth of concrete removal.

- **Cracking condition.** The footnotes of the Deck Decision Matrix discuss appropriate methods of filling cracks depending on their width, activity, and density.

- **Underside condition.** The Deck Decision Matrix requires the deck be replaced if the spalled area of the underside of the deck exceeds 3 percent (not shown in table 26.)

- **Cracking index (CI).** The footnotes of the Deck Decision Matrix state that if the visual inspection notes signs of ASR, a petrographic analysis to identify reactive aggregates is required, and if reactive aggregates are present, the severity of the ASR must be identified by measuring the CI. If the CI is less than 0.02 inches/yd, then a rigid overlay on a hydromilled surface is to be placed, and if the CI exceeds 0.02 inches/yd, then the deck is to be replaced.

- **Compressive strength.** Deck replacement is required if the compressive strength is less than or equal to 2,400 psi.

- **Bond strength of existing rigid overlay.** The footnotes of the Deck Decision Matrix state that bond strength is to be evaluated if more than 5 percent of the existing overlay is spalled and provide conditions for patching and overlay replacement when bond strengths of 100 psi or less are measured.

The Deck Decision Matrix also states that if the cost of repairing or rehabilitating the bridge deck exceeds 65 percent of the replacement cost, the deck should be replaced.

Table 26. Part of the VDOT's deck decision matrix for concrete decks (VDOT 2022).

Worse of these:[1]		Condition Category	Year Built[1]	Evaluation Results	Minimum Required Action
Deck GCR	Percent CA				
7 to 9	≤5	Good	Before 2003	Recommended, but not required.	Patch, epoxy overlay, fill cracks, clean drains, and sweep and wash annually.
			2003 or later	Recommended, but not required.	Patch, fill cracks, clean drains, and sweep and wash annually.
6	≤10	Satisfactory	Any	CA <5 percent and CF <1 inch	Patch and epoxy overlay
				CA ≤10 percent and CF ≤1.5 inch	Patch and rigid overlay on rotomilled substrate.
				No eval. or CF > 1.5 inches	Rigid overlay on shallow hydromilled substrate.
5	≤15	Fair	Any	CF ≤ avg. cover to top mat	Rigid overlay on shallow hydromilled substrate.
				4 inches > CF ≥ avg. cover to top mat	Rigid overlay over deep hydromilled substrate.
≤4	≤20	Poor	Any	CF ≤ avg. cover to top mat	Rigid overlay on shallow hydromilled substrate.
				4 inches > CF ≥ avg. cover to top mat	Rigid overlay over deep hydromilled substrate

[1]The year built reflects the deck concrete material. VDOT began requiring the use of high-performance concrete (HPC) for decks in 2003.

In addition to condition-based maintenance, VDOT allocates funding to schedule-based preventive maintenance of concrete bridge decks (table 27). The deck maintenance actions considered to be schedule-based, and the decks that qualify for each action are presented in table 27. Because of limited funds, VDOT acknowledged that applying schedule-based preventive maintenance to all bridge decks that qualify for such maintenance is impossible. However, VDOT would ideally like to conduct maintenance on at least 2 percent of the structures that have a minimum general condition rating of 6 and at least 6 percent of the structures that have a minimum general condition rating of 5 (VDOT 2022).

Table 27. Selection criteria for bridge deck candidates for schedule-based maintenance (VDOT 2022).

Schedule-Based Maintenance Action	Selection Criteria	
	Decks and Slabs that Are Candidates:	**Deck Condition Requirements:**
Deck washing	Concrete decks or slabs without asphalt overlays.	100 percent of element is in CS1 or CS2.
Deck sweeping	Concrete decks or slabs with asphalt overlays.	100 percent of element is in CS1 or CS2.
Thin epoxy overlay	Bare concrete decks.	100 percent of element is in CS1.

In summary, because of budget constraints, each district structure and bridge engineer is responsible for identifying the bridge decks that will undergo maintenance in their district, and there is no definitive algorithm for condition-based thresholds that automatically trigger maintenance. Once a bridge deck is chosen for maintenance, a deck evaluation is carried out following the requirements of the table Evaluation Requirements and Recommendations for Concrete Decks, which may require or recommend visual inspection, a delamination survey using sounding, infrared thermography, IE, or GPR; an HCP survey; chloride testing, concrete cover measurement using GPR or a pachometer, petrographic analysis, and compressive strength testing (VDOT 2022). Specific maintenance actions may be triggered based on VDOT’s Deck Decision Matrix's condition thresholds, which rely on general condition ratings and indepth inspection data. The condition-based thresholds in the Deck Decision Matrix are not communicated in terms of element-level condition states. However, schedule-based maintenance may be conducted for decks in good condition that do not trigger condition-based thresholds. The condition thresholds that preclude such decks from consideration for schedule-based maintenance are expressed in terms of the element-level condition states.

WisDOT Preservation Practice

WisDOT has a Concrete Deck and Slab Eligibility Matrix that identifies the different preservation activities that can be conducted on bridge decks and the condition-based criteria that make a bridge deck eligible for each activity (WisDOT 2021). The eligibility matrix includes both cyclical and condition-based maintenance actions. The thresholds are based on the deck's general condition rating and the distressed area of the top and underside of the deck, all of which can be determined from the NBI inspection.

As an example, table 28 reproduces the portion of the Concrete Deck and Slab Eligibility Matrix for decks with a general condition rating of 5. The distressed areas of the top and bottom of the deck are expressed according to the defect type and include the following:

- Defect 1080—Delamination and spall and patched areas.
- Defect 1130—Cracking (reinforced concrete).
- Defect 3210—Delamination and spall and patched area and pothole (wearing surfaces).
- Defect 3220—Crack (wearing surface).
- Defect 8911—Abrasion, wear, rutting, or loss of friction—Wearing surface.

According to WisDOT, NDE methods such as HSCD, GPR surveys, infrared surveys, and HCP surveys can also be used to quantify deck defects. However, as shown by table 28, indepth inspection data from NDE techniques is not necessary to use the Bridge Deck and Slab Eligibility Matrix, and while WisDOT's own inspectors should understand available NDE techniques, NDE is often performed by specialists.

Table 28. Concrete Deck and Slab Eligibility Matrix for decks with general condition rating of 5 (WisDOT 2021).

Top Deck Element Distress Area (percent)	Bottom Deck Element Distress Area (percent)	Preservation Activity	Benefit	Application Frequency (yr)
5 percent <3220<25 percent	—	Crack sealing	Service life extended.	3 to 5
3220 CS 3 + CS 4 >0 percent	—	Deck sealing	Service life extended.	3 to 5
—	1080<5 percent	Full depth deck patching.	Service life maintained.	As needed
3210 CS 3 + CS 4 <5 percent	1080<5 percent	Wearing surface patching.	Service life maintained.	As needed
>20 percent (3220 or 8911 CS 3 + CS 4) or	1080<5 percent or 1130 CS 3 + CS 4<25 percent	Concrete overlay	Improve NBI-58 ≥7	12 to 20
>15 percent 3210 (applied to bare deck)				
>20 percent (3210 or 8911 CS 3 + CS 4) or				
>50 percent 3220 (reapplication)				

—No data.

The criteria listed in the eligibility matrix are used to develop bridge work eligibility reports and quantify system needs. However, WisDOT cautions users that engineering judgment needs to be applied to decide if the recommended maintenance action is best suited for extending deck service life.

In summary, WisDOT relies on its Concrete Deck and Slab Eligibility Matrix to identify the bridge deck maintenance needs across its bridge network. The eligibility matrix consists of condition-based thresholds expressed in terms of the deck's general condition rating and element-level condition data collected in NBI inspections. Indepth data from NDE techniques is not routinely collected and is not needed to use the eligibility matrix. However, the eligibility matrix only provides maintenance recommendations, and the user needs to rely on engineering judgment to arrive at a cost-effective final decision on a case-by-case basis.

Specific Preservation and Maintenance Actions Based on SHAs Practices

A summary list of specific preservation actions that are tied to the condition rating of a given bridge deck based on analysis and synthesis of the SHA procedures is provided in table 29. This table also presents the preservation actions list as it relates to one of the condition state defects for bridge decks, namely reinforced concrete “Defect 1080 Delamination/Spall/Patched Area.” Because some NDE methods can be directly used to quantify delaminated areas on bridge decks, such as automated acoustic sounding, infrared thermography, and IE, these methods can be used to inform the decisionmaking process by providing more accurate and/or rapid data collection of the condition state of concrete bridge decks. In addition, spalls and patched areas can be determined using scanner technologies, which include car or drone-mounted cameras. These NDE methods can be used in tandem with or in lieu of the current state of practice, which includes visual inspection and acoustic sounding.

The information in table 29 is distilled from information provided in the agency decision matrices with some input from the project team to guide the definition of defect quantities because a wide range of defect quantities was found within the State guidance that was not necessarily uniform between the different states. In addition, the list of preservation and maintenance actions was also refined to include only the most appropriate actions based on the research team's experience. The information in the table provides an example of how SHAs can use the condition of a bridge deck to select a preservation and maintenance action. Additional defects, such as cracking and abrasion and wear, could be added to the guidance, but the information was not readily available in the reviewed agencies guidance and literature.

Table 29. Condition-based bridge deck preservation triggers based on element-level data, spalls, and delamination.

Rating	Primary Criteria (Defect 1080 Delamination and Spall and Patched Area)	Preservation and Maintenance Action
9*	0 percent spalls and delamination.	Surface sealer; do nothing.
8	0 percent < spalls and delamination <2 percent.	Repair and surface sealer; fill cracks, thin-polymer overlay.**
7	2 percent < spalls and delamination <5 percent.	Repair and surface sealer; fill cracks, thin-polymer overlay, HMA+ membrane, premixed polymer overlay.
6	5 percent < spalls and delamination <10 percent.	Repair and mill and hydrodemolition and HMA + membrane, premixed polymer overlay, rigid overlay.
5	10 percent < spalls and delamination <20 percent.	Repair and mill and hydrodemolition and HMA + membrane, premixed polymer overlay, rigid overlay.
4***	20 percent < spalls and delamination <30 percent.	Repair and mill and hydrodemolition and late-life asphalt overlay, rigid overlay, replace.
3***	30 percent < spalls and delamination.	Replace, mill and hydrodemolition and late-life asphalt overlay, repair, and rigid overlay.

*Some agencies place sacrificial and protective layers at construction such as HMA with membrane or dense concrete overlay.

**Some agencies do not apply polymer overlays until they reach a certain maturity.

***Not considered as preservation actions.

Best Practices for NDE Bridge Deck Condition Assessment

A comprehensive condition assessment of reinforced concrete bridge decks requires a complementary use of various NDE technologies, combined with limited exploratory probing for ground truth validation and laboratory testing. To that end, table 5 summarizes the most promising and practical NDE technologies for bridge deck evaluation and their application for the type of defect they can detect or characterize. Similarly, table 6 lists the most suitable technologies for a given feature of interest. The effectiveness of some of these technologies for the detection and characterization of a specific defect or feature, whereas the application of some other technologies is debatable.

The Second Strategic Highway Research Program (SHRP 2) identified the most used NDE methods for bridge deck evaluation and, through a series of field and laboratory testing and with the participation of both practitioners and academicians, ranked these technologies with respect to their capability to detect a certain type of defect (Gucunski et al., 2013). The study assigned grades of accuracy based on weighted factors of 1) ability to determine defect extent, 2) threshold for detecting defects, and 3) ability to characterize severity of deterioration, each on a scale of 1 to 5. Table 30 summarizes the average weighted grades on a scale of 1 (worst) to 5 (best), which the SHRP 2 report assigned to different technologies for their capability to detect the defects the authors deemed most critical for bridges. It must be noted that since the publication of this report, there has been significant improvement in data collection and processing using other technologies. For example, ultrasonic tomography is more routinely used in bridge deck evaluation, especially in the case of UHPC bridge decks.

Table 30. NDE Technologies based on accuracy (adapted from Gucunski et al. 2013).

Defect	Technology	Average Grade
Delamination	GPR	1.7
	IE	2.8
	IE-USW	2.8
	Infrared	2.2
	Chain drag	1.6
Corrosion	GPM-HCP	2.4
	GPR	1.6
	HCP	2.2
Vertical cracks	SASW	2.3
	SWT (surface wave transmission)	3
	TOFD (time of flight diffraction)	1.6
Concrete degradation	SASW	3.8

Most Suitable NDE Methods for Deck Condition State Assessment

While all the methods identified in Chapter 3 have applications for evaluating the condition or configuration of reinforced concrete elements, the following methods can be currently deployed on a broad production basis to assess relatively large surface area elements like a bridge deck. Other methods are typically applied on a pointwise basis and require too much time, maintenance of traffic, and analysis to be broadly used for preservation decisionmaking on a bridge inventory.

High-Resolution Imagery

Digital photography has been a boon to structural inspections in that it has made it far easier to collect and document information about the visible condition of structural components and to archive those for future reference. In addition to capturing visible conditions at a point in time, it is also useful for documenting the physical configuration of elements for analysis and to compare with other data collection techniques. With recent advances in digital image capture, the ubiquity of data storage and cloud computing, and digital image processing, capturing digital images as part of structural inspections has become commonplace. Most modern digital imaging devices (including tablets and smartphones) can geotag images to give precise location and directional reference, which is useful for mapping and compiling the images for future reference. For rapid surveys of large areas, practitioners can now use road vehicle or UAV platforms to collect imagery with coordinated georeferencing and distance measurement instrumentation to relate other types of data collected simultaneously with the imagery.

Advanced postprocessing algorithms make it possible to “stitch” together series or matrices of images to create large-scale composites or 3D renderings of elements. Image analysis algorithms automate this process by dynamically matching image content. Short-term temporal changes can be monitored by analyzing sequential series of images to recognize very fine differences, in a process termed digital image correlation (DIC). This, for example, makes it possible to measure strain fields (in two or even three dimensions, depending upon the camera configuration) that can be used to monitor structural response to imposed or in situ loads.

Research has been underway for many years to improve automated recognition of image content, such as crack or spall detection. Recent advances in machine learning combined with improved resolution and filtering of images have enabled the characterization of much finer details than was previously possible, such as crack widths measured over a visible crack length to a few thousands of an inch.

Ground-Penetrating Radar

GPR is one of the more commonly applied NDE methods, partly because the data can be obtained rapidly via several different platforms (e.g., hand-held, cart, or vehicle), and partly because the data can be evaluated to give a few different types of information that are of use in element characterization and condition assessment. One of the most direct products of GPR surveys is the location of embedded elements, particularly steel reinforcement, which includes mild steel, prestressing strands, and posttensioning tendons (grouted or nongrouted). For bridge decks, the location of bars in plan can be used to assess compliance with design documents, whether visible damage such as cracks correlates to the location of reinforcement within, or to determine where it may be feasible to probe without damaging the reinforcement. Similarly, GPR is frequently used to locate posttensioning ducts either to support direct investigation of the ducts or to allow the ducts to be avoided during invasive investigation, repairs, or retrofits.

For deck preservation, the distance to the reinforcing steel from the concrete surface (cover depth) is also useful information. It allows analysts to assess the effectiveness of the cover in protecting against chloride intrusion and subsequent reinforcement corrosion and to analyze the associated time for chloride diffusion. In preparation for deck rehabilitation, such as mill or hydro-demolition and overlay, a detailed map of cover depths can also be used to determine how deep it is safe to mill without contacting the reinforcement.

A secondary application for GPR in the assessment of reinforced concrete elements such as decks is through the evaluation of the strength of the radar wave that is reflected from embedded steel elements. A relative decrease in reflected wave amplitude (attenuation) may result from internal features refracting and dissipating the wave energy. In reinforced concrete, attenuation is commonly associated with regions of high moisture content, higher water-to-cement ratio (w/c), voids, or fractures. Areas at the surface of embedded steel that have begun to corrode also exhibit attenuation caused by the hydrated oxides (rust) at the steel surface. The presence of high concentrations of chloride is also known to influence GPR wave attenuation. Unfortunately, the method does not easily distinguish between these conditions.

It is a common misconception that GPR is useful for detecting delaminations in concrete. While GPR may give indications where delaminations exist and such delaminations are filled with water and of sufficient width to cause significant attenuation, GPR is not particularly well suited for directly identifying the presence of the fractures themselves. Acoustic and ultrasonic wave techniques are typically better suited to this task. Thus, while GPR is not the best method for identifying delaminations for quantification of deck repair needs, it is useful in determining areas of a reinforced concrete deck that are more prone to deterioration due to shallow cover, high moisture content (and, therefore, permeability), and the potential presence of active corrosion. In this regard, it may be considered more of a predictive tool.

Acoustic Wave Methods

Acoustic sounding of reinforced concrete has long been recognized as an effective method for detecting the presence of shallow voids or delaminations, which have been manually applied as chain drag or hammer sounding. The change in acoustic resonance and frequency of impacted concrete where a shallow defect exists is readily recognizable, even to untrained ears. However, there are limitations to this method. Manual sounding can be somewhat subjective in that it is influenced by the range of hearing of the operator, the level of ambient noise, and the precision with which the operator marks the resulting findings. Also, the audio response changes with the size and depth of the defect, meaning there comes a point at which the human ear cannot distinguish a difference even though a defect exists.

Several methods have been developed in recent decades to build on the basic principles of acoustic sounding by applying automation to make the measurements less subjective and more precise. Several developers have implemented methods that use portable microphones, analog-to-digital conversion, and digital filtering to automate the sounding process. The concrete may be excited by the impact of a solenoid or chain, for example, and the microphone captures the acoustic response. Filtering allows the user to remove exterior influences and extract the frequency ranges known to correspond to internal defects. The filtered results are recorded and correlated to digital positioning data to create precise maps of the resulting findings. This method has been employed in arrays deployed on vehicle-based platforms moving a few miles per hour to map large areas of the bridge deck, typically a lane width at a pass, in a short timeframe.

More sophisticated analyses of the acoustic response of concrete to impact or induced vibration include the impact echo method, which typically involves the use of a geophone or transducer instead of a microphone. The analysis is a bit more complex in that, in addition to filtering, the captured wave response is converted from the time to the frequency domain using a fast-Fourier-Transform. The data are analyzed in the frequency domain to indicate the absence or presence of features or flaws, such as the thickness of an element or the depth of a delamination or fracture. The processing of this type of data is more intensive, and in practice, the measurements are usually made on a point-by-point basis rather than automated via GPS or DMI reference. This method is particularly useful in determining the precise depth and location of deeper discontinuities but does not, in its present form, lend itself to rapid mapping over large areas such as a bridge deck.

Infrared thermography

The observation of heat radiating from a structural element through a special camera that measures in the infrared spectrum rather than the visible spectrum can be exploited to assess the presence of embedded features or defects. A shallow defect such as delamination will affect the heat transfer rate through the element relative to the intact areas surrounding it. Voids filled with water or air will transfer heat at different rates and hold different amounts of heat than bulk concrete. Such areas can be identified by viewing the element during a heat transition into or out of the element. Like high-resolution imagery, modern IR cameras have vastly improved in resolution, precision, and data collection speed and are frequently deployed in hand-held, UAS, or vehicle-mounted configurations to perform surveys of structures, including decks. A significant limitation of IR is the need for precise timing of temperature fluctuations, typically tied to the diurnal cycle, to obtain the greatest thermal contrast between defects and the base element. Inclement or overcast weather can result in inadequate heat transfer to highlight the features of interest, meaning defects may not be detected (false-negative). The images also need to be analyzed in conjunction with conventional imagery to account for variances caused by shade from nearby objects, differences in the reflectivity of surfaces, and changes in structural material being observed (e.g., a patch versus the surrounding concrete). Failure to account for these influences may result in false-positive indications. While IR permits documentation of relatively large areas quickly, they must be carefully deployed and analyzed to ensure appropriate results.

Currently, a new application for IR includes collecting time-lapse infrared images to be used in analysis for the detection of subsurface defects. This method, called IR-UTD, has the advantage that optimized weather conditions are not required to achieve the desired results. However, data still needs to be collected for subsequent advanced analyses.

Electrochemical HCP

A long-used method for characterizing the probability that corrosion of embedded reinforcement is occurring, the HCP method uses the difference in native potential of embedded steel in concrete versus a known reference electrode (e.g., copper-copper sulfate or silver-silver chloride) to assess the likelihood of corrosion as a function of the measured voltage. The techniques are semi-nondestructive, requiring electrical contact with the embedded reinforcement, which may require localized excavation. A voltmeter is connected in series between the embedded reinforcement and the reference cell. The reference cell is placed on the concrete surface (usually with an interface with a conductive solution), thereby completing the electrochemical circuit through the pore solution of the concrete. The voltage measurements are made pointwise (or via a wheel) over the concrete surface to indicate the corrosion probability of the internal steel reinforcement below. The method requires that the reinforcement grid be electrically continuous, and the presence of intermediate nonconductive layers, such as paint on the concrete surface, an asphalt membrane, or epoxy coating on the reinforcement, significantly affects the method's effectiveness.

Because it is a pointwise contact method, lane closures are required to perform HCP on a bridge deck, which makes this less practical from a production standpoint. However, it is often used by SHAs at the project level when engineers are trying to assess the total areas of repair that are needed.

CHAPTER 6. FRAMEWORK FOR NDE-SPECIFIC THRESHOLDS

This chapter will define NDE thresholds that can be used to trigger certain preservation actions for concrete bridge decks, which are by far the most used type of bridge decks in the United States. The goal was to develop triggers for preservation actions mainly based on NDE data. While the previous section shows how NDE data can be used to inform condition ratings and states for preservation and maintenance decisionmaking by quantifying the amount of damage for certain deterioration mechanisms, namely delamination, and spalling, the approach presented in this section (approach 2) is intended to show how NDE data can be the primary source to guide the selection of preservation actions. This is a complex approach because it requires using NDE in specific scenarios that may be challenging to generalize, and due to a lack of available literature and supporting data, to fully develop NDE thresholds for all the available NDE techniques. This approach focused on presenting a framework that can be used to develop NDE thresholds for some NDE methods. Three example uses of NDE methods to develop input for preservation strategies are presented in the following sections.

GPR-BASED PRESERVATION THRESHOLDS USING COVER DEPTH

This first example presents how cover depth data can trigger certain preservation actions for newly constructed bridge decks. As widely known, corrosion of reinforcement is the most common cause of deterioration in concrete bridge decks, especially in climates where de-icing salts are used and coastal environments. For a given bridge deck concrete mix, the concrete cover helps protect the reinforcing steel as it provides protection from the environment, where chlorides and moisture need to diffuse through the concrete cover before reaching the level of the reinforcement. As such, a reduction in concrete cover will increase the susceptibility of a given bridge deck to corrosion damage. Note that the presence of cracks also affects the bridge deck performance in such environments as it allows chlorides and moisture to infiltrate through the concrete and have more direct access to reinforcement. Therefore, using NDE methods to verify the as-built concrete cover, such as GPR, will help determine if a deck is more susceptible to corrosion damage if a construction error resulted in reduced concrete cover.

For this example, it was assumed that the service life of a given concrete bridge deck is controlled by chloride-induced corrosion due to the application of deicing chemicals during the winter. Chloride-induced corrosion of a generic bridge deck was modeled using a mechanistic service life modeling software. To investigate the effect of reduced concrete cover, service life modeling was completed to estimate the service life of a generic deck with a design concrete cover of 2.5 inches versus the same deck if reduced cover scenarios of 2.0, 1.5, 1.0, and 0.5 inches existed. The model considered cases for uncracked concrete decks as well as a deck with a 5 percent crack-affected area.

The modeling software generally follows the full-probabilistic modeling approach. The probabilistic approach considers the variability of key corrosion-controlling parameters, including exposure conditions, material properties, and as-built conditions, among other factors that affect service life. The probability of corrosion-related damage over time is determined by describing the key factors that govern corrosion as probabilistic variables with statistical distributions and performing a Monte Carlo analysis to estimate a statistical distribution for the probabilistic output, the "time-to-damage." The time-to-damage may be broken into two phases: the initiation phase, or time required for corrosion to initiate, and the propagation phase, or time required for distress to occur once corrosion has initiated. The initiation time and propagation time are added to calculate the time-to-damage. The time to corrosion initiation, t_i, was estimated using a full-probabilistic modeling approach, while the propagation time, t_p, was assumed to be a fixed value.

For the purposes of this modeling, the "end of service life" was defined as the time at which the percentage of deck area expected to show corrosion-related damage reaches 20 percent, as shown in figure 31.

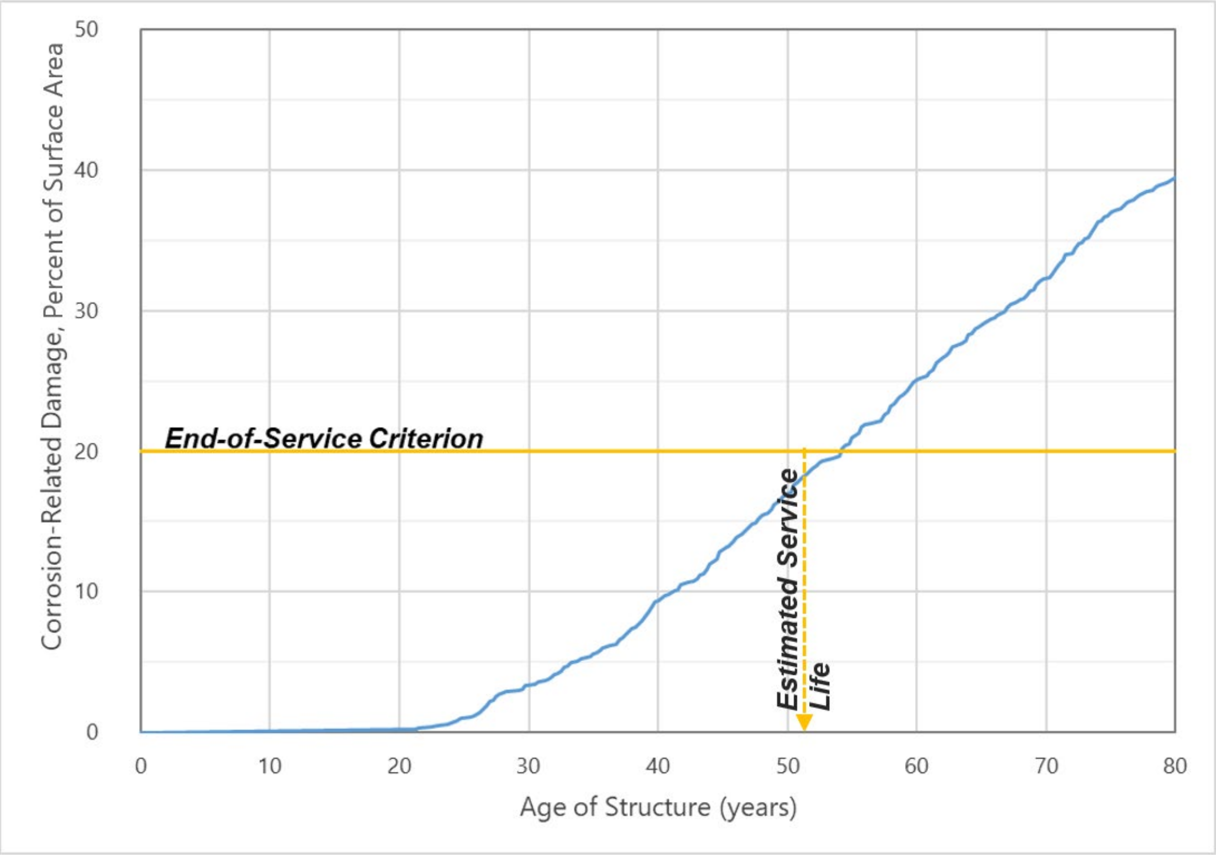


Figure 31. Chart. Example of service life model output.

The service life of a structure depends on several variables related to the exposure conditions, concrete properties, and reinforcing steel properties. The following discusses the input parameters considered by the model.

Input Parameters Related to Exposure Conditions

Temperature. Temperature impacts the rate of chloride diffusion and the rate of corrosion. The models used a mean annual temperature.

Surface chloride concentration . The surface chloride concentration is the chloride concentration at the top surface layer of the concrete deck due to the application of deicing chemicals each winter (or due to marine environments). Greater surface chloride concentrations correspond to more severe environments.

Buildup time. The buildup time is the time required for the chloride concentration at the top surface of the deck to build up to the long-term value that the structure will see over its remaining life, i.e., the surface chloride concentration. The buildup time depends on how frequently the deicing chemicals are applied and the type and concentration.

Input Parameters Related to Concrete Properties

Apparent chloride diffusion coefficient. The chloride diffusion coefficient of concrete describes how quickly chlorides can diffuse through the concrete cover. A greater diffusion coefficient indicates that chlorides can penetrate the concrete faster, while a smaller diffusion coefficient indicates that chlorides will penetrate the concrete more slowly. The chloride diffusion coefficient input parameter describes this parameter at a concrete age of 28 d.

Aging factor. The aging factor is used to model the improvement in chloride diffusion coefficient as the concrete ages past 28 d; the diffusion coefficient decreases because of continued hydration. This factor is affected by the percentage of SCMs in the concrete mix. If the concrete mixture contains SCM such as fly ash and slag cement, then a greater reduction in the chloride diffusion coefficient is expected compared to cement only mixes, because these materials continue to hydrate and more effectively reduce concrete permeability over time.

Variables Related to Reinforcing Steel

Concrete cover. The concrete cover refers to the clear cover over the top mat of reinforcing steel in the bridge deck.

Chloride threshold. The chloride threshold is the chloride concentration required to initiate corrosion. It depends on various factors, including the type of reinforcing steel and the cementitious materials in the concrete mixture. Recognizing that the chloride threshold can vary across the deck, this parameter is modeled using a probability distribution.

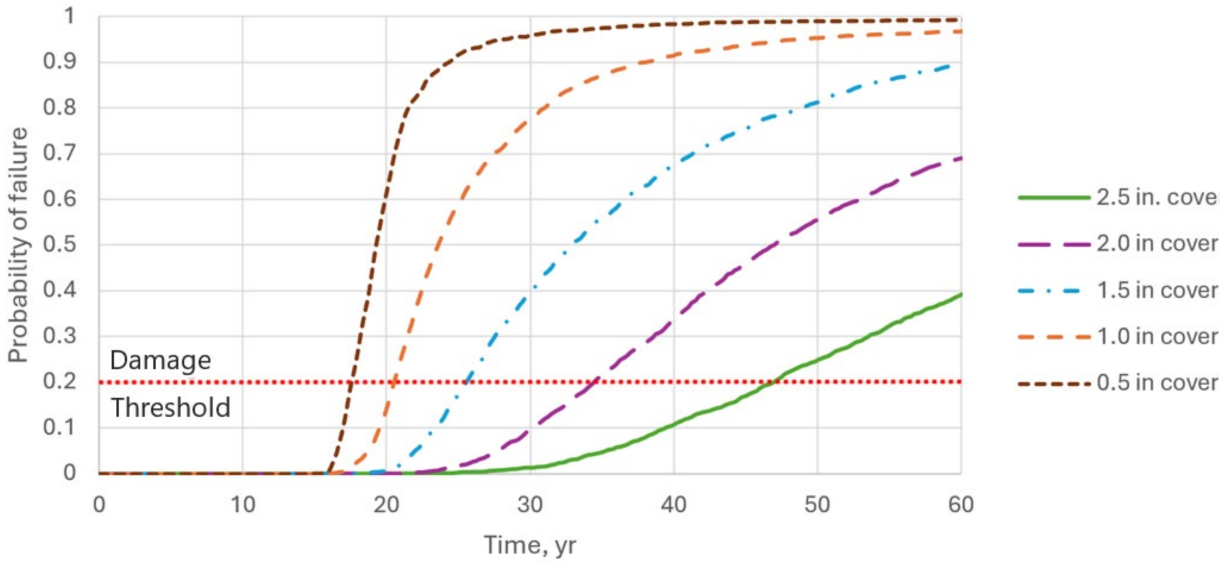
Corrosion propagation time. The corrosion propagation time is the number of years required for the corroding reinforcing bars to cause cracks, delaminations, or spalls after corrosion initiation.

From a study for Iowa DOT, the model inputs utilized for a generic uncracked bridge deck are summarized in table 31 (ElBatanouny et al. 2022). The base model assumes a concrete cover of 2.5 inches. All the properties remain the same for bridge decks with lower covers of 2.0, 1.5, 1.0, and 0.5 inches. For cracked concrete decks, the impact of cracks on chloride transport could be represented by increasing the apparent chloride diffusion coefficient of the concrete to account for the increased chloride ion penetrability and faster chloride diffusion to the reinforcing steel in the local area around the crack. For this example, no crack-affected area is used as the focus is a reduction in concrete cover. The service life model results for the different cases are shown in figure 32 and table 32. The service life of the modeled bridge deck decreases significantly as the cover decreases. For instance, the model indicates that at a cover depth of 1.5 inches, the service life decreases by approximately 45 percent.

Table 31. Summary of model inputs for a generic Iowa bridge deck with no cracking (ElBatanouny et al. 2022).

Parameter, Unit	Distribution	Generic Uncracked Iowa Bridge Deck	
Exposure Conditions			
Mean annual temperature, °F	Constant	51	
Surface chloride concentration, ppm	Normal	m: 5500;	*s*: 1100
Buildup time, yr	Constant	5	
Concrete Properties			
Apparent 28-d diffusion coefficient, inches^2/yr	Normal	*m*: 0.32;	*s*: 0.063
Aging factor	Constant	0.2	
Background chloride concentration, ppm	Constant	0	
Reinforcing Steel Properties			
Concrete cover, inches	Normal	*m*: 2.50;	*s*: 0.31
Chloride threshold (epoxy-coated reinforcement), ppm	Normal	*m*: 1760;	*s*: 536
Propagation time, yr	Constant	15	

m = mean; s = standard deviation.



Source: FHWA.

Figure 32. Chart. Effect of cover loss on the service life of a generic bridge deck.

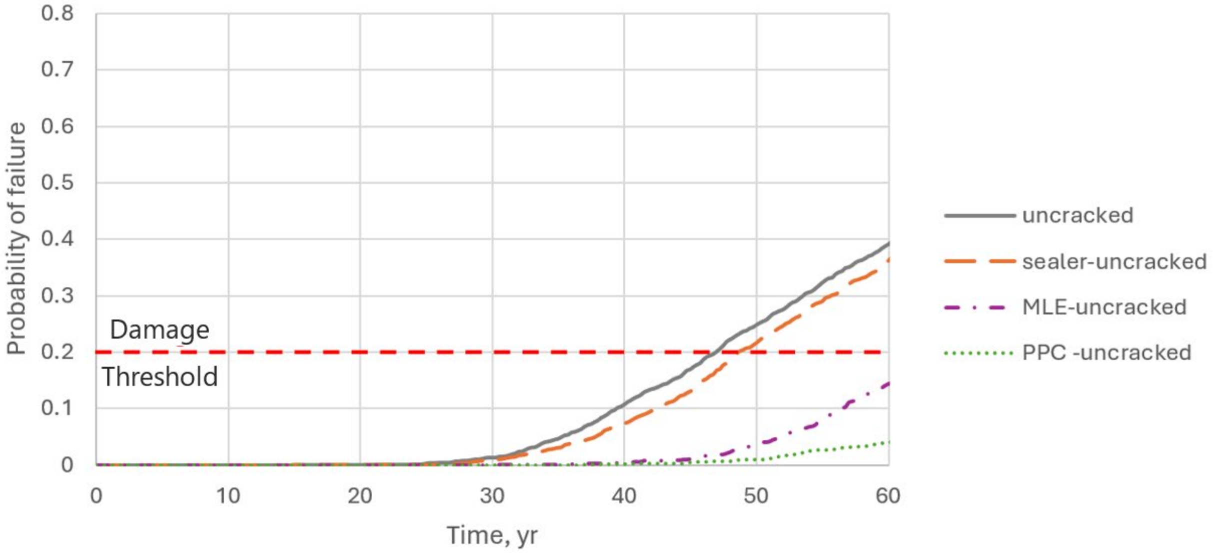
Table 32. Predicted service life of an uncracked and a cracked generic bridge deck with varying concrete cover.

Modeling Case	**Cover Depth**				
	2.5 inches	2.0 inches	1.5 inches	1.0 inches	0.5 inches
Uncracked deck service life (yr)	47	35	26	21	18

Due to the observed reduction in service life, preservation actions can be used to extend the service life of bridge decks with lower cover to achieve the service life of the assumed design case of 2.5 inches. Three different preservation treatments were considered for the uncracked bridge deck as follows:

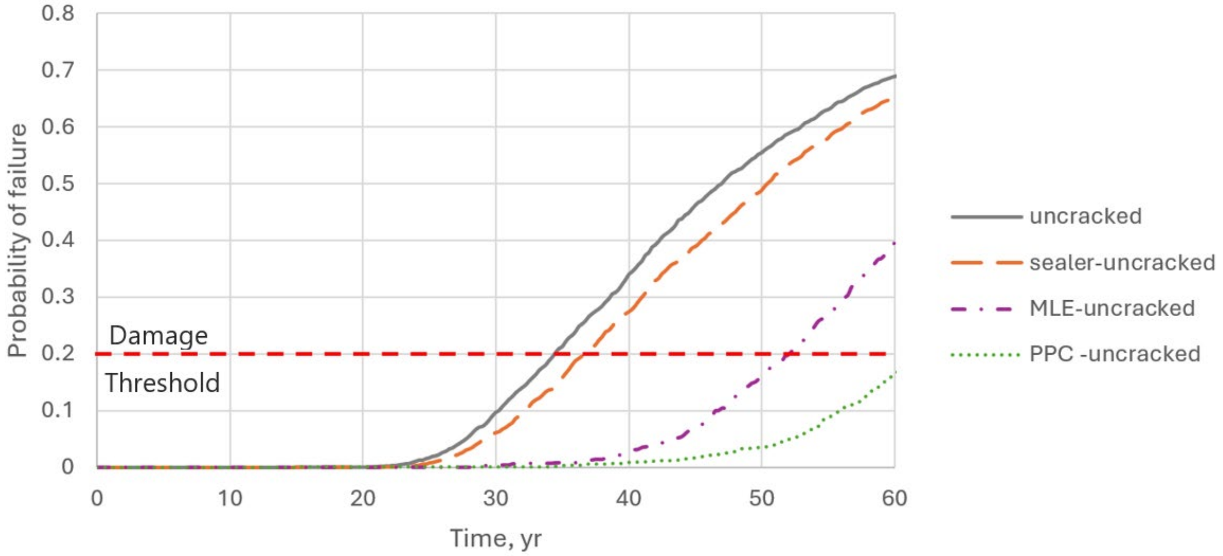
- Apply a penetrating sealer.
- Apply a thin polymer overlay (multilayer epoxy) with a thickness of three-eighths inches.
- Apply premixed polymer overlay with a thickness of three-fourths inches.

The results of treatments are shown in figure 33 through figure 37 for the five assumed design covers. The results are also shown in table 33, which summarizes the expected service lives of uncracked bridge decks based on varying assumed concrete cover for different preservation treatments. As shown in the table, for the 2.5-inches concrete cover, any of the preservation treatments will result in a service life extension greater than the base case of an uncracked bridge deck. For the remaining covers, while a sealer provides some service life extension, the reduced service life due to cover depth always exceeds the benefits for applying a sealer. The polymer overlay scenarios achieve higher service life extension that can be used to offset the effect of cover loss. This example shows that cover data collected after construction as a quality assurance can be used to guide the selection of preservation treatments in the case of construction errors, where it was shown than a less than design cover can greatly affect the durability and service life of bridge decks in corrosive environments.



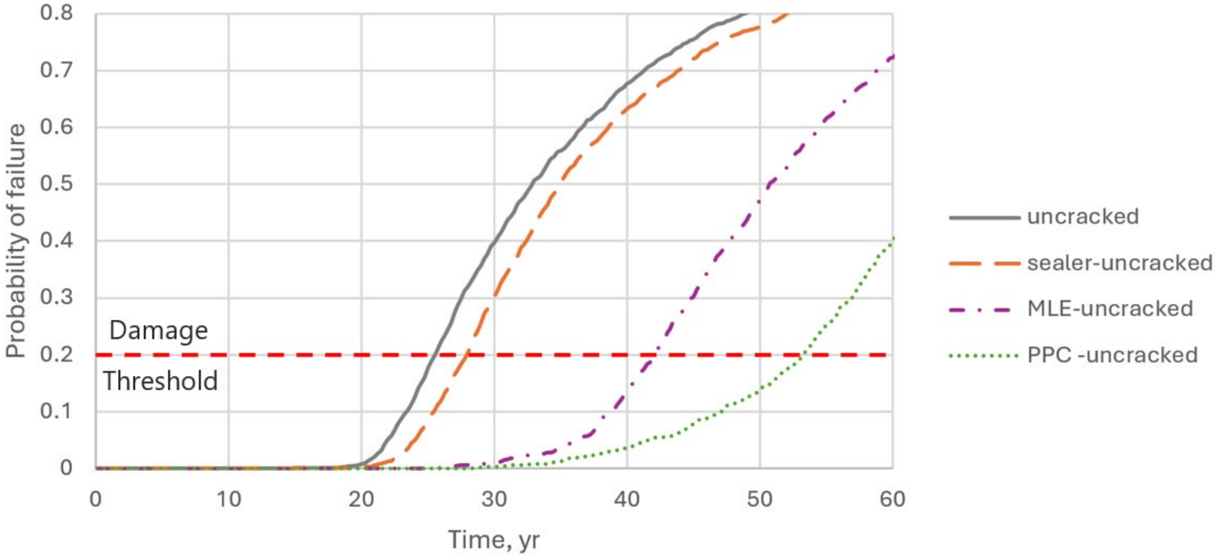
Source: FHWA.

Figure 33. Chart. Effect of preservation actions on the service life of a concrete deck with 2.5-inch cover.



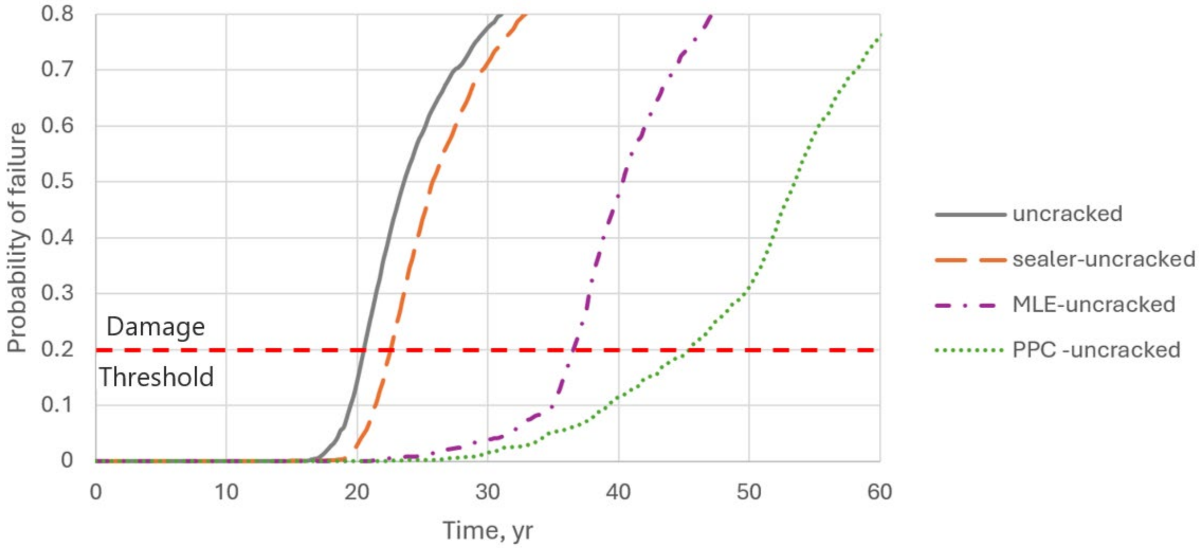
Source: FHWA.

Figure 34. Chart. Effect of preservation actions on the service life of a concrete deck with a 2.0-inch cover.



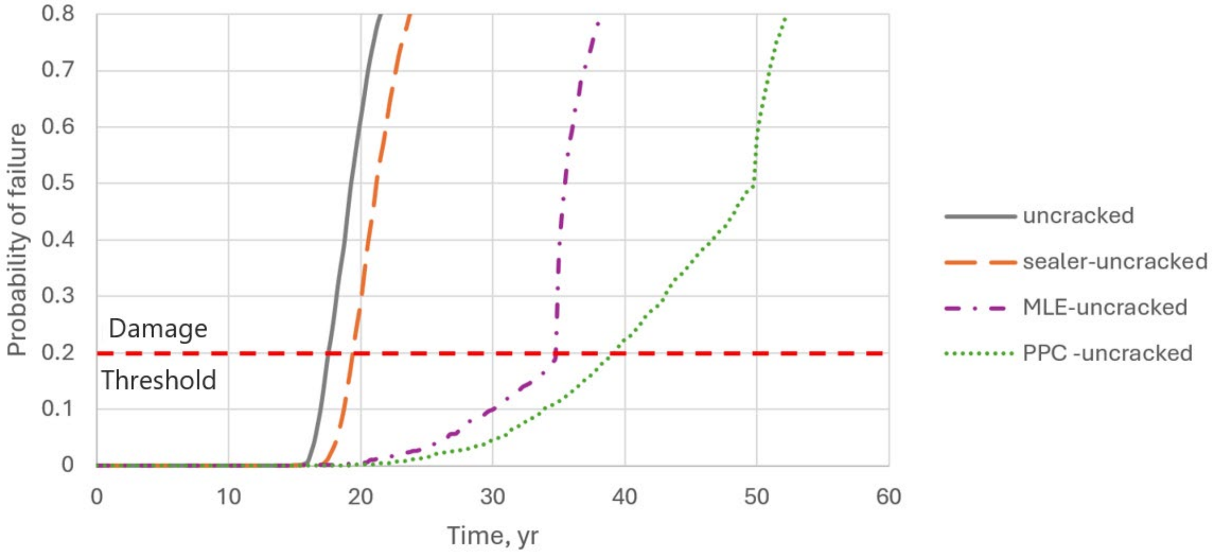
Source: FHWA.

Figure 35. Chart. Effect of preservation actions on the service life of a concrete deck with a 1.5-inch cover.



Source: FHWA.

Figure 36. Chart. Effect of preservation actions on the service life of a concrete deck with 1.0-inch cover.



Source: FHWA.

Figure 37. Chart. Effect of preservation actions on the service life of a concrete deck with 0.5-inch cover.

Table 33. Predicted service life of uncracked generic bridge deck with varying concrete cover under preservation treatment alternatives.

	Cover Depth				
Treatment Alternative	**2.5 inches**	**2.0 inches**	**1.5 inches**	**1.0 inches**	**0.5 inches**
Uncracked deck—untreated (years)	47	35	26	21	18
Uncracked deck—penetrating sealer (years)	49	37	28	23	19
Uncracked deck—TPO (years)	65	52	42	37	35
Uncracked deck—premixed polymer overlay (years)	75	62	53	45	39

Crack Classification for Selection of Crack Remediation Options

Concrete cracking is a widely observed issue in bridge decks across the United States. Many factors can lead to formation of cracks in concrete especially at early age including cracks formed due to autogenous shrinkage, drying shrinkage, differential drying, plastic shrinkage, volumetric changes, and subsidence. While the presence of these cracks may not influence the strength and load carrying capacity of the deck, cracks have a great influence on the durability performance of bridge decks as they facilitate access to chlorides and moisture, which can lead to corrosion related damage in bridge decks.

The main goal of a recent study in Iowa was to develop decision matrices for the Iowa DOT to aid in the selection of the most appropriate preservation actions to remediate the effect of early age cracks (ElBatanouny et al. 2022). This goal was achieved by completing an extensive study using service life models to estimate the service life of hundreds of modeling cases that assumes specific crack affected area with and without the application of different preservation treatments applied at different ages of a generic Iowa bridge deck. Through this work, different decision matrices were developed, with varying degrees of complexity, along with a summary data-driven decision trees for easy implementation in future decision making by the Iowa DOT. An example of such a decision tree is shown in table 34.

Table 34. Data-driven selection of crack remediation options based on cracking characteristics of a generic Iowa DOT bridge deck (adapted from ElBatanouny et al. 2022).

Crack Width	Low Crack Density (<0.10 ft/ft^2)	Moderate Crack Density (0.10 to <0.22 ft/ft^2)	Severe Crack Density (0.22 to <0.37 ft/ft^2)	Very Severe Crack Density (≥ 0.37 ft/ft^2)
Narrow cracks <5 mils or map cracks	Do nothing or penetrating sealer; flood coat	Do nothing or penetrating sealer; flood coat	Do nothing or penetrating sealer; flood coat	Flood coat; penetrating sealer; do nothing
5 to <15 mils	Do nothing; penetrating sealer + reapplication; crack fill or flood coat; polymer overlays	Flood coat; penetrating sealer + reapplication; TPO or premixed polymer overlay	Flood coat; polymer overlays	Polymer overlays; flood coat
15 to <30 mils	Crack fill or flood coat; TPO	Flood coat; TPO or premixed polymer overlay	Flood coat; TPO or premixed polymer overlay	Flood coat; thin polymer overlay or premixed polymer overlay
30 to <40 mils	Crack fill; TPO	TPO; premixed polymer overlay	TPO; premixed polymer overlay	TPO; premixed polymer overlay
≥40 mils	Requires further investigation	Requires further investigation	Requires further investigation	Requires further investigation

Note: Treatments are listed in decreasing order of suitability, where "or" indicates equal suitability.

The remediation options in table 34 can be summarized as follows:

- Do nothing—leave deck as-is.
- Penetrating sealer—apply a super-low viscosity material (e.g., silane) that permeates the concrete but does not form a film or coating; + reapplication—reapply on regular intervals (e.g., every 5 yr).
- Crack fill—apply polymer crack sealant into individual cracks by the gravity feed method.

- Flood coat—apply a low viscosity polymer sealer (e.g., methyl methacrylate or epoxy) by flooding the surface of the deck to allow cracks to be filled by gravity; usually includes topical application of sand for skid resistance.
- TPO—apply a multilayer polymer (e.g., epoxy, polyurethane or polyurea) with intermittent applications of sand to create a thin (0.25 to 0.5 inches) overlay.
- Premixed polymer overlay—apply a polymer (e.g., polyester) concrete in thicknesses typically 0.75 inches or greater.

The selection criteria depend on the appropriate classification of the cracking condition of the bridge deck. This classification utilizes data related to the crack density (defined as a summation of the total length of cracks divided by inspected area) and crack width observed on the deck. While this task can be completed through visual inspection, this process is typically labor-intensive and requires lane closures if the bridge deck is already open to traffic. Recent progress in NDE scanners, such as using high-resolution imagery, presents opportunities to use truck or drone-mounted cameras to complete this task, and as such, this NDE data can then be used to trigger certain preservation actions based on the observed bridge deck condition states. While still a developing field, currently, a few firms have this capability and can provide crack mapping data for bridge decks.

Prediction of Imminent Deterioration

The last example relates to the use of NDE techniques to detect deterioration that can be considered imminent during inspections. NDE techniques can be used to estimate the amount of delamination and spalling in concrete bridge decks, which can then be used to trigger specific preservation actions. For example, if the bridge condition is between rating 7 and 9, i.e., areas of delaminations and spalls are less than 5 percent, less rigorous actions are typically recommended. However, if additional areas are likely to deteriorate or delaminate in the near future, the recommended actions may not be the most appropriate as a more extensive rehabilitation strategy would be required to achieve the desired service life.

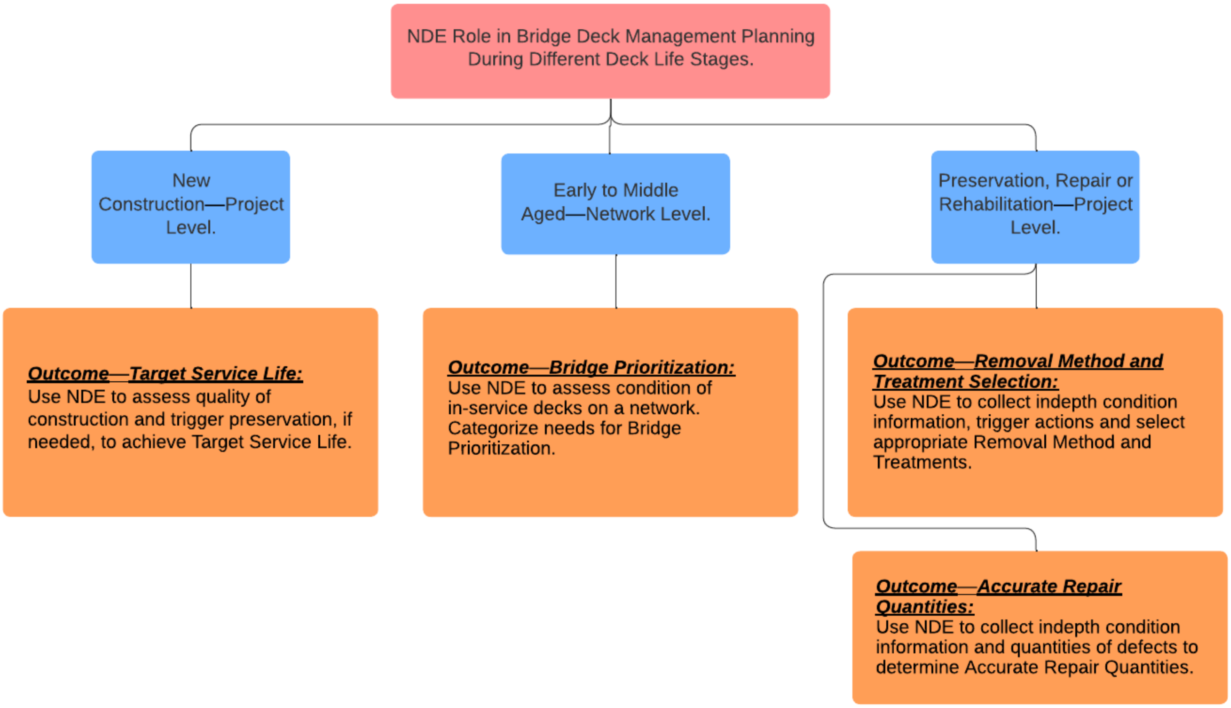
NDE techniques can help with quantifying areas that can be classified as areas with imminent deterioration, which can then be added to quantities of delaminated or spalled areas in a bridge deck to refine the selection of treatment options. One technique that is particularly effective in detecting imminent damage is half-cell potential measurements. This technique can give an indicated of areas with high corrosion potential, which will likely deteriorate faster even though distress is not yet visible, nor can it be detected using sounding techniques. GPR attenuation can also provide information on deck areas that have a high likelihood of imminent deterioration. It is noted that both NYSDOT and NJDOT specify adding areas with a high probability of active corrosion, as indicated by HCP, to areas that are delaminated and spalled in their maintenance decisionmaking recommendations.

Several emerging NDE methods currently under development can also be considered for this task. These techniques work on the principle of detecting the relative condition of concrete, which can aid in defining areas that are deteriorated or are likely to have ongoing active deterioration.

Determining the chloride concentration at the reinforcing bar levels in association with service life modeling can also help estimate the amount of expected damage in a bridge deck. Additional information regarding the concrete cover, steel properties, concrete properties, and exposure conditions are typically needed to create a representative model.

CHAPTER 7. RECOMMENDATION FOR NDE PROGRAMS

NDE may be useful to support bridge preservation decisionmaking at several stages in the life of a bridge or bridge deck ranging from new construction to rehabilitation. Figure 38 summarizes some of the more promising applications that may already be in use by some agencies and summarizes the expected outcomes.



Source: FHWA.

Figure 38. Diagram. Applications and outcomes of NDE during the life of a bridge deck.

As outlined in figure 38, for new construction, NDE can assess the quality of the construction and determine if certain defects exist that can affect the bridge deck's service life. As such, the use of NDE can trigger the selection of certain preservation practices if needed to achieve the Target Service Life of the bridge deck.

During the early to middle age of a deck, NDE can be used to assess the condition of in-service bridge decks on a network level. The collected NDE information can help categorize the needs of different bridges in the network in terms of preservation, repair, or rehabilitation. This approach allows stakeholders to use NDE data for bridge prioritization to maximize the utilization of available funds to achieve the goals for their network planning.

At later stages of deck life when damage becomes manifest, NDE can be used to collect indepth information regarding the condition of bridge decks. Based on available guidance from different agencies, criteria could be developed to trigger specific preservation, repair, or rehabilitation actions and enable bridge owners to select appropriate removal methods and treatments.

Before implementing the treatments, NDE can provide indepth information regarding the condition and quantities of specific defects on bridge decks. This can enable bridge owners to determine accurate repair quantities for bidding and repair planning purposes.

Each of these life-stage applications is discussed with indications of suitable NDE methods.

NEW CONSTRUCTION

During construction of a new bridge or new bridge deck, NDE methods may be useful to support quality assurance, to ensure the deck was constructed as specified. A simple example is the use of GPR to map the location and cover depth of the reinforcement. Variations from specified cover can have implications for both durability and structural performance.

Lack of cover will reduce the distance through which moisture and chloride would need to diffuse to cause corrosion and related deterioration. The use of a pachometer to conduct cover checks is not an unusual practice, but often, it is useful to use GPR to give a more comprehensive documentation of cover depth. In one example, during the placement of a staged construction reinforced concrete deck, the exterior girder was not adequately braced to accommodate the loads from the screed rail. The exterior girder rotated during placement, causing the stay-in-place forms and reinforcement above to shift. The result was inadequate deck thickness and inadequate cover in some regions of the deck and excessive cover in others, which was documented by the GPR survey. That stage of the deck was required to be replaced.

In another example, a reinforced concrete deck was placed on a new steel multigirder bridge in two stages. The deck extended (cantilever) past the exterior girder and, in turn, supported a new Jersey-style barrier. A routine random check of the reinforcement cover found that steel could not be detected near the surface of the cantilever region of the deck. A GPR survey revealed that the top mat of reinforcement had not been adequately supported before concrete placement and that the top mat had dropped to the elevation of the bottom mat, leaving no steel in the tensile region of the cantilever to resist gravity and potential impact loads related to the barrier. In this case, it was necessary to demolish and reconstruct the deck to ensure the capacity of the cantilever and barrier. There are numerous cases in which a GPR survey of a recently placed concrete deck showed inadequate reinforcement cover in regions due to poor control of bar placement, camber, or other causes. For durability purposes, some of the required placements of protective overlays are meant to supplement the inadequate cover. In addition, or as an alternative, the owner may use the NDE information to support the development of a lifecycle preservation plan for the deck.

Another common issue with reinforced concrete deck construction is the development of shrinkage-induced cracking, particularly where mixtures contain pozzolans and exceed 650 pounds per cubic yard cementitious material. NDE can be useful for baselining the construction and verification of service life assumptions. A combination of GPR and high-resolution imagery after a few months or after the first winter season can be used to baseline the condition of the deck, including its reinforcement configuration and clear cover distribution, as well as the presence and distribution of cracking. These data can be used with chloride-induced corrosion service life models to estimate service life and compare to design assumptions.

Early- to Middle-Aged Structures

After a bridge deck has undergone several seasons in service, exposure and contamination begin to accumulate. Certain NDE methods lend themselves to rapid data acquisition that can be used to screen for early onset of deterioration or indicators of likely imminent deterioration. As noted previously, GPR can be collected from vehicle platforms at highway speeds without lane closures. Scanning series of decks in this manner can allow the user to highlight those that have shallow reinforcement and areas of high attenuation that may be associated with poorer quality, moisture, and chloride-laden concrete that are prone to deterioration. In this way, it can be used as a screening tool to identify decks that will need intervention earlier versus others and to prioritize those decks. Similarly, high-resolution imagery and infrared thermography can be deployed, together or separately, on a terrestrial vehicle, UAS, or manned aerial platform on a screening basis to gather evidence of visible cracks, spalls, joint deterioration, and shallow delaminations that require intervention.

For bridge owners, network-level information on the relative deterioration of bridge decks and NDE data on the relative damage for specific defects are valuable resources that can improve bridge management decisions and asset management planning. Such data can be used to customize deterioration models and service life expectancy, which informs the selection of deck treatments or bridge repair and rehabilitation. NDE information can be utilized to improve inspection data quality and enable bridge owners to use custom deterioration or service life estimated with improved confidence. These improvements would also positively impact the data analytics in Transportation Asset Management Plans and agency resource allocation, informing asset management at different stages of the process.

Bridge Deck Preservation, Repair, or Rehabilitation

More focused NDE applications can be used to inform project-level assessment, where the purpose is detailed damage assessment and determination of anticipated repair quantities. While some of the data from screening activities may be informative in determining damage and quantities, usually a more focused survey using manual or cart-based tools allows greater precision in measuring and locating defects. At the project level, some of the more localized tools, like acoustic response, impact echo, or ultrasonics, as well as half-cell potential, become more useful and viable to support decisionmaking. For most agencies, the most important goal is to obtain a realistic estimate of repair quantities so that cost overruns can be avoided. This goal requires a combination of visual and sonic-based methods to quantify existing damage as well as electrochemical methods to assess where deterioration may be imminent but not yet manifest as damage. Many of the latter areas may not be detected as damage but may evolve as the demolition activities are underway because the underlying deterioration has already begun to occur. Additional damage may manifest in these areas in a short time after the already spalled and delaminated areas are repaired.

In addition to characterization before implementing a repair program, NDE can also be useful for validation of repairs, in some ways like new construction (e.g., verifying adequate cover), but also in supplemental ways, such as determining whether repairs are well-bonded or do not contain voids.

CHAPTER 8. PRESERVATION DECISION MATRIX TO INCORPORATE NDE/SM METHODOLOGY INTO BRIDGE PRESERVATION STRATEGIES

As outlined in the previous chapters, specific NDE information can be used to guide preservation or maintenance actions during different life stages of bridge decks. As such, the importance and effectiveness of applying certain NDE techniques differ based on the age of the bridge decks in question. The following sections outline a framework for developing decision matrices to incorporate NDE methodology into bridge preservation strategies to trigger specific preservation actions based on the following subobjectives:

- Incorporate NDE methodology into bridge preservation strategies to optimize results.
- Recommend timing for NDE applications.
- Establish a framework for triggering preservation actions based on NDE outputs.

In chapter 7, the project team provided recommendations for applying NDE techniques at different stages in the deck lifecycle. This was done by recognizing the relationship between the different NDE methods and bridge deck characteristics of interest during that life stage. Recommendations for NDE programs were classified into the following three categories:

- New construction.
- Early to middle age bridges.
- Bridge deck preservation, repair, or rehabilitation.

For each of the different life stages, a framework for decision trees that target a given characteristic of a bridge deck (concrete cover, cracking, damage) or a network of bridges was developed. A recommendation was also provided for the most suitable NDE technique(s) to be used. Use cases in chapter 10 were then used to exemplify how the framework can be used to develop state-specific decision matrices that can be used to trigger preservation or maintenance actions based on the NDE input.

NEW CONSTRUCTION DECISION TREE—PROJECT LEVEL

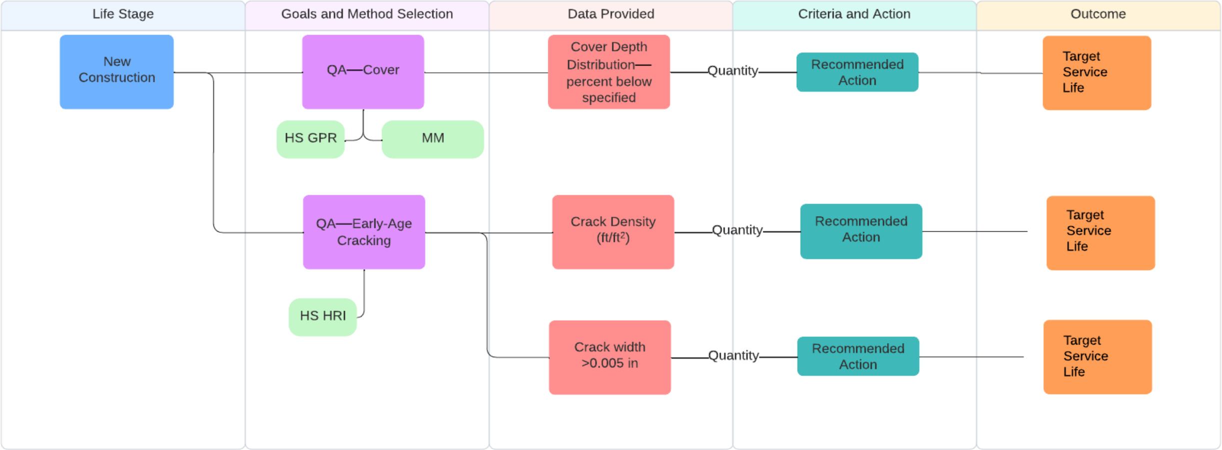
Newly constructed bridge decks are free of damage, except for rare cases where construction defects or concrete material degradation (such as shrinkage-induced cracking) affect their condition. As such, most NDE techniques that focus on damage detection will not be useful when applied to new decks. The main use of NDE techniques for new construction is, therefore, typically focused on quality assurance to ensure that the deck is constructed as intended.

The main characteristics of interest that can affect the service life of a new bridge deck are concrete cover and early-age cracking. Concrete cover is the component that provides protection to reinforcement steel from corrosive elements, such as chloride in deicing salts. While the concrete mix design and permeability also have a significant effect on bridge deck durability in corrosive environments, these parameters are not typically quantified in situ using existing NDE methods. In addition, many of the states use standard mix designs to construct their bridge decks; as such, and assuming similar concrete properties, the major factor that affects the service life is concrete cover. Therefore, if the cover depth is less than that specified, the bridge deck will be expected to have a shorter life span compared to the life span intended by the design. Based on the literature review and interviews in chapter 3, magnetometers (based on eddy current principles, also known as cover meters or pachometers) and GPR are the main NDE methods that can measure concrete cover with high reliability. GPR has the advantage of being able to collect such data at high speed.

Early age cracking is the second bridge deck characteristic that can have a significant effect on service life, especially in corrosive environments. The presence of cracks allows direct access of corrosive elements, such as chloride and moisture, to the reinforcement by bypassing the cover. This can accelerate the corrosion process and shorten the service life of the deck. Crack characteristics, such as crack density and width, can be used to select appropriate deck preservation actions. Traditionally, crack mapping has been completed using manual visual inspection. Recent developments in digital imaging in terms of high-resolution cameras and image processing software allow the automation of the crack mapping process where vehicle-mounted systems can be used to collect digital photographs that can be analyzed to develop detailed crack maps. This high-resolution imagery technique can, therefore, be used at high speed to create crack maps of bridge decks and trigger appropriate preservation actions based on the NDE input.

A decision matrix was developed as shown in figure 39 to provide the framework for using NDE techniques to trigger preservation actions for newly constructed bridge decks. The decision tree includes information related to the following:

- Bridge deck life stage: New Construction.
- Goal of using NDE and recommended methods.
- Cover depth: GPR or magnetometer (MM).
- Crack density and/or width: High-resolution imagery.
- Data provided.
- Cover depth distribution (percent).
- Crack density (ft/ft^2).
- Crack width (inches).
- Criteria and action.
- Outcome.



Source: FHWA.

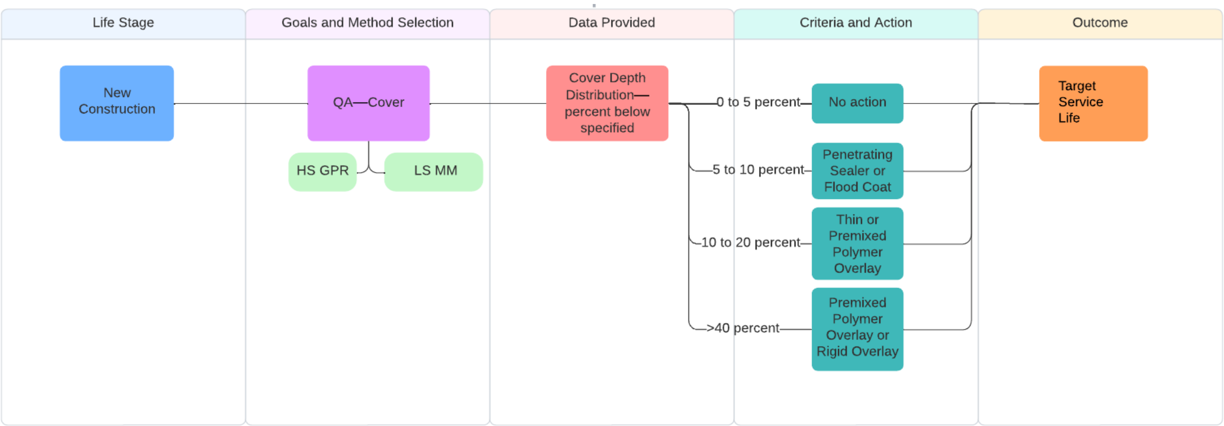
Figure 39. Diagram. Decision tree framework for using NDE data to trigger preservation actions for new construction.

Example Decision Tree: GPR to map the location and cover depth of the reinforcement

Chapter 6 provided an example of how to use cover data to trigger certain preservation actions in case a bridge deck was constructed with a lower cover than the design cover. The example was completed by assuming a generic bridge deck with a specific mix design, design concrete cover, and exposure conditions. The assumptions for material properties and exposure follow a recent research project for Iowa DOT-TR-782, *Guide to Remediate Bridge Deck Cracking* (ElBatanouny et al. 2022). In addition, cost information related to maintenance options was obtained from the same report (ElBatanouny et al. 2022).

Different cases were modeled wherein a design concrete cover of 2.5 inches was assumed versus the same deck if reduced cover scenarios of 2.0, 1.5, 1.0, and 0.5 inches existed. Several preservation treatments were also modeled, and the results in terms of service life expectations, assuming the end of service life occurs at 20 percent surface damage, as summarized in table 33.

Based on these results, an example decision tree was developed as shown in figure 40. The decision tree criteria can be customized for a given state's preference in NDE methods and policies for preservation. Under the example decision tree, a specific preservation treatment can be selected based on the NDE. Due to the wide variability in the bridge deck design characteristics (mix design, reinforcement type) and exposure conditions across the States, each State could develop its own decision trees following the same logic presented in this example.

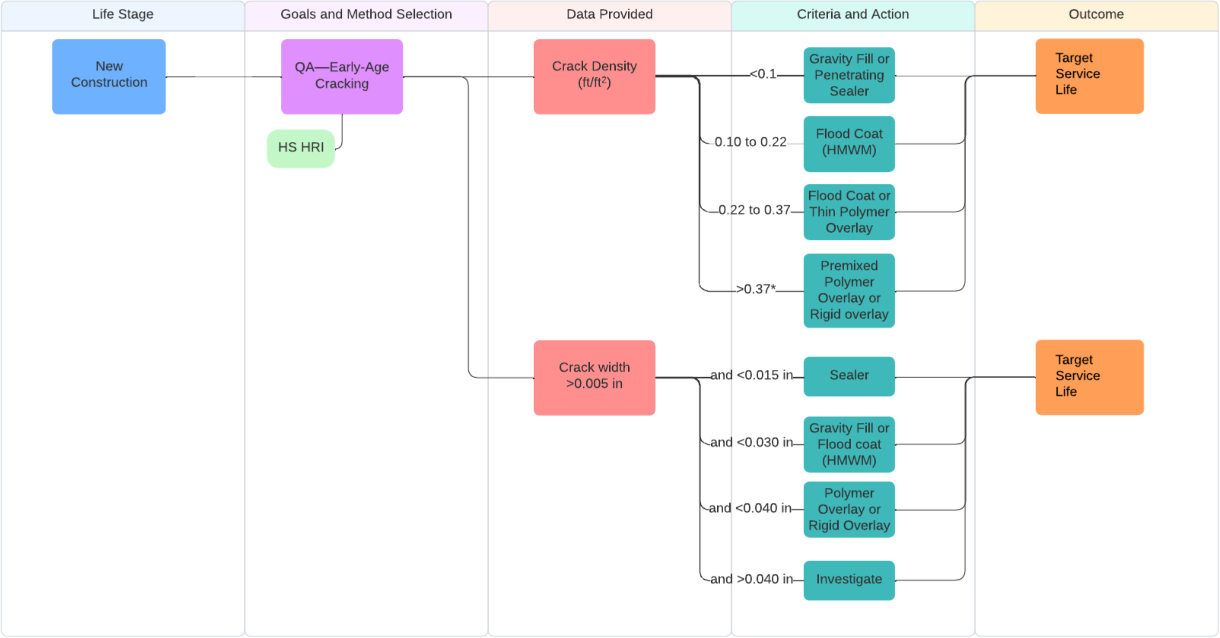


Source: FHWA.

Figure 40. Diagram. Decision tree framework for using NDE data to trigger preservation actions for new construction based on measuring concrete cover.

Example Decision Tree: High-resolution imagery for crack density and width

As described, high-resolution imagery can be used to determine the crack characteristics of a bridge deck in terms of crack density and width. Chapter 6 included an example from a recently completed research study for Iowa DOT that used these parameters to create a decision matrix for the selection of optimal crack remediation options (ElBatanouny et al. 2022). The developed decision tree from this study is shown in table 34. The framework that targets cracking in newly constructed decks (0 to 2 yr) can be extended to an example decision tree (figure 41) that uses HRI to trigger preservation actions based on the crack density and width. The example decision tree also reflects the ranges of crack widths and densities (i.e., criteria) assumed in developing the results of the referenced study. Other States that have different bridge deck design parameters and exposure conditions can develop similar state-specific decision trees using the same logic.



Source: FHWA.

Figure 41. Diagram. Decision tree framework for using NDE data to trigger preservation actions for new construction based on evaluating early-age cracking.

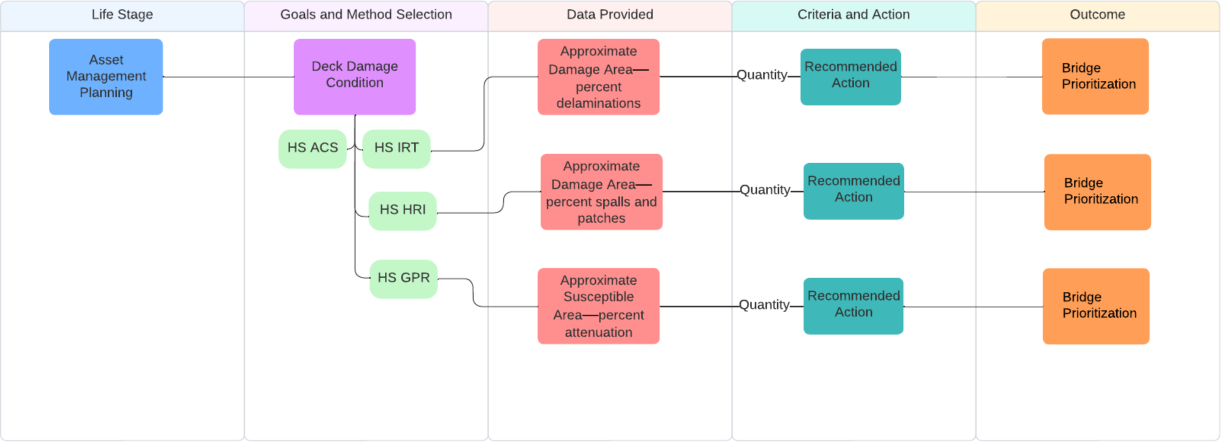
Early to Middle Aged Bridges—Network Level

Early to middle aged bridges are those that have been in service long enough that exposure to the environment may lead to early deterioration or damage. The exact number of years is dependent on several factors including exposure conditions, concrete material properties, concrete cover, and steel reinforcement type. For example, bridge decks in severe environments, such as those exposed to extensive de-icing practices, may have enough chloride exposure to initiate corrosion damage in less than 20 yr. As such, this category is better defined as bridge decks with no or little manifestation of damage.

The use of NDE on bridges within this life stage can help with the early detection of damage, which can enable the selection or prioritization of the preservation and maintenance of specific bridge decks to achieve optimal resource allocation. As such, applying NDE techniques at this life stage on a network of bridges can help with asset management planning. To perform inspections at this life stage on a bridge network, NDE techniques that can be deployed at high speed and without lane closures are more appropriate for this application.

Based on this logic, a decision matrix was developed as shown in figure 42 to provide the framework for using NDE techniques for asset management planning of early- to middle-aged bridge decks. The decision tree includes information related to the following:

- Bridge deck life stage: Early- to middle-age.
- Goal of using NDE and recommended methods and data provided.
- Approximate damage area, percent delamination: high-speed automated acoustic sounding (HS ACS) or high-speed infrared thermography (HS IRT).
- Approximate damage area, percent spalls and patches: high-speed-high-resolution imagery (HS HRI).
- Approximate susceptible area, percent areas of high attenuation: High-speed ground penetrating radar (HS GPR).
- Criteria and action.
- Outcome.



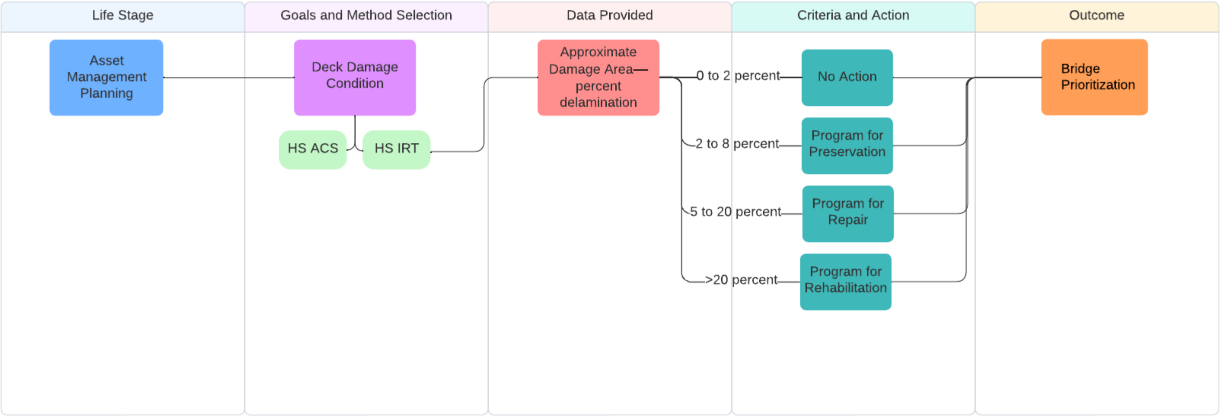
Source: FHWA.

Figure 42. Diagram. Decision tree for using NDE data for asset management planning of early to middle age bridge decks.

Example Decision Tree: Approximate Damage Area—Percent Delaminations

The project team completed a literature review of SHAs practices for triggering preservation or maintenance actions based on element-level data related to delaminations, spalls, and patched areas. These actions ranged from *do nothing* to *full bridge deck replacement* based on specific damage thresholds employed by the different SHAs. This information was summarized as shown in figure 43.

Based on the summarized results, an example decision tree for using NDE data for asset management planning for early to middle age bridge decks based on approximate damage area (percent delaminations) was developed as shown in figure 43. This decision matrix uses NDE information collected using HS ACS or HS IRT along with the developed percent delaminations thresholds to guide the selection of certain preservation or maintenance options for asset management planning. For this decision tree, the recommended actions are categorized as a program for preservation, repair, or rehabilitation based on the percent delamination measured. Specific actions beyond the general recommendations are provided in the project-level decision trees presented in the following section on preservation, repair, and rehabilitation decision trees.

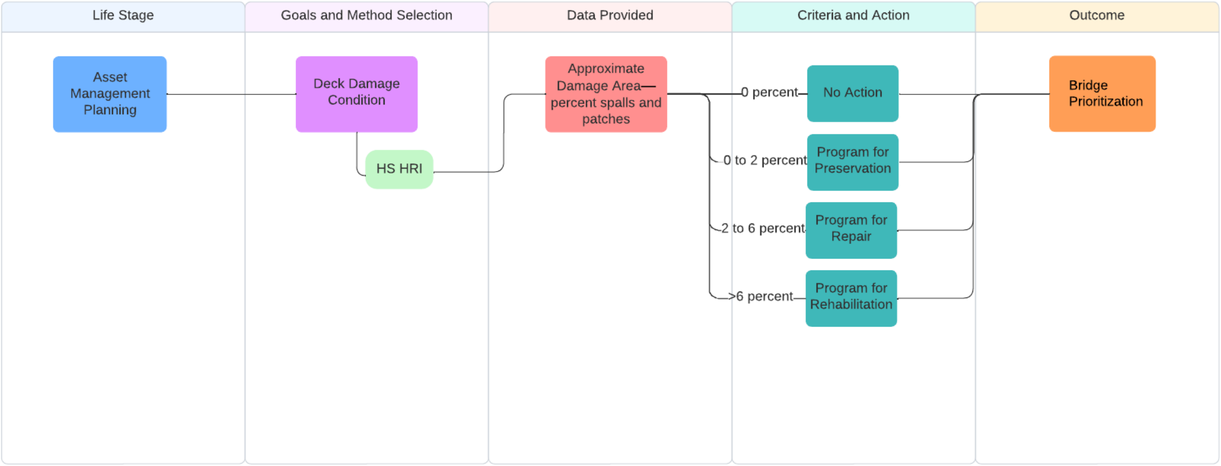


Source: FHWA.

Figure 43. Diagram. Decision tree for using NDE data for asset management planning for early to middle age bridge decks based on approximate damage area (percent delaminations).

Example Decision Tree: Approximate damage area—Percent spalls and patches

The approximate damage area (percent spalls and patches) can be used for asset management planning following the same logic presented in the previous section. While the spalls and patched areas on a bridge deck were typically lumped in the same category as delaminations as shown in table 2, it is assumed that their percentage will only make up a small portion of the summation of delaminations, spalls, and patch areas. An example decision tree was developed that solely uses information related to spalls and patched areas for triggering recommendations as shown in figure 44. Criteria used in the decision tree are based on the engineering judgment of the project team. SHAs can use the presented decision tree and criteria as a basis to develop state-specific decision trees following the same logic presented herein.



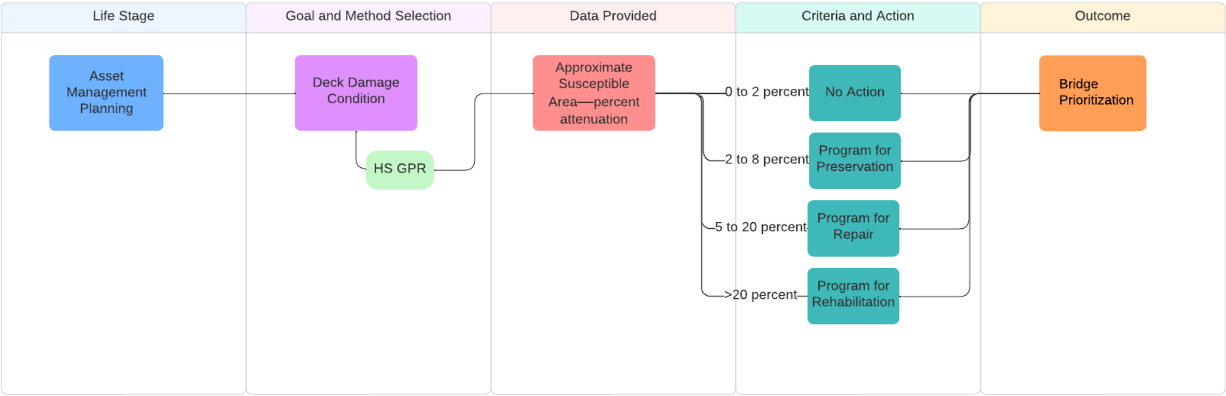
Source: FHWA.

Figure 44. Diagram. Decision tree for using NDE data for asset management planning for early- to middle-aged bridge decks based on approximate damage area (percent spalls and patches).

Example Decision Tree: Approximate susceptible area—Percent area of high attenuation

A major advantage of NDE is that it can provide information related to early or developing damage that has not yet manifested as visible surface damage. NDE can be used to estimate areas that have a high susceptibility to become damaged in the future. Few NDE techniques can be used to detect damage in this early stage, and even fewer techniques can be used for this purpose at high speed. Based on the information collected in task 2, high-speed GPR is one of the techniques that can be used for this purpose. However, careful data analysis and interpretation are needed to achieve this goal, which is highly dependent on the quality of the data collection and the expertise of the NDE analyst or specialist.

An example decision tree for the use of NDE to measure approximate susceptible areas is shown in figure 45. The decision tree criteria were developed based on the information presented in table 2. This was done because susceptible areas can be considered equivalent to or added to damaged areas when it comes to condition assessment and asset management planning. Like the other example decision trees, this example is provided for information, and agencies should consider developing their own criteria based on their specific exposure conditions and the goals of their bridge deck asset management program.



Source: FHWA.

Figure 45. Diagram. Decision tree for using NDE data for asset management planning for early- to middle-aged bridge decks based on approximate damage area (percent attenuation).

Preservation, Repair, or Rehabilitation Decision Tree—Project Level

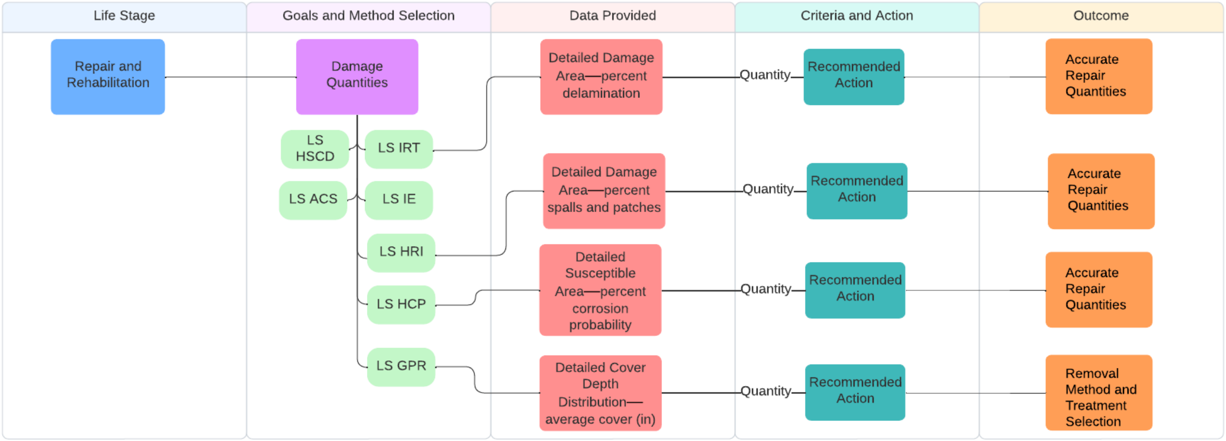
One of the main goals of this study is to develop decision trees that can rely on NDE data to trigger certain preservation or maintenance actions for bridge decks. For in-service bridge decks, several factors, including detailed damage area, detailed susceptible area, and detailed cover depth distribution, can guide the selection of preservation and maintenance actions.

The use of NDE on bridges within this life stage can help with the accurate determination of required repair quantities, which is a measure typically used by SHAs to differentiate between the different available actions. For example, bridge decks with only small areas of deterioration can be repaired and preserved by applying a surface treatment while decks with extensive damage will often require an overlay as part of the rehabilitation process. Since this process is typically applied on the project level, both low-speed and high-speed NDE methods can be used, with low-speed data collection preferred to ensure more reliable estimates.

A decision matrix was developed as shown in figure 46 to provide the framework for using NDE techniques for the selection of preservation, repair, or rehabilitation options for bridge decks. The decision tree includes information related to the following:

- Bridge deck life stage: Selection of preservation, repair, or rehabilitation.
- Goal of using NDE and recommended methods and data provided.
- Detailed damage area, percent delamination: low-speed hammer sounding and chain dragging (LS HSCD), low-speed automated acoustic sounding (LS ACS), low-speed infrared thermography (LS IRT), or low-speed impact echo (LS IE).

- Detailed damage area, percent spalls and patches: low-speed high-resolution imagery (LS HRI).
- Detailed susceptible area: low-speed half-cell potential (LS HCP).
- Detailed cover depth distribution, cover depth inches: low-speed ground penetrating radar (LS GPR).
- Criteria and action.
- Outcome.



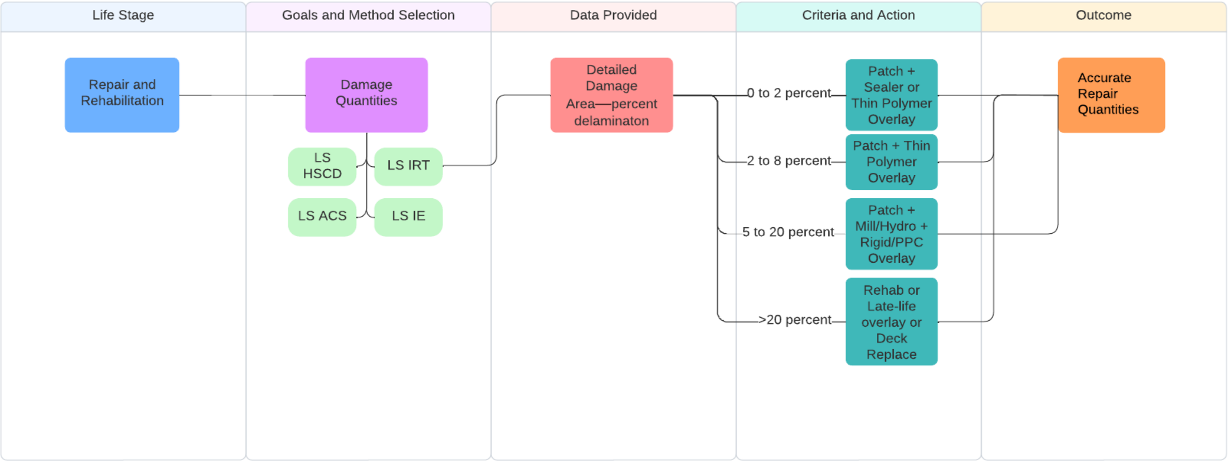
Source: FHWA.

Figure 46. Diagram. Decision tree for using NDE data for preservation, repair, or rehabilitation of bridge decks.

Example Decision Tree: Detailed Damage Area—Delaminations

One of the main parameters widely used to inform decisionmaking by most transportation agencies is the percentage of damaged or delaminated areas including LS HSCD, LS ACS, LS IRT, and LS IE. Several NDE methods can be used to accurately detect delaminated areas. While the accuracy of the different methods varies, as discussed in chapter 2, all the NDE methods can offer good-quality results if applied at low speeds.

Figure 47 shows an example decision tree for using NDE data for preservation, repair, or rehabilitation of bridge decks based on detailed damage area (percent delaminations). The criteria used in the decision tree were presented in table 34 in chapter 6. Note that the criteria presented are for general guidance, and different SHAs may have or prefer using different thresholds.

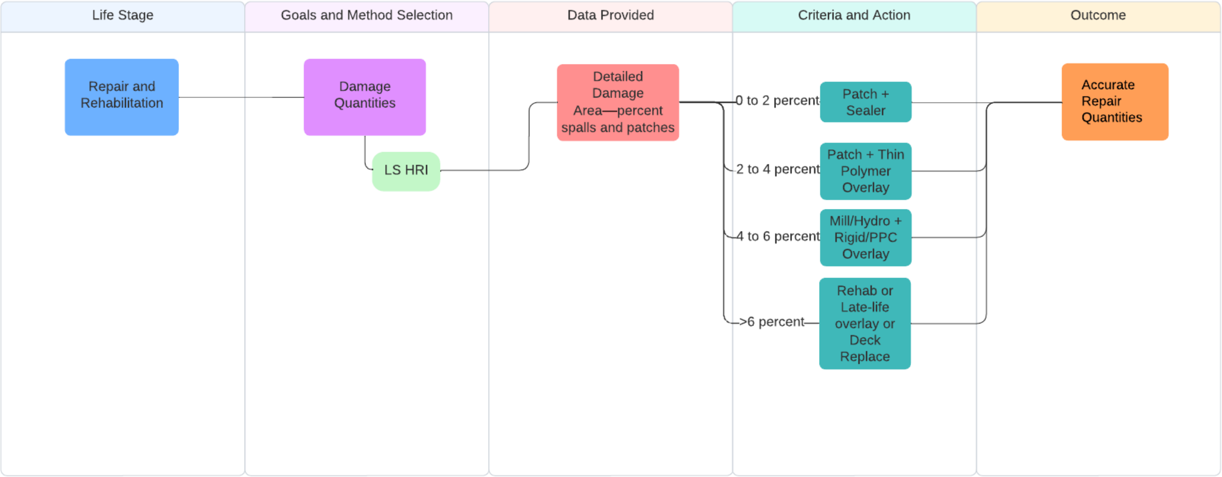


Source: FHWA.

Figure 47. Diagram. Decision tree for using NDE data for preservation, repair, or rehabilitation of bridge decks based on detailed damage area (percent delaminations).

Example Decision Tree: Detailed Damage Area—Spalls and Patches

Another criterion that can be used to inform the decisionmaking process for the preservation and maintenance of bridge decks is the amount of visible damage, represented by the area of spalls and patches. In most cases, HRI cannot distinguish between sound patches that are performing as intended and unsound patches that need repair. While there is limited guidance and literature for a separate criterion to determine triggers based on visible damage alone, it is expected that even a small amount of spalls can have a significant impact on the ride quality and serviceability of a bridge deck. The project team developed an example decision tree with criteria to trigger preservation, repair, or rehabilitation actions for bridge decks based on the detailed area of spalls and patches as shown in figure 48. Like the other decision trees, the criteria and recommended actions presented are meant to be used as an example of how this logic can be adopted by SHAs to develop their own decision trees based on their experience and exposure conditions.



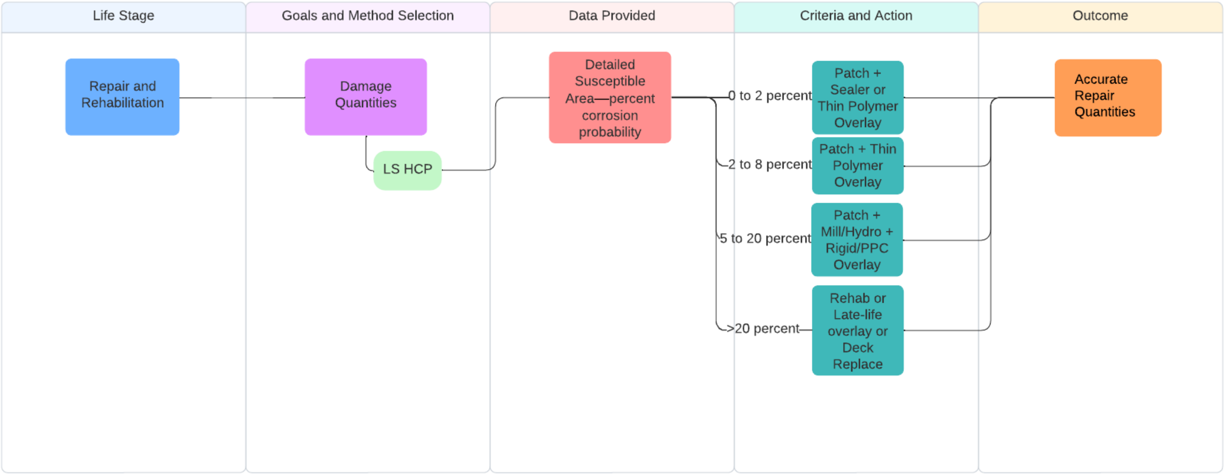
Source: FHWA.

Figure 48. Diagram. Decision tree for using NDE data for preservation, repair, or rehabilitation of bridge decks based on detailed damage area (percent spalls and patches).

Example Decision Tree: Approximate Susceptible Area—Percent Corrosion Probability

Chloride-induced reinforcement corrosion is the major driver for deterioration in bridge decks in states that use de-icing salts or in coastal areas. Actively corroding areas manifest surface damage about 5 to 15 yr after corrosion initiation, depending on the type of reinforcement used. As such, decisions made only based on detected damage areas may underestimate the area of the deck where corrosion is active. These actively corroding areas, if not addressed, will eventually result in surface damage, which may compromise the treatment applied on the deck. For example, thin polymer overlays used on actively corroding areas may delaminate once surface damage is reached at the active corrosion regions.

Corrosion NDE methods, such as HCP measurements, can be used to detect areas with active corrosion. This can better inform the decisionmaking process and enable the selection of optimal preservation, repair, or rehabilitation options. Some SHAs have guidance on adding active corrosion areas to damaged areas for decisionmaking purposes. An example of using NDE data for preservation, repair, or rehabilitation of bridge decks based on approximate susceptible area (percent corrosion probability) is shown in figure 49. The criteria used in this decision tree are like those used for detailed damage area shown in figure 47.

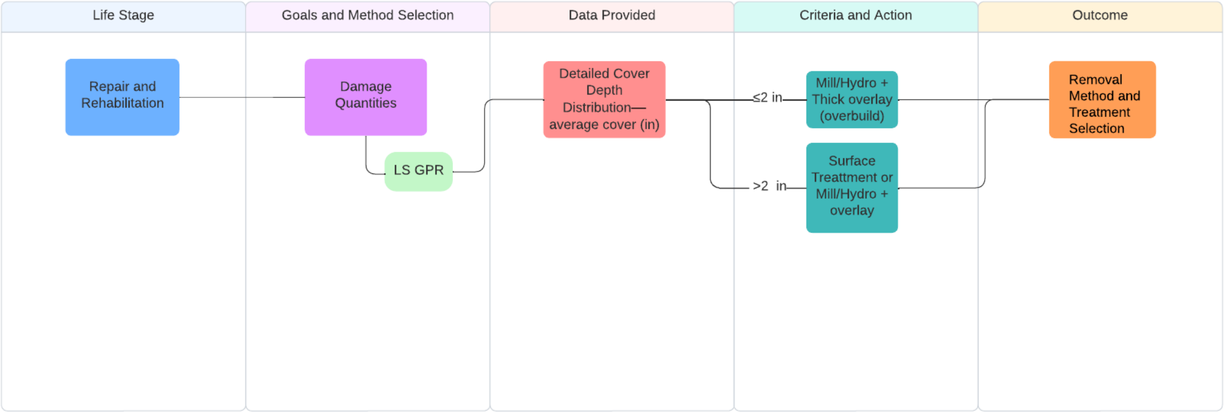


Source: FHWA.

Figure 49. Diagram. Decision tree for using NDE data for preservation, repair, or rehabilitation of bridge decks based on approximate susceptible area (percent corrosion probability).

Example Decision Tree: Detailed Cover Depth Distribution—Average Cover (inches)

The concrete cover is another criterion that can be used to guide the selection of preparation methods for the existing deck to receive treatment and the selection of optimal repair options. When planning a bridge deck repair, surface preparation of the existing concrete deck is one of the considerations. Concrete decks with low cover typically require an overbuild of the concrete cover to achieve longer service life, while bridge decks with adequate cover can be candidates for surface treatments, such as sealers and flood coats or thin polymer overlays. The surface preparation selection can also include the preparation method, such as, for example, whether micro-milling or hydro-demolition should be used. Figure 50 shows an example decision tree for using NDE data for the preservation, repair, or rehabilitation of bridge decks based on detailed cover depth distribution. This parameter should be used in conjunction with the other parameters described in the previous sections to better address the bridge deck conditions.



Source: FHWA.

Figure 50. Diagram. Decision tree for using NDE data for preservation, repair, or rehabilitation of bridge decks based on detailed cover depth distribution (average cover, inches).

Decisionmaking

Synthesis of NDE Methods

As described in the decision matrices, several NDE methods can be used to provide information regarding a certain parameter or damage type. In addition, more than one parameter can be used to assess the condition of a bridge deck or network of bridges. Synthesis of information collected using more than one NDE method can significantly increase the reliability of the assessment and further improve the data used to inform the decisionmaking process. For example, preservation, repair, and rehabilitation decision trees can rely on data collected to measure damaged areas in terms of percent delamination only. However, if HCP data are available, this information can be used to determine additional areas of the bridge deck that are likely to have surface damage soon. Engineering judgment and evaluation are, therefore, needed to synthesize all the information collected from different sources. The benefits of using more than one technique should also be compared to the costs incurred through this process. Case examples generally indicated that the value of having indepth data for better decisionmaking generally exceeds the NDE costs. FHWA has funded other research studies to specifically evaluate the return on investment (ROI) from using NDE data.

Other considerations

There are several other factors that can be used to determine the appropriate action that should be taken to preserve or maintain a bridge deck. These factors include material testing to determine the characteristics of the bridge deck concrete, such as the diffusion coefficient, which may indicate the susceptibility of the bridge deck to corrosion damage. Another factor that can be used is chloride content, which can indicate if corrosion initiation is likely at the reinforcing level. These factors, and others, can also be used in service life modeling to provide information regarding the potential amount of damage in the bridge deck. The effectiveness and benefits of the treatment options can also be studied using a calibrated service life model, which will determine the lifecycle cost benefits of the treatments and ultimately select the most suitable options for that bridge based on the purpose of the repair. All of the example decision trees are presented for guidance only. Engineering selection of suitable options will still be required even for fully developed decision trees.

Selection of Appropriate Actions

This report included several examples of decision trees that were developed to enable the triggering of preservation and maintenance actions based on NDE data. As shown in the examples, in some cases there is an overlap between the thresholds used to select between different options. In other cases, there are multiple repair options that could be selected based on the condition of the bridge deck. In all the decision trees, engineering evaluation must be completed to enable the selection of the optimal option, often including additional nontechnical considerations within a certain trigger. The engineer must be able to evaluate the advantages and disadvantages of selecting an option. Other considerations, such as the purpose of the repair, the desired service life extension, the lifecycle cost, and traffic disruption associated with implementing each option should also be considered in the decisionmaking process.

CHAPTER 9. ECONOMICS MODELS FOR NDE AND SM FOR PRESERVATION DECISIONMAKING

One of the objectives of this research was to quantify the economics of incorporating NDE and SM methodology into bridge preservation strategies. Due to the lack of SM methods that can be used for bridge decks, the research only focused on the NDE methods. Aligned with the stages in the life of a bridge or bridge deck ranging from new construction to rehabilitation as presented in chapter 7, engineering economics, service life models, deterioration models, and simulation analysis were used to achieve this objective. Based on theoretical use cases and real case studies, the analysis compared the combined cost of NDE and intervention cost to the cost of not collecting NDE data and enacting intervention based on traditional visible and sounding deterioration detection methods to quantify potential "savings" associated with finding specific types of deterioration at an earlier stage. In this chapter, the research subtasks and methodology are presented. In chapter 10, analyses findings are presented to show promising NDE applications and use cases.

Identify NDE Methods Mature and Available to Include in Preservation Decisions

Based on the information collected, the researchers selected the following NDE methods and analysis to illustrate the economics of NDE for deck preservation decisionmaking:

- GPR for cover depth.
- Automatic acoustic sounding for delaminations.
- High-resolution imagery for crack density and width.
- HCP for probability of corrosion.

Conduct Quantitative Analysis on Value and ROI Related to NDE Methods

For the chosen NDE methods, LCCA was used to contrast a timely preservation decision guided by NDE versus do-nothing, LCCA to contrast delaying a preservation action that leads to a costly repair, rehabilitation versus preservation, and captured service life extensions and ROI, as suitable. The findings of these analyses are presented in chapter 10, Use Cases and Analyses.

Develop Analytical Platform with Condition Indicator, Performance Indicator

The research team reported on the impact of the use of NDE on condition measures (e.g., GCR, CS, and HI), LCCA savings, service life extension, and other savings, as suitable. The project team recognized the variability of the NDE techniques that would be suitable and informative in detecting different types of defects and damage at different stages in the deck lifecycle. Recommendations for NDE programs were classified into the following three categories:

- New construction.
- Early to middle-aged structures.
- Bridge deck repair or rehabilitation.

The LCCA also focused on these three stages of the deck lifecycle, illustrating the economic impact of using NDE and making bridge management decisions with the NDE information in comparison to making decisions based on traditional visual inspection or sounding methods. The findings by each category, based on either hypothetical cases or real-life case studies, are presented with the intent to illustrate the value of NDE information in providing a more indepth condition assessment than traditional methods and enabling agencies to make more cost-effective decisions.

Analysis Methodology

The analyses findings presented in chapter 10 used engineering economics, deterioration models, service life models, and Monte Carlo simulation methods to quantify and present the economics of incorporating NDE methods into bridge preservation strategies. A brief background on these methods and the approach used in this research are presented in this section.

Engineering economics provides tools to properly analyze and solve economic problems that are faced by engineers by breaking the most complex problems into components to produce sensible solutions (Newnan, Eschenbach, and Lavelle 2004). Depending on the time duration and nature of the cash flows, different economic metrics, assumptions, and approaches may be suitable.

When economic comparisons are made for asset preservation or treatment plans, it is critical that the analysis duration is kept long enough to capture at least one asset replacement. LCCA is an economic evaluation technique that determines the total cost of owning and operating an asset over a defined period. The most common economic metrics used for LCCA are net present cost (NPC) and equivalent uniform annual cost (EUAC). When lifecycles are kept long enough, while the nature and value of these metrics are different, the suggestions on the cost-effective decision typically do not change, regardless of which metric was preferred in the analysis.

Ideally, when lifecycles with different durations are compared, EUAC should be used as the metric of choice, since it can be used when comparing lifecycles of varying durations (Sinha and Labi 2011). EUAC gives the yearly cost of owning and operating an asset under given cash flows and assumes that the same preservation plan is repeated in subsequent lifecycles. EUAC is also reasonable to calculate and uses NPC for a common duration for all alternatives when the selected cash flows represent full lifecycle treatments for all alternatives. Ideally, NPC should be calculated for the least common multiple of all compared lifecycle durations.

Another useful and frequently used method in engineering economic analysis is Monte Carlo simulation. A Monte Carlo simulation is a model used to predict the probability of a variety of outcomes when the potential for random variables is present, to explain the impact of risk and uncertainty in predictions (Mooney 1997). For most of the LCCA presented here, Monte Carlo simulation was used when random variables were present (e.g., service life estimates or NDE cost) to address the potential sensitivity of the results to that variability.

Both nominal and real interest rates can be used for cost-effectiveness analysis, but suitable assumptions and parameter values should be used to properly incorporate them (Office of Management and Budget 2022). The nominal interest rate is not adjusted to remove the effects of actual or expected inflation and, therefore, should be used in conjunction with expected inflation.

The real interest rate has been adjusted to remove the effect of expected or actual inflation. Real interest rates can be approximated by subtracting the expected or actual inflation rate from a nominal interest rate. In most of the LCCA presented a current nominal interest rate of 2.6 percent is suitable for long-term analysis with a conservative inflation for nonbuilding infrastructure inflation at 2 percent (historical average 1–4 percent) (2022) were used.

While the most likely sequence of treatments was incorporated into the LCCA, the hypothetical examples are best assumptions and are not cast in stone. When real-life case studies were presented, the treatment timing and costs were kept consistent with the analysis and data available in reports or based on agency input. LCCA heavily depends on custom treatment effectiveness and deterioration models, which are research areas with significant needs in the United States. Data-driven estimates and models were used for most LCCA, and hypothetical cases were tailored to available models to present analysis results that are based on vetted research or data.

Bridge management decisions made by transportation agencies almost always focus on agency costs. While alternative costs (e.g., user costs, social costs, environmental impact costs) sometimes are incorporated into cost-effectiveness models, the analysis presented here specifically focused on agency costs to provide a realistic comparison.

CHAPTER 10. USE CASES AND ANALYSES

NDE may be useful to support bridge preservation decisionmaking at several stages in the life of a bridge or bridge deck ranging from new construction to rehabilitation. The following are some of the more promising applications that may already be in use by some agencies.

NEW CONSTRUCTION

GPR to Map the Location and Cover Depth of the Reinforcement

Variations from the specified concrete cover can have implications for both the durability and structural performance of the deck. GPR can be used to map the location and cover depth of the reinforcement and to select the most cost-effective decision and help set up specific bridge preservation plans. Minimum lifecycle cost (LCC) will change based on the treatment and whether the treatment was the right choice at that time, given the cover depth. Here, we present LCCA results of treatment decisions made based on GPR data and known cover depth versus decisions made without NDE input assuming sufficient cover depth is available. The service life estimates by cover depth, given in table 35, are based on deck service life prediction models. For this example, it was assumed that the service life of a given concrete bridge deck is controlled by chloride-induced corrosion due to the application of deicing chemicals during the winter. Chloride-induced corrosion of a generic bridge deck was modeled using a mechanistic service life modeling software. The assumptions for material properties and exposure follow a recent research project for Iowa DOT, TR-782 *Guide to Remediate Bridge Deck Cracking*. In addition, cost information related to maintenance options was obtained from the same report (ElBatanouny et al. 2022).

GPR cost is based on the agency interviews (Chapter 4) and was used as a variable with a range of \$0.08–\$0.2 per SF for Monte Carlo simulation. Service life was also kept variable, ± 20 percent for all cases. Monte Carlo Simulation was done for and converged at 1,000 runs. The EUAC values are calculated for a deck area of 6,600 SF The cost values were inflated on a construction inflation rate of 2 percent and a 2.6 percent nominal interest rate was used for compound interest calculations.

Table 35. Effect of preservation treatments of uncracked generic bridge deck with various assumed concrete cover on service life and cost.

Treatment Alternative	Cover Depth					Cost ($/SY)
	2.5 inches	2.0 inches	1.5 inches	1.0 inches	0.5 inches	
Uncracked deck (years)	47	35	26	21	18	900 (replace)
Penetrating sealer (years)	49	37	28	23	19	9
Thin polymer overlay (years)	65	52	42	37	35	66
Premixed polymer overlay (years)	75	62	53	45	39	136

The LCCA results are presented in table 36, which has colors indicating the magnitude to make it easier to see the high and low costs, but the costs can also be compared in the magnitude of values. The EUAC values for uncracked deck service life present the baseline for comparison, representing no NDE for quality control and a deck replacement at the end of service life. For all other modeling cases, it is assumed that GPR was used right after construction, and the selected treatment was applied. These EUAC values include the GPR cost at the beginning of the service life, in addition to the treatment cost and a deck replacement at the end of the service life. All EUAC values can be interpreted as the yearly cost of owning and operating an average bridge deck based on the modeled lifecycle. Knowing the exact cover depth enables the agency to either work with the contractor to satisfy a minimum cover depth requirement or select an immediate treatment that will remedy the insufficient cover depth in the most cost-effective way. For example, with the assumption of a 2.0-inch cover depth, replacing the deck at the end of service life with a $24,000 per year cost may be reasonable for an agency. However, if the real cover depth is 1.5 inches and is identified by GPR data, the same agency may decide to go for a TPO or a PPC and forego a penetrating sealer or do-nothing to save $7,000–8,000 per year. Replacing the deck without any preservation treatments at the end of service life is the least cost-effective option regardless of the accurate cover depth. The hypothetical case presented here illustrates the cost-effectiveness of using GPR as a construction quality tool and shows how negligible the cost of GPR is in comparison to LCC savings that can be realized.

Table 36. EUAC of generic bridge deck with various assumed concrete cover.

Treatment Alternative	**Cover Depth**				
	2.5 inches	**2.0 inches**	**1.5 inches**	**1.0 inch**	**0.5 inch**
Uncracked deck	$18,796	$24,096	$30,738	$37,742	$43,607
Penetrating sealer*	$18,573	$23,552	$29,308	$35,382	$41,034
TPO*	$16,343	$19,321	$22,818	$25,319	$26,429
Premixed polymer overlay*	$16,296	$18,519	$20,864	$23,427	$26,189

*Includes NDE cost.

High-Resolution Imagery for Crack Density and Width

Cracks in concrete infrastructure are undesirable because they facilitate the ingress of water and aggressive ions that cause or accelerate material degradation and thereby increase maintenance needs and costs. As a result, many infrastructure-owning agencies specify repairs to fill in or otherwise address cracking, such as crack-chasing or flood-coating with a gravity-fed polymer, i.e., a low-viscosity epoxy or HMWM. However, the repairs or treatments suitable for each situation depend on a variety of variables, including crack features. For example, application of an HMWM is preferred for deep, narrow cracks on horizontal surfaces, while epoxy is preferred for wider cracks because epoxy is often thicker than methacrylate and cannot penetrate cracks as easily. As another example, area treatments such as flood coats or overlays are preferred over crack-chasing methods for areas with high crack density because they are often more economical in these scenarios than crack-chasing repairs. Therefore, accurate characterization of the cracking scenario is important for selecting technically appropriate and economical maintenance, and high-resolution imagery that captures crack width and density more quickly or accurately can help decisionmakers reach more economical repair or treatment decisions.

As an example of a decisionmaking process where crack inspection by high-resolution imagery can be advantageous, a decision matrix for selecting a crack repair or treatment to address cracking on bridge decks is shown in table 37. The matrix shown has been adapted from the decision trees developed in project TR-782 *Guide to Remediate Bridge Deck Cracking*, in which developed decision trees for selecting repairs or treatments for cracked bridge decks that are between 0 and 2 yr and located in Iowa (ElBatanouny et al. 2022). The decision trees rely on bridge deck age and crack width, density, and depth to recommend repairs and treatments. In the study, "crack density" was defined as the total cracked length within a unit area, expressed as ft/ft^2. The decision trees provide a list of viable crack repairs or deck treatments with supplemental service life benefit, initial cost, and lifecycle cost information such that the user can make an informed decision. Table 37 was modified from the original such that the equivalent uniform annual cost is shown instead of the lifecycle cost, which was expressed as the present value (PV) in the study.

Table 37. Data-driven decision table for selecting repairs or treatments to address cracked bridge decks between 0 and 2 yr and located in Iowa (ElBatanouny et al. 2022).[3]

Crack Density (ft/ft^2)	Remediation Options	Crack Width Limit[1]	Initial Cost ($/SY)	EUAC ($/SY)	EUAC with NDE ($/SY)	Time-to-5 Percent Distress Compared to Do Nothing (yr)	Time-to-20 Percent Distress Compared to Do Nothing (yr)
<0.10	Do nothing (T_5=34; T_{20} =46)	Up to 10 mils	0	43.09	43.09	0	0
	Penetrating sealer	Up to 15 mils	8.6	42.30	42.38	+3	+4
	Penetrating sealer + reapplication	Up to 15 mils	22.3[1]	42.66[1]	42.75[1]	+6	+5
	Crack fill	Up to 40 mils	0.8[2]	42.81[2]	42.90[2]	+1	+1
	Flood coat	Up to 30 mils	24.5	43.32	43.40	+3	+3
	TPO	Up to 40 mils	66.4	41.93	42.01	+16	+19
	Premixed polymer concrete overlay	Up to 40 mils	135.9	43.75	43.82	+27	+29

Crack Density (ft/ft^2)	Remediation Options	Crack Width Limit[1]	Initial Cost ($/SY)	EUAC ($/SY)	EUAC with NDE ($/SY)	Time-to-5 Percent Distress Compared to Do Nothing (yr)	Time-to-20 Percent Distress Compared to Do Nothing (yr)
0.10 to 0.22	Do nothing (T_5=27; T_{20}=44)	Up to 10 mils	0	43.80	43.80	0	0
	Penetrating sealer	Up to 15 mils	8.6	43.18	43.26	+3	+3
	Penetrating sealer + reapplication	Up to 15 mils	22.3[1]	43.21[1]	43.30[1]	+6	+5
	Flood coat	Up to 30 mils	24.5	43.32	43.40	+10	+5
	TPO	Up to 40 mils	66.4	42.38	42.46	+17	+18
	Premixed polymer concrete overlay	Up to 40 mils	135.9	44.05	44.13	+28	+28
0.22 to 0.37	Do nothing (T_5=19; T_{20}=40)	Up to 10 mils	0	45.47	45.47	0	0
	Penetrating sealer	Up to 15 mils	8.6	44.60	44.69	+2	+3
	Penetrating sealer + reapplication	Up to 15 mils	22.31	44.511	44.601	+5	+5
	Flood coat	Up to 30 mils	24.5	43.62	43.70	+17	+8
	Thin polymer overlay	Up to 40 mils	66.4	42.90	42.98	+21	+19
	Premixed polymer concrete overlay	Up to 40 mils	135.9	44.53	44.61	+33	+28
0.37 <	Do nothing (T_5=17; T_{20}=28)	Up to 10 mils	0	54.01	54.01	0	0
	Penetrating sealer	Up to 15 mils	8.6	51.66	51.76	+3	+3

Crack Density (ft/ft^2)	Remediation Options	Crack Width Limit[1]	Initial Cost ($/SY)	EUAC ($/SY)	EUAC with NDE ($/SY)	Time-to-5 Percent Distress Compared to Do Nothing (yr)	Time-to-20 Percent Distress Compared to Do Nothing (yr)
	Penetrating sealer + reapplication	Up to 15 mils	22.31	50.821	50.921	+5	+5
	Flood coat	Up to 30 mils	24.5	45.38	45.47	+13	+15
	TPO	Up to 40 mils	66.4	45.93	46.01	+21	+19
	Premixed polymer concrete overlay	Up to 40 mils	135.9	45.98	46.06	+29	+31

[1] Calculation assumes 3 reapplications at 4-yr intervals. The cost of future applications is included in the value.
[2] Price per square yard assuming a crack density of 0.10 ft/ft^2.
[3] Modified to express lifecycle cost as EUAC instead of PV.

The EUAC was calculated for each scenario by multiplying the lifecycle cost expressed as the PV by the capital recovery factor (CRF) as shown by the following equation:

$$EUAC = PV \times CRF \tag{5}$$

The capital recovery factor is defined by the following equation, in which *i* is the discount rate and *n* is the service life:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{6}$$

The discount rate was assumed to be 4 percent, as was assumed in the previous project TR-782. The service life, defined as the time at which 20 percent of the deck area was distressed in TR-782, varied between each scenario considered. For example, the service life estimated for an Iowa deck with a crack density less than 0.10 ft/ft^2 is approximately 46 yr, and as such the CRF is 0.048, while the service life for an Iowa deck with a crack density between 0.22 and 0.37 ft/ft^2 is approximately 40 yr, which corresponds to a CRF of 0.051. Because the PV presented in TR-782 was for an analysis period of 100 yr, all subsequent deck replacements or subsequent work after the service life were subtracted from the present value (PV) when calculating the EUAC. The EUAC was calculated without and with applying high-resolution imagery, which was assumed to cost $0.20/SF. As indicated in the table, the increase due to adding NDE is minimal compared to the construction cost, and, as such, any repair decisions based on the NDE results have significant benefits on the overall lifecycle cost.

Following the example, to make an informed decision, the Iowa bridge owner needs to know the crack density and the crack width. Bridge owners will be aware of deck cracking since it is required to be reported, if present, in the biennial inspections for the NBI. However, the crack characteristics, including density and width, are not typically characterized in these inspections. Obtaining these data through traditional methods, i.e., crack mapping conducted by either a contractor or in-house forces is undesirable because it requires the bridge deck to be closed for inspection and may be infeasible due to limited funds or forces. Crack mapping is a relatively time-intensive process, especially with increasing crack density. Therefore, the typical bridge owner may only have a qualitative understanding of the cracking present and, in the absence of density and width data, may choose a default option, such as “do nothing” if the cracking is perceived as minor or placement of a robust overlay if the cracking appears to be severe.

However, the use of high-resolution imagery decreases the time and labor required and the need for traffic closures, and this technology can obtain both crack density and width. Continuing with the example, based on table 37, an Iowa bridge owner who knows that their bridge deck has a crack density of 0.09 ft/ft^2 and crack widths ranging from 15 to 25 mils would likely choose to apply a thin polymer overlay, which has the smallest EUAC and would result in a decrease in the EUAC of $1.16/SY compared to the “do nothing” option. However, if the initial cost of the thin polymer overlay is too high, the owner may choose to conduct crack-chasing, which would reduce the EUAC by $0.28/SY compared to the “do nothing” option. Due to the use of high-resolution imagery, the owner would know that even though the cracking appears to be “minor” based on the cracking quantity, and a one-time penetrating sealer treatment results in the second smallest EUAC with a decrease of $0.79/SY, a penetrating sealer would be an ineffective treatment for the crack widths present.

The example given considers the crack repairs and deck treatments considered by the Iowa DOT, reflects cost savings based largely on data from Midwest States and presents service life estimates specific to bridge decks constructed following the policies and practices used in Iowa and having similar exposure conditions. The specific treatments presented under each scenario, approximate costs, and estimated service life benefits would vary between localities. However, the inclusion of crack density and width data from high-resolution imagery in the decisionmaking process can prevent the selection of inappropriate maintenance techniques or materials and result in cost savings.

VDOT New Decks

VDOT adopted NDE methods, specifically eddy current pulse induction (i.e., pachometer) and then GPR, as tools for quality assurance in new deck construction. The objective was screening to determine that clear concrete cover over top mat reinforcement was achieved. The following case studies discuss the evolution of this practice.

Beginning in the 1990s, VDOT road and bridge specifications required clear concrete cover for bridge decks to be 2.0 inches with a tolerance of –0/+½ inches. Following this rule, VDOT’s practice has been for contractors to be eligible for payment for up to one-half inch additional concrete placed beyond the specified thickness of the deck, with the intent that the additional thickness would ensure adequate cover depth is achieved.

Rt 340 bridge

In 2009, VDOT completed construction of the reinforced concrete deck of a 9-span continuous multigirder bridge. The deck was configured to carry 4 lanes of traffic, two in each direction, and included a flush median, full shoulders, and sidewalks. The sequence of deck construction was in two stages with a longitudinal closure pour.

VDOT construction inspection personnel used pachometers to conduct "spot-checks" of cover depth to verify that requirements had been met. After one of the placements, spot checks indicated areas of potentially inadequate cover. To avoid coring for verification throughout the suspect areas, a ground-coupled, cart-based GPR system was deployed to obtain line scans of the deck. Line scans were conducted longitudinally along the 1,068-ft length of the bridge and distributed laterally at 5-ft intervals across the second stage and closure portion of the deck. The target was to determine the cover over the transverse top mat bars, which were oriented most closely to the deck surface. Results are shown in figure 51, which contrasts pachometer measurements in spans 1 and 2 to GPR measurements in spans 1 and 2 (top two plots), and then shows GPR measurements of spans 3 through 8 (span 9 was also measured but is omitted). A review of statistical cover depth results indicated that spans 1 and 2 were highly variable and, in some cases, substantially less than specified. Although the average cover was 2 and one-eighths inches, nearly 35 percent of cover depths measured in span A and 18 percent in spans 1 and 2 together were below 2 inches, with a minimum of 1.4 inches. To resolve the deficiency, the contractor installed a thin epoxy polymer overlay on the first two spans of the southbound lanes and closure region (stage 2) totaling approximately 9,300 ft^2.

The NDE work was performed by VDOT in-house personnel with in-house equipment; labor was approximately 1 day (8 h) in the field + 1 d (8 h) of postprocessing + 4 h administrative. Using a labor raw unit rate of $36.00 and an assumed overhead multiplier of 2.5, the loaded hourly rate would be about $126/h. Twenty hours of effort for the testing would be estimated at $2,520. Assuming an equipment cost recovery rate of $300/d and including travel to the project site of $94, the cost of NDE is estimated at $2,914. If work were outsourced, assuming the same base costs, an additional 10 percent profit would bring the total to $3,205.

For the LCCA to contrast the economic impact of using and making decisions based on NDE, three cases are presented and modeled:

Case 1: A TPO is applied based on the NDE information, and the deck is replaced at the end of service life (actual case).

Case 2: No NDE is done, and insufficient cover depth is not noticed. A premature mill and overlay are done in 10 yr, followed by a deck replacement at the end of service life (hypothetical case).

Case 3: No NDE is done, and insufficient cover depth is not noticed. A premature deck replacement is done at the end of service life (hypothetical case).

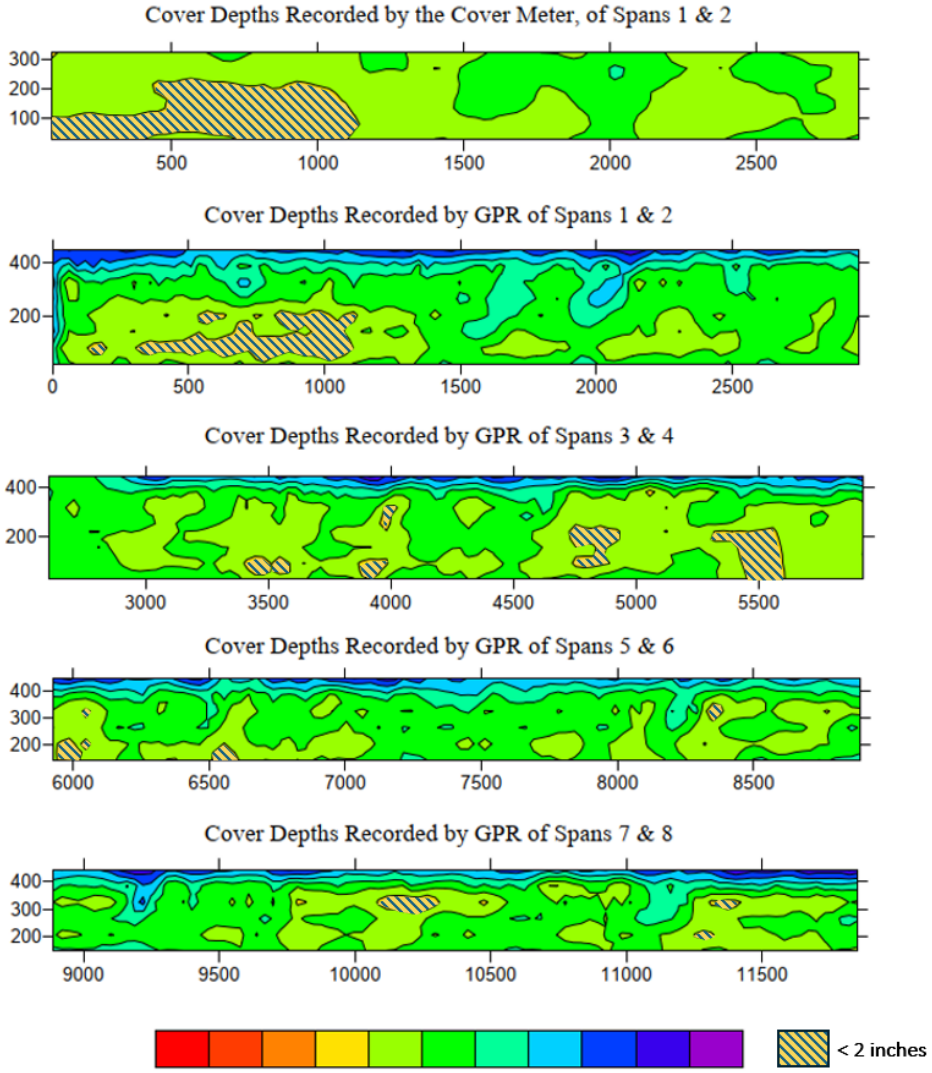


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Figure 51. Plan. Pachometer (top) and GPR cover depth survey (inches).

Parameter values used for the engineering economic analyses and Monte Carlo simulation are presented in table 38. Case 1 presents the potential lifecycle for the actual case study, while cases 2 and 3 are chosen as the most likely lifecycles when NDE information is not available. The use of NDE and the resulting lifecycle results in the most cost-effective lifecycle with more than $10,000/yr savings over the deck lifecycle.

Table 38. Parameter values for the LCCA cases for Rt 340 bridge.

Parameter	Case 1	Case 2	Case 3
Treatment Cost	\$4.21/SF	\$51.4/SF	\$105/SF
NDE Cost	\$3,205	0	0
Service Life*	42 ± 20 percent year	53 ± 20 percent year	26 ± 20 percent year
Mean EUAC**	\$31,975	\$42,033	\$45,093

*Based on service life estimates based on cover depth for Iowa DOT following assumptions in TR-782 *Guide to Remediate Bridge Deck Cracking* and 1.5-inches cover depth (ElBatanouny et al. 2022).
**Monte Carlo simulation with 1,000 runs.

Rt 774 Bridge

In 2009, for a newly constructed 2-span, 2-lane bridge on State route 774, initial checks by construction inspectors suggested as-placed concrete clear cover on the reinforced concrete deck was inadequate. GPR line-scans were conducted at 5-ft intervals along the 164-ft long deck to detect the top transverse layer of steel bars. Figure 52 shows the resulting cover depth distribution wherein more than 10 percent of areas had less than 2 inches cover, with minimum cover measured at approximately 1.5 inches. In this case, in lieu of drilling holes for verification, GPR results were calibrated against spot pachometer readings. The contractor questioned the validity of the measurements and requested specific depth measurements and locations for verification. Drilling to physically measure the bar depths at these locations revealed that reported GPR results were accurate to within one-eighth inch. The contractor resolved the deficient cover by providing a thin epoxy polymer concrete overlay over the 4,587-ft^2 deck to restore the corrosion protection lost by insufficient cover.

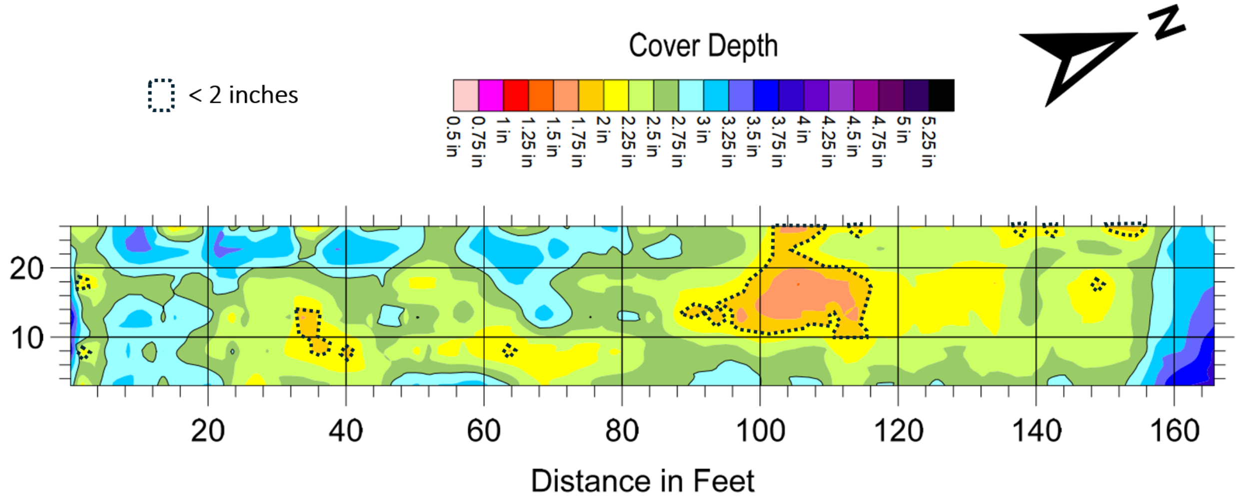

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Figure 52. Plan. Rt 774 bridge GPR cover depth survey.

The NDE work was performed by VDOT in-house personnel with in-house equipment; labor was approximately 8 h in the field, 4 h postprocessing, and 4 h administrative (\$2,016). Assuming an equipment cost recovery rate of \$300/d and including travel to the project site of \$60, the cost of NDE would be estimated at \$2,376 (\$2,614 with profit).

For the LCCA, the following three cases are presented and modeled, similar to the Rt 340 bridge:

Case 1: A TPO is applied based on the NDE information, and the deck is replaced at the end of service life (actual case).

Case 2: No NDE is done, and insufficient cover depth is not noticed. A premature mill and overlay are done in 10 yr, followed by a deck replacement at the end of service life (hypothetical case).

Case 3: No NDE is done, and insufficient cover depth is not noticed. A premature deck replacement is done at the end of service life (hypothetical case).

Parameter values used for the engineering economic analyses and Monte Carlo simulation are presented in table 39. Case 1 presents the potential lifecycle for the actual case study, while cases 2 and 3 are chosen as the most likely lifecycles when NDE information is not available. The use of NDE and the resulting lifecycle result in the most cost-effective lifecycle, with more than $3,000/yr savings over the deck lifecycle.

Table 39. Parameter values for the LCCA cases for Rt 340 bridge.

Parameter	Case 1	Case 2	Case 3
Treatment cost	$4.21/SF	$51.4/SF	$105/SF
NDE cost	$2,614	0	0
Service life*	42 ± 20 percent year	53 ± 20 percent year	26 ± 20 percent year
Mean EUAC**	$15,773	$18,925	$22,313

*Based on service life estimates based on cover depth for Iowa and 1.5-inch cover depth.
**Monte Carlo simulation with 1,000 runs.

Rt 130 Bridge

A third event occurred in 2010, involving a bridge on a 5-span river crossing along Rt 130. The deck was constructed in a single stage of 9 concrete pours and configured to carry 2 lanes of opposing traffic plus shoulders. The bridge deck was placed by the same contractor who had constructed the Rt 774 bridge. A GPR survey, consisting of longitudinal line-scans conducted at 5-ft intervals, was performed like the previous surveys and calibrated against pachometer readings. In this case, the cover depths were found to substantially comply with the specifications and no adjustments were necessary.

This case is different from the first two examples because it presents confirmation of the sufficient cover depth. While there is not a decision based on the NDE information here that can be modeled in an LCCA, VDOT's confirmation of the sufficient cover depth provides the agency with information that can be used in future decisions. Also, this case demonstrated that NDE, used for this purpose, provides the contractor with the motivation to ensure that the required cover depths are achieved to avoid the possibility of having to take costly remedial measures.

I-81 Bridge

A contrasting case involved the first of two stages of deck construction for a single-span steel multigirder bridge designed to carry 3 lanes and two shoulders of I-81 over a local road. An inquiry was made by construction inspectors after "spot-check" pachometer measurements were unable to detect top mat reinforcement. Records of manual probing during the placement of fresh concrete indicated that the deck thickness averaged 9 inches. A series of GPR line-scans were conducted with cart-based, ground-coupled GPR at 2-ft intervals along the 125-ft long deck. GPR measurements were correlated with the pachometer and core measurements of the cover. The resulting average cover depth was shown to be 4 in, with areas of the deck exhibiting cover depths up to 6 inches (see figure 53), particularly near the exterior cantilevered edge of the deck supporting the jersey-style barrier rail. The implication in this instance was that the top mat reinforcement had been pushed down near the elevation of the bottom reinforcement, reducing the structural effective depth of the section. Thus, with top mat steel placed below the tensile region of the deck, its capacity to resist negative moments from gravitational live loads and dead load of the deck and to support the barrier in the instance of a vehicle impact was compromised. As a result, the contractor was required to remove and replace the stage 1 deck to ensure structural capacity was as designed. A GPR survey of the replaced section showed clear cover met project requirements.

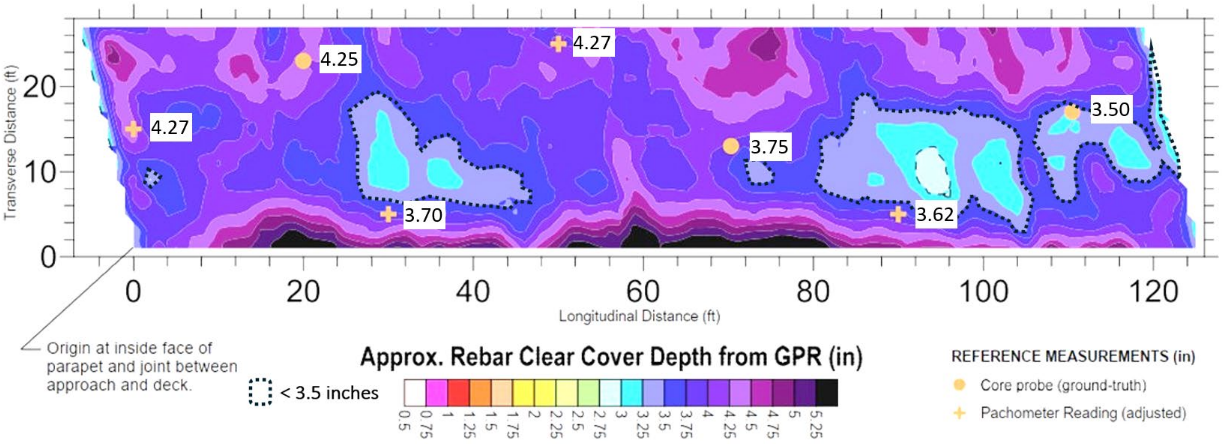

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Figure 53. Plan. I-81 bridge GPR survey of cover depths.

In this case, approximately $3,000 spent on the NDE helped the agency identify a structural deficiency that could have led to expensive reconstruction costs at a very early age. The contractor's removal and replacement of the deck is estimated at $630,000. Identifying this quality issue and the subsequent fix by the contractor provided the agency with more than $625,000 in net savings.

As a result of these and similar cases, VDOT subsequently updated its guidance to incorporate NDE as a standard method for quality assurance of reinforcement cover depths. Current VDOT *Road and Bridge Specification*s, Section 404.04–Bridge Deck Construction, requires cover depth surveys to be performed by the contractor after deck concrete placement (VDOT 2020). Cover measurements, to the nearest one-eighth-inch accuracy, are to be distributed uniformly over the deck area in lots, and measurement frequency is ≥10 measurements per 1,500 SF with a maximum spacing of 20 ft transversely and 15 ft longitudinally between measurements. The specification does not indicate the method of measurement but eddy current or GPR are both considered acceptable methods. Per the specification, "The depth of cover will be deemed acceptable for any lot if the average depth of cover is within ½ inch (either greater or less) of the clear cover required by the plans or specifications and at least 90 percent of the cover measurements within the lot are within .80 inch of the required cover" (VDOT 2020). For areas found to have inadequate cover, the contractor is required to place an epoxy concrete overlay over the deficient area at no additional cost to VDOT.

Early- to Middle-Aged Structures

Typical Wisconsin Bridge

For early- to middle-aged structures, using NDE can help identify the actual damage or level of deterioration and inform the selection of the right treatment. In visual inspections, there is inherent subjectivity and variation. Therefore, visual inspections themselves are not sufficient to select the right treatment for decks at certain condition ratings. As presented in the decision trees in chapter 8, data on percent delamination, percent spalls, and patches, or percent areas of high attenuation acquired by using technologies such as high-speed automated acoustic sounding or high-speed infrared thermography, high-speed high-resolution imagery or high-speed GPR can help agencies differentiate the relative damage in their bridge decks that may have good or fair deck condition ratings based on visual inspections.

Preservation treatments, such as TPOs, provide an option with a lower lifecycle cost to extend deck service lives for decks that are in relatively good condition and do not have substantial damage or structural issues. For decks that do have such damage and wear, rehabilitation options such as a deeper concrete overlay provide a better lifecycle cost. When agencies are better informed of the damage level, they can use improved estimates of service life and select the right deck treatments that provide the most cost-efficient option.

In this hypothetical example, we have a bridge in Wisconsin, which was given a deck NBI rating of 7 based on a traditional visual inspection. The use of NDE (HCP) shows more damage to the deck and indicates that the deck NBI rating should be dropped to 6. When considering repair options, particularly overlays, the agency would go with a TPO at a deck rating of 7. For the actual deck NBI rating of 6, the agency would prefer a more substantial concrete overlay. Here, we will contrast the economic impact of a wrong TPO decision with the concrete overlay option.

For the analysis, median time-in-state (time spent in an NBI rating, TIS) observations based on Wisconsin data and analysis from a research project are used (Bektas et al. 2020). Table 40 and table 41 present the median time spent in deck NBI ratings and their standard deviation for decks that received thin polymer and concrete overlays at deck rating 6, respectively. For the Monte Carlo simulation, time in state (TIS) values were simulated within a range described by [(Mean TIS -Standard Deviation of TIS), (Mean TIS + Standard Deviation of TIS)], within which approximately 68 percent of the potential TIS values lie, based on the 68-95-99.7 rule.

Lifecycle profiles were started at a deck rating 9 as a new deck. The TPO was assumed to have been applied at the end of the TIS of deck rating 7, extending the time spent in deck rating 6 by 5.7 yr. Since WisDOT does not apply a TPO for decks at rating 6, this life extension is based on the average time extension for TPOs applied at rating 7, based on historic Wisconsin data. It can be argued that a TPO for a deck that is at a rating of 6 would not really extend service life. Here, the life extension for the decision without NDE input is introduced to the analysis to keep the analysis conservative. For the concrete overlay, the overlay was assumed to have been applied at the end of TIS for deck rating 6, based on Wisconsin data. A typical concrete overlay at rating 6 increases the deck rating to a 7, which then drops to another 6 in time. Before the overlays are applied, TIS ranges for untreated decks are used. Following the overlay, the TIS ranges that reflect the increased TIS ranges after treatment were used in the simulation for the concrete overlay.

EUAC was chosen as the economic measure for comparison since it can be used regardless of the number of years in the lifecycle profiles. The assumption here is that all lifecycle profiles portray a deck in service within a GCR range of 9 to 4.

Treatment costs were calculated based on the cost values provided by the WisDOT Bureau of Structures and included estimated project costs that included secondary items and mobilization. All costs were calculated for a deck of 6,600 SF, the median deck area for State-owned Wisconsin bridges according to 2019 NBI data. The cost values were then inflated based on a construction inflation rate of 2 percent and on the cumulative TIS values at that point in the lifecycle. The future net worth of all treatment costs was then calculated at the end of the lifecycle profile based on a 2.6 percent nominal interest rate. Finally, EUAC values were calculated based on the sum of the TIS for the lifecycle profile. For the concrete overlay, the cost of NDE (HCP with lane closure) was included at the beginning of the second deck rating of 7 (7-II). The TIS value for rating 6 in table 40 is selected to be conservative and to keep the EUAC for the TPO as low as possible for a comparison with the EUAC for the concrete overlay with NDE cost.

Table 40. TIS by deck condition rating for a TPO.

Deck NBI Rating	Mean (yr)	Std. Dev. (yr)	Lower Limit (yr)	Upper Limit (yr)
9	2.7	1.4	1.3	4.1
8	5.1	4.5	0.6	9.6
7	6.5	5.3	1.2	11.8
6*	10.8	4.4	6.4	15.2
5	4.3	3.5	0.8	7.8
4	3.4	2.7	0.7	6.1

*Additional 5.7 yr based on epoxy overlay application at GCR 7.
Std. Dev. = standard deviation.

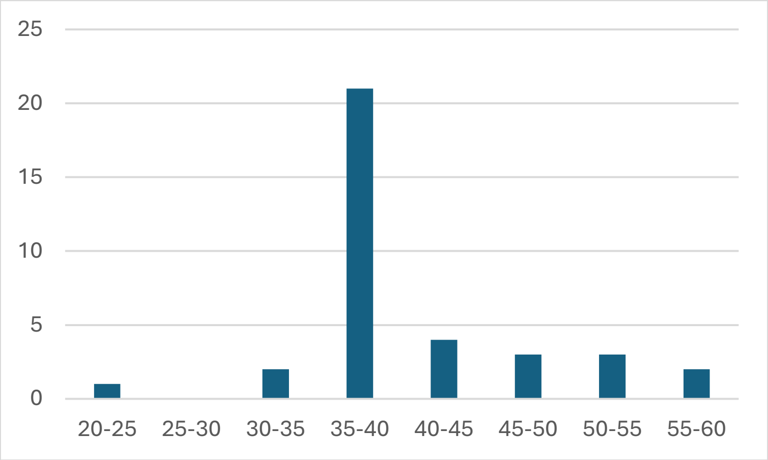
The simulations appear to have converged (i.e., experienced minimal changes to mean and median EUAC with more runs) at approximately 200 repetitions, but 1,000 runs were performed to be on the safe side. The mean EUAC for a lifecycle with the TPO (No NDE) is $28,091 while the mean EUAC for a lifecycle with the concrete overlay (with NDE) is $25,862 (table 41). For a deck with a 45-yr lifecycle, the net present savings from using NDE and choosing the right treatment option would be approximately $59,000.

Table 41. TIS by deck condition rating for a concrete overlay.

Deck NBI Rating	Mean (yr)	Std. Dev. (yr)	Lower Limit (yr)	Upper Limit (yr)
9	2.7	1.4	1.3	4.1
8	5.1	4.5	0.6	9.6
7	6.5	5.3	1.2	11.8
6	5.1	4.4	0.7	9.5
7-II	9.1	6.3	2.8	15.4
6-II	6.4	4.5	1.9	10.9
5	5.8	3.4	2.4	9.2
4	5.1	3.3	1.8	8.4

Utah I–80 Corridor Study

A project completed in 2022 for the Utah DOT (UDOT) involved the assessment of 36 highway bridges that carry portions of mainline I–80 or intersecting primary roadways, ramps, and overpasses extending from milepost 104.2 to 118.5 near Salt Lake City International Airport. The subject bridges, constructed between 1963 and 2001, include simple and continuous prestressed concrete and steel girder superstructures supporting reinforced concrete decks. At the time of testing, 8 were 49–58 yr old, 27 were 33–41 yr old, and 1 was 20 yr old (figure 54).



Source: FHWA.

Figure 54. Chart. Age distribution of UDOT I–80 corridor study bridges.

The purpose of the study was to develop a 20-yr Corridor Asset Management Plan for the group of bridges to recommend preservation actions and bundle them into appropriate future contracts. To inform the management plan, the team reviewed available design, inspection, and maintenance records (desk study), followed by field visual assessment. Based on the findings of this review, a testing plan was developed for each bridge. The project leveraged NDE where possible to increase the speed of data acquisition and provide detailed quantification of conditions. NDE methods employed varied according to the superstructure and deck-wearing surface types. Most of the bridges still had the original bridge decks except for five I–80 mainline bridges built from 1963–1967, for which decks were replaced in 1989, and three Redwood Road bridges built in 1972 that had decks replaced in 2006–2007. Wearing surfaces for the bridges were as follows:

- Bare concrete (15).
- TPO (2).
- HMA overlay only (16).
- HMA over TBPO (3).
- Polyester concrete overlay (1).

Ten of the decks have stay-in-place metal forms, three of which also have HMA covering the decks, and one of which has both TPO and HMA. The presence of SIPs makes inspection of the underside of the deck difficult. Similarly, the presence of an overlay obscures the top surface of the structural deck, which complicates visual inspection.

NDE methods can be used to investigate the subsurface condition within or below an overlay, but the material and geometric properties of the various overlays influence which NDE method(s) may be applicable. For example, HMA, TPO, or polyester overlays are all composed of binder systems that are dielectric, thereby limiting the application of methods that rely on the conduction of electrical current, such as HCP or ER. However, GPR, which is based on the propagation of high-frequency electromagnetic waves, does have the ability to permeate these dielectric materials. HMA poses a limitation on the use of sonic and ultrasonic methods as the viscoelastic asphalt binder media tend to rapidly attenuate stress waves, particularly as temperatures increase.

IR can be applied to the various overlays to detect embedded anomalies that disrupt the conduct of heat into and through the element; however instantaneous, or static, IR is very sensitive to the time of measurement, which must be carefully coordinated with a time of significant thermal transfer, typically related to diurnal temperature changes, to provide an appropriate thermal contrast of sound versus unsound regions. Static IR is also effectively limited to indications of relatively shallow discontinuities that are filled with a media (typically air or water) with substantially different thermal conductivity than the substrate in which they occur. A time-lapse form of IR, called ultra-time domain infrared thermography, captures repeated IR responses over a period of thermal change and analyzes not just the instantaneous contrast in temperatures, but the cumulative rates of thermal change across a field of view over the observation period. The method permits the identification of deeper thermal anomalies (defects) and mitigates the extreme sensitivity to the timing of IR measurement by repeated measurement over a period of thermal transition. While some methods can be conducted on the underside of decks, the presence of SIPs, with the potential for voids between the forms and concrete, as well as difficulties in access for methods that require direct contact, make such surveys difficult or ineffective. IR may be a useful noncontact method, subject to the limitations previously outlined.

The I–80 Corridor study employed an array of NDE methods to evaluate the condition of the bridge decks, including automated acoustic sounding, vehicle-based GPR, vehicle-based and drone-based high-resolution imagery, push-cart-based GPR, static IR, and IR-UTD. Multiple methods were applied to each deck, but the selection of methods for a given deck was dependent upon the deck and wearing surface configurations. In general, HRI, GPR, IR, and automated sounding were applied to bare and TPO decks. For HMA and polyester-covered decks, automated acoustic sounding was omitted and IR-UTD was applied instead. The project also explored the use of IR-UTD on deck undersides that did not have SIPs.

Analysis of the ACS, IR, HRI, and IR-UTD were interpreted as indications of manifest (i.e., already existing) damage typically resulting from either corrosion-related delamination and spalling or possibly debonding of an existing overlay. Analysis of attenuation of GPR signals was used as a predictive method to assess whether corrosion activity might be supported or active in the deck. Because GPR is sensitive to the presence of moisture, ions such as chloride, and corrosion products, the attenuation response can be interpreted as a predictor of corrosion-related damage. NDE and visual assessment methods were supplemented with concrete core samples that were used to generate chloride concentration profiles. GPR was also used to determine if voids (caused by subgrade settlement or erosion) had occurred under concrete approach slabs, and exploratory cores were drilled through the approach slabs to confirm whether suspected voids were present.

The relative areas of indicated damage from the NDE methods were compiled, and responses from the different methods were compared to assess the overall condition of the deck and overlay. Using the damage-oriented outputs, areas of the deck were characterized as good, fair, or poor, analogous, but not directly equivalent, to AASHTO’s condition states CS 1, CS 2, and CS 3/CS 4 derived from routine safety inspections (AASHTO 2022). Table 42 presents a comparison of the conditions measured by NDE and testing versus the reported conditions from inspections as of 2018, with a determination of whether the results of testing confirmed the reported condition, were less severe (better) than the reported condition or were more severe (worse) than the reported condition from the routine inspections for each bridge.

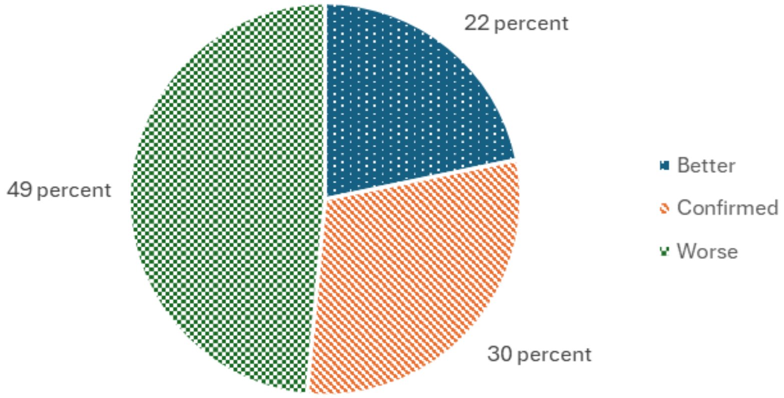
Table 42. Summary of NDE and NBI assessments of I–80 corridor bridges.

		NDE and Testing Results			Routine NBI Inspection			
Bridge Number	Deck Surface	ACS/IR-UTD Percent Damage	GPR Percent Fair/Poor	HRI/Previous Percent Patch/Spall	Item 58 Deck GCR	Element 12 Percent in CS 2	Element 12 Percent in CS 3	Relative Assessment NDE Versus NBI
0F 6	Bare	2.2	1.1	1.0	6	30	1	Better
0F 7EB	Bare	0.6	0.3	8.0	5	7	1	Confirmed
0F 7WB	HMA	4.0	9.9	8.0	5	7	1	Worse
0F 33	Bare	0.1	0.0	2.0	6	100	0	Better
0F 34	Bare	3.1	0.5	1.0	6	75	0	Better
0F 35	Bare	0.3	0.9	0.0	6	48	0	Better
4F 36	HMA	7.0	3.5	0.0	6	3	6	Confirmed
0F 344	Bare	1.3	2.9	0.0	6	19	16	Confirmed
0C 369	Bare	0.3	0.6	0.0	6	100	0	Better
0C 377	Bare	5.6	2.0	0.3	5	6	25	Better
4F 415	TBPO	4.0	1.6	0.0	5	3	18	Confirmed
0F 547	Bare	16.0	0.0	14.0	6	11	1	Worse
2C 624	HMA	10.0	1.1	12.0	6	49	1	Worse
3C 625	HMA	4.0	8.7	11.0	6	60	0	Worse
1C 628	HMA	22.0	3.2	35.0	5	41	5	Worse
2C 631	Bare	4.8	0.8	23.8	5	1	43	Confirmed
2C 633	HMA/TBPO	2.0	1.4	4.0	6	2	7	Worse
0C 635	Bare	12.0	3.2	27.0	6	20	0	Worse
2C 637	HMA/TBPO	6.0	0.8	4.0	6	6	0	Worse
1C 668	HMA	5.0	5.1	15.0	5	1	0	Worse
3C 668	HMA	1.0	1.3	19.0	6	2	0	Worse
0C 669	Polyester	10.1	1.1	8.0	5	22	2	Worse

		NDE and Testing Results			Routine NBI Inspection			
Bridge Number	**Deck Surface**	**ACS/IR-UTD Percent Damage**	**GPR Percent Fair/Poor**	**HRI/Previous Percent Patch/Spall**	**Item 58 Deck GCR**	**Element 12 Percent in CS 2**	**Element 12 Percent in CS 3**	**Relative Assessment NDE Versus NBI**
0C 692	HMA	3.0	0.4	21.0	6	41	0	Confirmed
3C 696	HMA/TBPO	7.0	0.9	5.0	6	33	0	Worse
1C 700	HMA/TBPO	12.0	0.4	5.0	6	28	3	Worse
1C 701	HMA	17.0	3.3	16.0	6	41	0	Worse
2C 702	HMA	6.0	0.5	29.0	6	25	10	Worse
3C 703	HMA	7.0	0.8	19.0	6	75	0	Worse
2C 710	Bare	4.9	1.8	4.3	6	72	2	Better
4C 710	Bare	9.7	0.8	2.1	5	22	51	Better
2C 732	Bare	6.9	0.1	0.6	6	25	12	Confirmed
1C 737	HMA	2.0	4.2	16.0	6	12	0	Worse
3C 737	HMA	4.0	2.7	16.0	6	15	0	Worse
1C 738	HMA	3.0	1.0	33.0	5	25	0	Confirmed
3C 738	HMA	3.0	5.7	33.0	5	6	20	Confirmed
3C 739	TBPO	0.1	0.1	5.0	5	50	0	Confirmed
4C 917	Bare	0.0	0.0	0.0	7	50	0	Confirmed

In many cases, the condition indicated by NDE was worse than NBI inspections would suggest, particularly where an overlay tended to obscure the underlying deck condition. In some cases, the indicated condition is better, particularly for bare decks. One consideration is that CS 2 and CS 3 ratings relate not only to delaminations and spalls, but also to the presence of cracking. Therefore, an inspection rating may indicate significant quantities of CS 2 and CS 3, but the overall level of NDE-indicated damage and the level of tested chloride ingress may have been lower, suggesting better condition than visual inspection may indicate.

The NDE-based assessments, as summarized in table 42, provided UDOT with much more granular data and a much more informed assessment of the condition than NBI assessments only. Based on the findings of the study, NDE-based assessments identified that 22 percent of the decks were in better condition, while 49 percent were in worse condition (figure 55), changing preliminary condition assessments of the decks and initial treatment plans. In the remaining 30 percent of cases, the most recent NBI condition ratings were confirmed. As illustrated in earlier use cases and analyses (e.g., new construction cases and typical Wisconsin Bridge), indepth condition assessment informs the selection of ideal treatments, service life estimates, and in relation to lifecycle cost analysis. Earlier use cases also illustrated that NDE-informed decisions can lead to substantial savings in lifecycle costs. In this corridor study, treatment plans were reviewed for 70 percent of the structures based on NDE guidance, potentially providing cost savings for most of the corridor bridges. Furthermore, longer-term plans are now better informed. UDOT can also use the NDE information to customize and adjust planning and BMS models.



Source: FHWA.

Figure 55. Chart. NDE Versus NBI condition assessment for Utah I–80 corridor study.

The NDE-based assessments were used to inform an optimized treatment selection for each bridge deck, ranging from structural pothole patching through various grades of hydro-milling and overlay to deck replacement. A few bridges were slated for full bridge replacement due to conditions beyond those of the deck or as part of capital planning projects. Based on the prescribed treatments and considerations of geographic location, traffic control requirements, urgency of repair, and need to spread costs over time, the treatments were bundled into 8 prioritized projects to be implemented over the 20-yr planning horizon. UDOT surmised benefits to the NDE approach included rapid testing speeds, lower overall user impacts, and more informed decisionmaking. The corridor approach supported prioritizing multiple bridge candidates, preliminary project scoping, and strategic bundling. Overall, UDOT found the study data extremely useful in evaluating and programming future projects for the corridor. The expected outcome of utilizing NDE methods to efficiently identify conditions and prioritize structures for treatment was achieved.

Bridge Deck Repair or Rehabilitation

South Dakota Bridge No. 41-161-156

This case study is for Structure No. 41-161-156, which carries US-14A over Whitewood Creek in Deadwood, South Dakota (figure 56). An NBI Inspection on August 16, 2018, rated the deck at 5, the superstructure at 7, and the substructure at 5. A representative excerpt from the NDE report for the deck and resulting defect quantities are provided in figure 57.

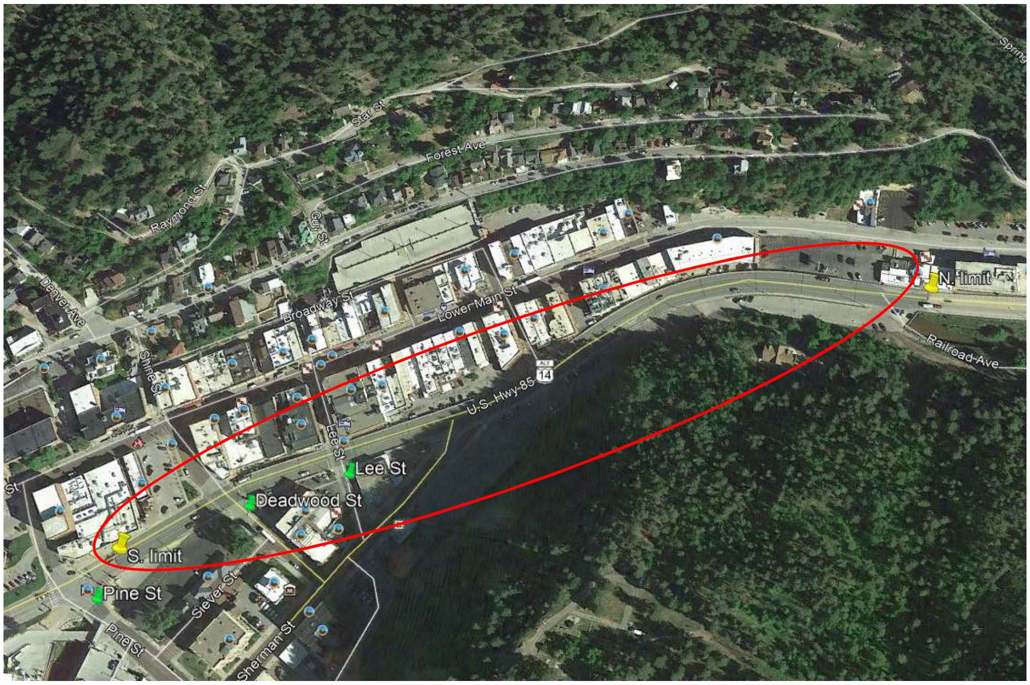


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Figure 56. Photo. Structure Number 41-161-156, South Dakota.

The deck element 12 is 104,502 SF in total, with inspection quantities: CS 1 = 98,902 (95 percent), CS 2 = 1852 (2 percent), and CS 3 = 3748 (4 percent). The NDE was performed 2 w after the NBI inspection on September 4, 2018, and the total cost was $43,000. GPR, IR, high-resolution visual (HRV), electrical resistivity, and chloride ion concentration tests were performed.

The South Dakota DOT (SDDOT) was originally going to replace the failing polymer chip seal with another but was also looking at doing a low slump dense concrete overlay. The polymer chip seal would also include some abutment repair, joints, and erosion repair along with the polymer chip seal and was estimated at $1.3 million. The low slump dense concrete overlay was estimated at $2.6 million.

NDE data showed SDDOT more damage than anticipated. SDDOT decided not to do any more deck treatments, which would not hold and would not necessarily delay a necessary replacement. Due to the complexity of the location as far as being within the historical City of Deadwood in the Black Hills, environmental considerations, and how to handle the traffic during the replacement and even how and where to replace—they initiated a further study that is still ongoing. This structure is currently programmed for fiscal year 2028 as a replacement.

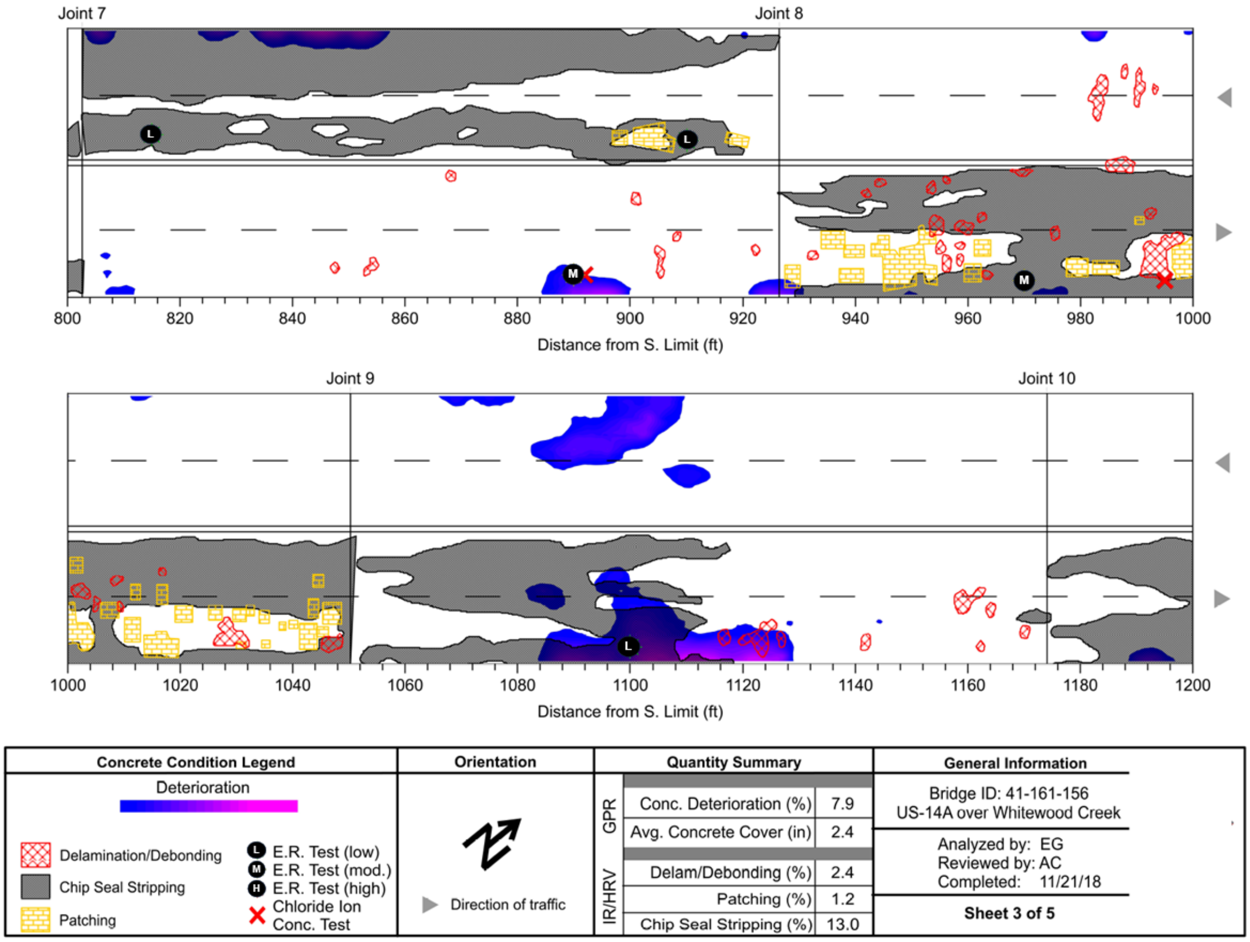

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Figure 57. Plan. NDE excerpt for deck condition and concrete cover (Joint 7 to Joint 10).

This case was discussed with the SDDOT bridge management engineer to identify the benefit of the NDE here and its economic impact. He noted that the polymer chip seal that they were strongly considering before the NDE (estimated at $1.3 million) would have a negligible impact on the deck lifecycle and would not have delayed the pending replacement. Therefore, the $43,000 they spent on the NDE saved the agency $1.3 million they would have otherwise spent on a polymer chip seal, providing a significant economic benefit.

John A. Blatnik Bridge

The John A. Blatnik Bridge spans the St. Louis River between Duluth, MN, and Superior, WI. The 7,975-ft bridge is composed of 49 approach spans composed of various span combinations of built-up and rolled multigirder spans, and 3 main truss spans composed of 2 cantilevered deck trusses (275 ft each) and 1 through arch truss (600 ft) with the deck supported by wire rope suspenders. The bridge was constructed in 1961 and widened in 1993. The Blatnik Bridge carries 33,900 vehicles per day in 4 traffic lanes (2 in each direction) of I–535 and US–53 between Superior and Duluth. As a border bridge, MnDOT and WisDOT share responsibility for the maintenance and operation of the structure.

The bridge has provided over 60 yr of service between the two cities in the harsh northern Minnesota environment. Over the years, significant deterioration developed in several areas of the bridge causing the MnDOT and WisDOT to implement periodic rehabilitation and frequent maintenance efforts to maintain the condition of the bridge. MnDOT undertook a study in 2017 to identify investments necessary to maintain the crossing efficiently and effectively. The study reviewed existing bridge conditions, identified the risks to the long-term bridge performance, recommended bridge maintenance and rehabilitation strategies for future actions, and proposed replacement strategies. Estimated costs and implementation time frames were generated for the recommended strategies and that information was used to generate multiple scenarios for consideration by MnDOT using a lifecycle cost analysis as a basis of comparison. In addition to identifying actions and required investments necessary to maintain the condition of the bridge in a better than a structurally deficient state for the next 15 to 40 yr, the study also highlighted information gaps, where existing records did not provide a full understanding of the condition of certain bridge elements. As a result, a technical evaluation was undertaken to test and document conditions and causes of deterioration. The gaps in knowledge about the structure were identified, including specifically the need for information about the condition and predicted service life of key components (deck, piers, structural steel coatings).

The total deck area of the bridge is approximately 508,000 SF. To evaluate such a large deck, vehicle-based HRI, GPR, and IR, trailer-based deck acoustic response (i.e., ACS, a form of automated sounding), were conducted and augmented by selective cart-based GPR and manual chain-drag for comparison, as well as physical sampling on concrete for compressive strength tests and chloride concentration profiles. A visual assessment showed extensive transverse cracking throughout the deck in approaches and the main truss spans, which had been treated by gravity-fed polymer crack filling. It was expected that the presence of such extensive cracking in a concrete deck on a bridge in a harsh environment that receives frequent deicing applications would have significant chloride infiltration and associated corrosion-induced damage.

Analysis of the NDE results, particularly ACS and IR, showed relatively little corrosion-induced damage along the length of the bridge. GPR showed approximately 7.8 percent of the deck area had higher levels of signal attenuation that may indicate conditions conducive to corrosion, including high levels of moisture and chloride (figure 58). IR indicated only 1.4 percent of the deck area had indications that suggest delamination within the concrete above the reinforcement. ACS similarly only indicated 1.7 percent of the deck area degraded or delaminated (figure 59). HRI showed that despite the extensive distributed transverse cracks, no substantial deck patching has been performed to date.

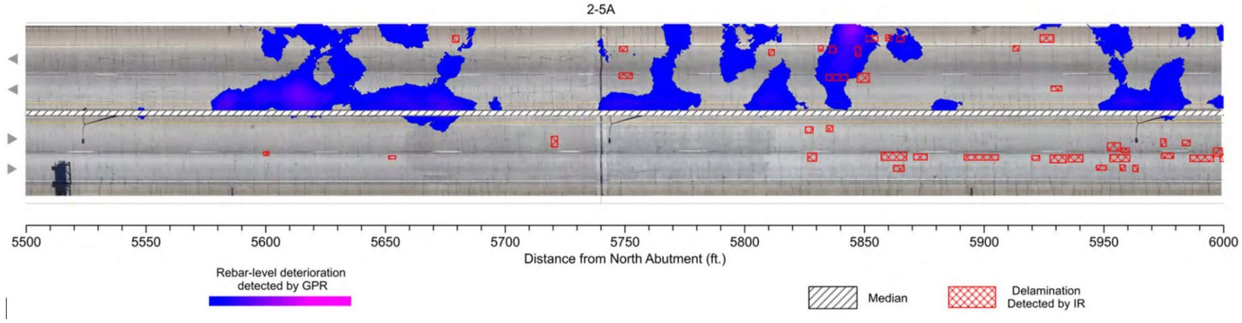

Figure 58. Plan. Excerpt showing GPR, and IR overlaid on high-resolution images.

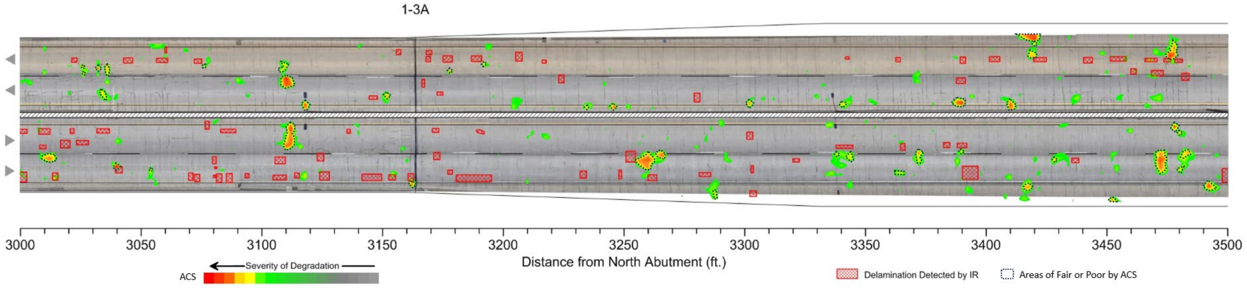

Figure 59. Plan. Excerpt showing ACS results overlaid on high-resolution images.

Chloride penetrations were relatively low, indicating that the crack treatment had been effective. Using the collected information, modeling of chloride diffusion and corrosion was performed to estimate the expected remaining service life of the deck in its current condition. Then, alternatives regarding the timing of deck rehabilitation by scarification and rigid overlay of the deck were considered. Reinforcement cover depth distributions differed between the Main Truss deck and that of the Minnesota approach spans, and the Wisconsin approach spans, with average cover depths of 4.09 inches, 3.79 inches, and 3.84 inches, respectively. Chloride surface concentrations and depths of penetration also varied; however, only 8 of 77 cores had chloride concentrations exceeding 500 ppm (~2 lb./yd3) at top mat reinforcement depth, and average chloride concentrations are about 300 ppm (1.2 lb./yd3) at that depth. The depth of carbonation of concrete was found to be negligible to 0.3 inches from the surface. The result is that the expected remaining service life of the Main Truss is longer than that of the approaches, as shown in figure 60. The agency had planned an overlay rehabilitation around 2031 and was considering deck replacement as early as 20 yr thereafter. It is expected that the approaches will require preservation actions within the next 20 yr. However, based on the results of the study, such action might be deferred from the original plan or eliminated depending on MnDOT's capital plan. MnDOT is already in the process of planning for the replacement of the structure to address other nondeck-related concerns, and it may be possible to maintain the existing deck until such replacement occurs.

To quantify the economic impact of using NDE for this case study, most likely timeline of agency actions and cost with and without NDE input were compared. The planned actions, their cost estimated, and EUAC of these costs over the 2018–2080 period are presented in table 43.

The timing and cost of potential actions come from the detailed study performed in 2018. The cost of NDE was $116,383 for vehicle-based NDE of the deck; ~$65,000 for physical sampling, lab testing, and hand and cart NDE of the deck; ~$40,000 for service life analysis and report of the deck, an overall estimate of $221,000. The deck area for the Minnesota approach, main truss, and Wisconsin approach is 160,715 SF, 72,580 SF, and 360,787 SF, respectively. For the LCCA, a construction inflation rate of 2 percent and a nominal interest rate of 2.6 percent were used.

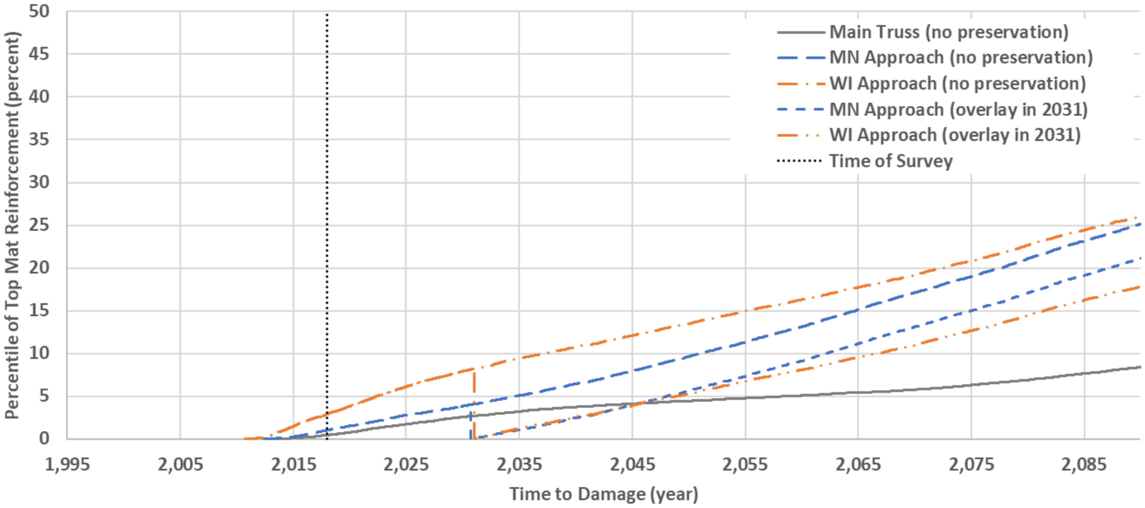

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Figure 60. Chart. Corrosion-based service life projection for the Blatnik Bridge deck.

Table 43. Economic comparison of potential treatment plans for John A. Blatnik Bridge.

	Plan With NDE			Plan Without NDE		
Year	**Event**	**Cost**	**EUAC**	**Event**	**Cost**	**EUAC**
2018	Inspection	$221,000	$7,215	—	—	—
2032	Mill and overlay WI approach	$7,199,702	$ 216,530	Whole deck overlay	$11,855,232	$ 356,544
2045	Mill and overlay MN approach	$3,207,156	$ 89,374	—	—	—
2052	—	—	—	Deck replacement	$107,213,867	$2,867,547
2080	Deck replacement	$107,213,867	$2,433,264	—	—	—
Total	$2,746,383			$ 3,224,092		
Savings/yr						$ 477,708

—No data.

The application of the methodology in this case study was a middle age bridge assessment where NDE data were used to estimate the expected urgency of future rehabilitation and prioritize among other planned work. MnDOT originally intended to do a whole deck overlay in 2032 followed by a deck replacement in 20 yr. Because NDE showed the effectiveness of the crack treatment, instead of mill and overlay of the whole deck in 14 yr, staging and doing the mill and overlay for Wisconsin and Minnesota approaches was suggested. Based on the projections, this staged mill and overlay could push the deck replacement another 30–35 yr. For the LCCA, the deck replacement was pushed another 28 yr to be conservative. The LCCA shows that using NDE and adjusting the treatment plan accordingly leads to agency savings of approximately $500,000 per year over the next 60 yr for this structure.

Delaware Memorial Bridge

The Delaware Memorial Bridge, composed of twin suspension bridges completed in 1951 and 1968, carries I–295 and Highway U.S. 40 across the Delaware River connecting New Castle, DE, and Pennsville, NJ (figure 61 and figure 62). The existing bridge deck of the First Structure of the Delaware Memorial Bridges was placed between 1969 and 1971 as part of a deck replacement and lane widening project immediately following the construction and opening of the Second Structure.

Figure 61. Photo. Delaware Memorial Bridge—Overview looking Southwest.

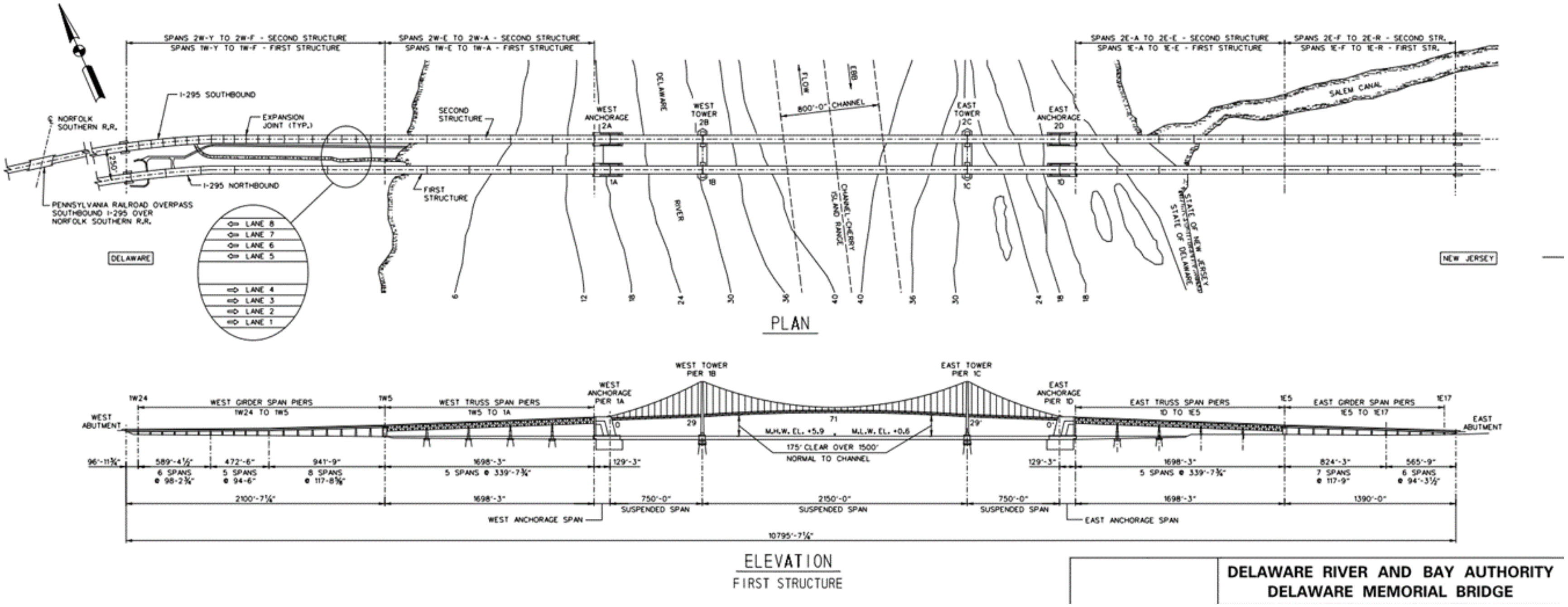

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Figure 62. Plan. Delaware Memorial Bridge—Plan (top) and elevation (bottom).

In 2017, the Delaware River and Bay Authority (DRBA) performed an evaluation of the deck of the first structure to identify and quantify the extent of the deck condition and deterioration. The desired outcomes of this assessment were two-fold. The first outcome was to make an informed decision about rehabilitation versus replacement of the deck. The assessment compared current and previous conditions to help provide a better understanding of deterioration rates, flag areas that are deteriorating more rapidly, and to prioritize continued repair needs until the deck was repaired or replaced. The second desired outcome was the selection of an appropriate treatment method for the rehabilitation as well as the determination of the appropriate removal method and depth.

The deck assessment incorporated data from rapid nondestructive evaluation, including HRI, IR, GPR, and ACS to complement materials sampling and laboratory testing of the deck concrete. An analysis was also performed to forecast the remaining service life of the deck by segment. Quantifying and understanding the deterioration growth rate helped the DRBA make the best data-driven decisions to program its preservation and capital programs.

The overall results of the field study included the following:

- GPR data indicated that 13.0 percent of the bridge deck showed precursors to deterioration.
- IR data indicated that 4.2 percent of the bridge deck is degraded.
- ACS data indicated that 4.3 percent of the bridge deck is delaminated or debonded above the top reinforcing bar mat.
- HRI data indicated that approximately 5.7 percent of the bridge deck is patched.
- Chloride levels at the top mat of the reinforcing bar continued to increase over time.

An example of the results from the deck acoustic response is shown in figure 63. The GPR data collected was also used to determine reinforcing bar cover depths as shown in figure 64. Based on this evaluation, many of the sections of the deck, including those overlaid over the past 25 yr, were expected to reach unsustainable levels of deterioration that would impact the deck's serviceability over the next 5 to 10 yr without significant intervention.

At the onset of the effort to evaluate options for the rehabilitation of the bridge deck on the Delaware Memorial Bridge, DRBA’s team of engineers developed a detailed lifecycle cost analysis for the various options available. Numerous options were evaluated including replacement of the deck using cast-in-place concrete, replacement with either precast concrete or orthotropic deck panels, and LMC, and UHPC overlays. The analysis considered the construction costs involved, the expected duration of construction needed for each option, and the projected maintenance and repair costs over a 50-yr period. Table 44 presents the summary of the lifecycle cost analyses for the options. All methods were compared based on the net present value of the costs, using a 1.5 percent discount rate. The discount rate was derived from the Real Treasury Interest Rate for 30-yr maturity (OMB 2022).

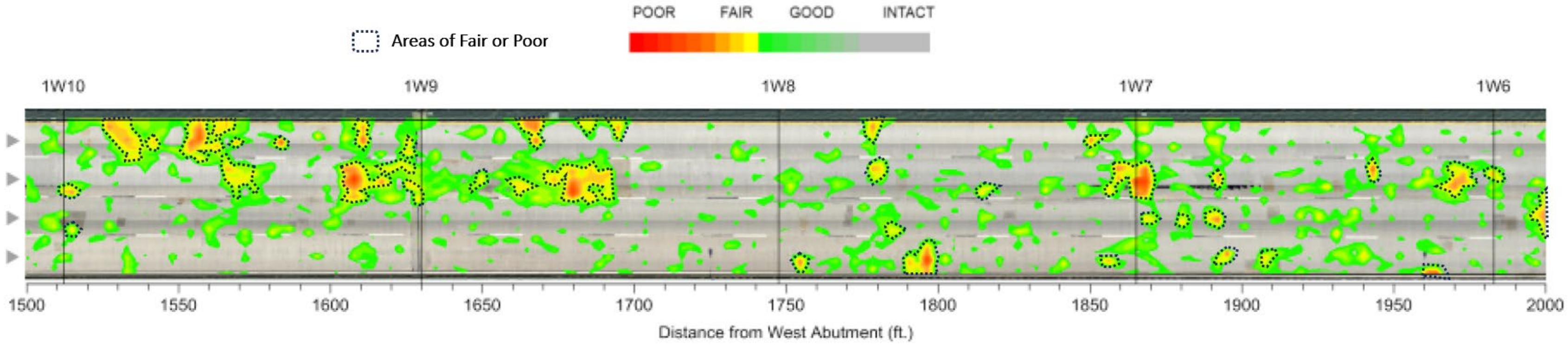

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Figure 63. Plan. Excerpted composite image with ACS condition information for the Delaware Memorial Bridge.

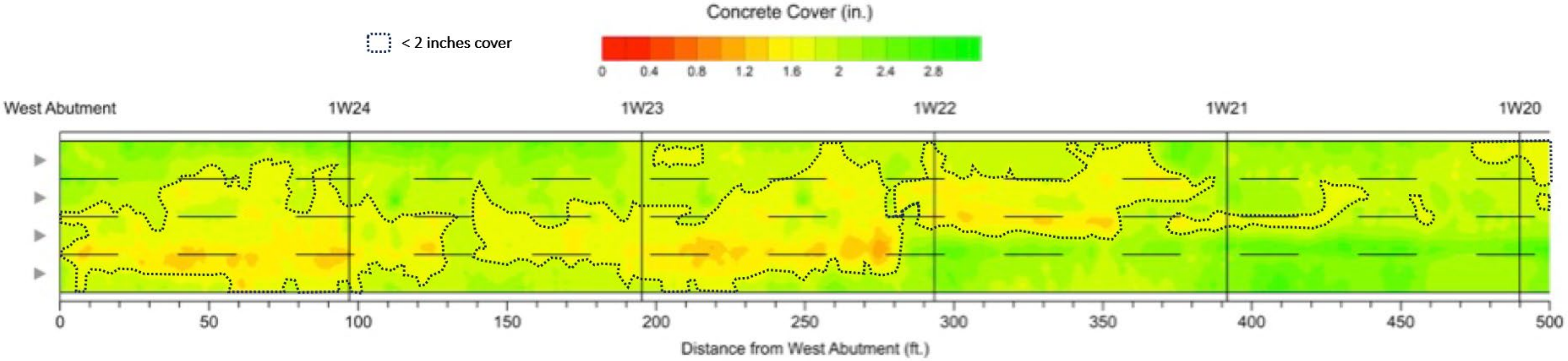

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Figure 64. Plan. Excerpted GPR cover depth results for the Delaware Memorial Bridge.

As shown in table 44, methods have different service lives (life span), timing, and frequency of treatments. For any expenditure, the net present value (value for year 0) of the cost was calculated and presented. The analyses were done over a 50-yr analysis period. The net present value of the remaining service life was calculated at year 50 for all options for a comparable economic assessment of all options. The value of the overlays and new deck were assumed to decline linearly over their entire projected life (straight-line depreciation). The remaining service value in the analyses indicates this value for each option, which was used as a residual or salvage value to calculate the net present cost. The net present cost is calculated by summing the net present value of each cost and subtracting the remaining service value.

Table 44. Summary of LCCA for the Delaware Memorial Bridge.

Material	UHPC Method -1 1.75 inches UHPC	UHPC Method -2 3.75 inches UHPC	UHPC Method -3 2.5 in UHPC and 1.25 inches of Asphalt	LMC Method -1 1.75 inches LMC	LMC Method -2 3.75 inches LMC	New Precast New Deck with Stainless Reinforcing bar
Life Span	30 yr	50 yr	45 yr	12 yr	25 yr	75 yr
Unit Cost	$45.00 /SF	$70.00 /SF	$60.00 /SF	$23.00 /SF	$39.00 /SF	$312.00 /SF
Year 0	$34,777,000	$48,541,500	$43,036,000	$22,663,700	$31,473,200	$171,786,000
Year 5	—	—	—	—	—	—
Year 10	—	—	$1,637,592	—	—	—
Year 12	—	—	—	$141,556,305	—	—
Year 20	—	—	$1,411,060	—	—	—
Year 25	—	—	—	—	$116,646,220	—
Year 30	$108,278,058	—	$1,215,864	—	—	—
Year 35	—	—	—	—	—	—
Year 40	—	—	$1,047,670	—	—	—
Year 45	—	—	$86,606,368	—	—	—
Year 50	—	—	—	—	—	—
Future Cost	$108,278,058	—	$91,918,553	$141,556,305	$116,646,220	—
Residual Value	$59,839,379	—	$76,159,210	$40,255,583	$54,399,436	$26,111,729
NPV	$83,215,500	$48,541,500	$58,795,500	$123,964,500	$93,720,000	$145,674,500

—No data.

Note: Assumptions:

1. Lifecycle cost analysis is for 50 yr.
2. All costs shown are in present value.
3. Annual discount rate used is 1.5 percent (real discount rate).
4. For all overlay options it is assumed the deck will be replaced at end of overlay service life.
5. UHPC method 3 asphalt overlay replacement is every 10 yr.
6. Cost of the full deck replacement is assumed to be $118,500,000.

Results of the lifecycle cost analyses concluded that a UHPC bridge deck overlay was the option with the lowest overall lifecycle cost. Moreover, UHPC also seemed to provide the benefit of an impervious overlay that could protect the lower portion of the deck from chloride ingress, which concrete deck core tests showed was in relatively good condition. Apart from having the lowest lifecycle cost and the advantages presented by the impervious, protective nature of UHPC, an additional benefit was that UHPC has excellent strength, bond, and durability characteristics, and as such it is an extremely resilient material that could be placed and finished in a much shorter timeframe compared to the deck replacement options and still be expected to provide a maintenance-free deck for 50 yr or more.

A workshop was then organized by DRBA's engineers in which experts in bridge engineering and bridge rehabilitation were invited to participate. Participants included bridge designers and bridge contractors, as well as representatives from FHWA. Following the completion of this workshop, a report was developed which documented the discussions as well as the presentations made in the workshop by the various participants. After extensive consultations and consideration of numerous options, in 2018 the DRBA decided to move ahead with the use of a UHPC overlay as a partial-depth deck rehabilitation as the preferred option for the bridge deck on the northbound twin span.

The detailed information about the existing deck condition obtained from the variety of NDE methods deployed played a pivotal role in the decision to rehabilitate the deck with a UHPC overlay instead of replacing it. The deck condition assessment provided confidence to the DRBA and the engineering team that the rehabilitated deck could provide the expected service life. This decision saved DRBA an estimated $100 million ($99,833,000) in terms of net present value compared to a complete deck replacement. The overall cost of NDE that informed this decision was just under $100,000 at the time of the study, which is 0.1 percent of the total net savings and entirely negligible in comparison.

CHAPTER 11. CONCLUSIONS AND RECOMMENDATIONS

The researchers drew the following conclusions based on this study:

- NDE techniques can be used to evaluate the condition of bridge decks. The applicable NDE techniques operate on a variety of physical principles, and the data output varies by method and sometimes by application.

- The confidence in, and adoption of, NDE methods varies widely among highway agencies. Different agencies have different perceptions of the accuracy and value of information provided by each technology and by different providers. Agencies need to ensure that the appropriate technology is employed properly to achieve the desired results. Uniform guidance would be helpful to ensure consistent application of NDE methods.

- Current practice rarely uses SM (i.e., in-place instrumentation) of deck conditions for assessment and preservation decisionmaking.

- NBI GCR and NBE/bridge management element condition state values are commonly used to trigger decisions for the preservation and maintenance of bridge decks.

- Cost information collected as part of the survey indicates that the cost of different NDE methods varies widely. For example, the method(s) selected, the number of bridges, the distance between bridges, and the total deck surface area assessed at the same time can affect the unit cost of NDE testing.

- High-resolution imaging, GPR, acoustic wave methods, IR, and HCP are the most common NDE methods for use on bridge decks based on current practice.

- The current state of practice indicates that NDE is used to augment SHA's decisionmaking processes that are primarily based on condition states, as NDE can provide a more accurate estimate compared to visual inspection.

- Few agencies have progressed to use NDE as the direct input for bridge deck preservation or maintenance decisionmaking.

- A framework for the use of NDE during different life stages of bridge decks was developed in this project. The framework considers the use of different NDE methods that are most applicable to certain parameters that can be measured and tied to the expected service life of bridge decks. Examples of the framework are presented in three life stages of a bridge deck:

    - New construction.
    - Early to middle age.
    - Bridge deck preservation, repair, or rehabilitation.

In this report, LCCA analysis findings or estimated savings from hypothetical and real-life case studies were presented to compare the combined cost of NDE and intervention, to the cost of not collecting NDE data and enacting intervention based on traditional visible and sounding methods. Consistently for all presented examples, the cost of NDE was negligible in comparison to the potential benefits or savings that would be realized during the deck lifecycle by making informed decisions.

Recommendations

The framework developed can be used by individual SHAs to develop State-specific NDE-based decision matrices to implement the use of NDE to trigger specific preservation or maintenance actions for bridge decks. The researchers recommend that States develop their own NDE inspection manuals that can describe the different techniques to be used during the different bridge life stages, standard operating procedures for NDE data collection, and NDE-based thresholds for followup actions and decision matrices.

This work identified the following gaps that should be addressed in future research:

- Develop methodologies for synthesizing data from multiple NDE methods in addition to creating a standardized scale and tie certain actions to the scale.
- Develop uniform guidance for the application of most NDE methods for the assessment of bridge decks (e.g., NDE pocket guides).
- Develop a standardized approach to augmenting condition state data in BMSs using NDE sources.
- Develop a correlation between predictive NDE methods and associated rates of deterioration that they represent.
- Tie NDE outputs to physical (rather than statistical) deterioration models.

ACKNOWLEDGMENTS

The original maps shown in figure 21 is the copyright property of Google® Earth and can be accessed from https://www.google.com/earth (Google 2020). Figure 21 was modified to include an overlay of impact echo results showing the presence of delamination. The photo is an aerial photograph of I–90 bridge deck, Boston, MA.

APPENDIX A. QUESTIONNAIRE

Questionnaire—NDE and SM Methods for Bridge Deck Preservation. This questionnaire is being administered by a research team on behalf of the Federal Highway Administration. The questionnaire is designed to solicit information about the current state of the practice among representative State highway agencies concerning use of nondestructive evaluation (NDE) and structural monitoring (SM) methods to determine and track condition of highway bridge decks. We are also interested in how that information may be used to guide bridge preservation planning, action selection, and implementation. Respondents are encouraged to discuss the range of their agency's experience and may provide supplemental information in the form of document links or files by email to [e-mail redacted].

Please note that all answers should be based on your agency's experience regarding bridge decks.

Contact Information Please fill in your contact information:

- First name:
- Last name:
- Title:
- Agency:
- Email:
- Phone number:

1. Please indicate which methods you use and your level of confidence in NDE methods for concrete deck evaluation.

NDE Method	No Experience (6)	Not reliable (1)	Somewhat unreliable (2)	Neither (3)	Somewhat reliable (4)	Reliable (5)
Visual inspection (1)	—	—	—	—	—	—
High-resolution imagery (2)	—	—	—	—	—	—
Manual chain dragging and hammer sounding (3)	—	—	—	—	—	—
Automated acoustic response (4)	—	—	—	—	—	—
Impact echo (5)	—	—	—	—	—	—
Ultrasonic Pulse Velocity (6)	—	—	—	—	—	—
Spectral analysis of surface waves (USW/SASW) (7)	—	—	—	—	—	—
Ultrasonic shear wave tomography (8)	—	—	—	—	—	—

Ground Penetrating Radar (9)	—	—	—	—	—	—
Infrared Thermography (10)	—	—	—	—	—	—
Half-cell potential/Electrochemical potential (11)	—	—	—	—	—	—
Electrical Resistivity (12)	—	—	—	—	—	—
Corrosion rate (13)	—	—	—	—	—	—
Other (please note below) (14)	—	—	—	—	—	—

—Blank for respondent entry.

2. Please indicate which methods you use and your level of confidence in NDE methods for steel deck evaluation.

NDE Method	No Experience (6)	Not reliable (1)	Somewhat unreliable (2)	Neither (3)	Somewhat reliable (4)	Reliable (5)
Visual inspection (1)	—	—	—	—	—	—
High-resolution imagery/digital photography (2)	—	—	—	—	—	—
UT thickness (D-meter) (7)	—	—	—	—	—	—
Ultrasonic testing (3)	—	—	—	—	—	—
Phased Array Ultrasonic Tomography (PAUT) (4)	—	—	—	—	—	—
Magnetic particle (5)	—	—	—	—	—	—
Dye penetrant test (6)	—	—	—	—	—	—
X-ray radiography (8)	—	—	—	—	—	—
Strain instrumentation (9)	—	—	—	—	—	—
Other (please note below) (14)	—	—	—	—	—	—

—Blank for respondent entry.

3. Does your agency choice of NDE vary with respect to bare deck versus various overlay types? Please explain how.

- Yes (1).
- No (2).

4. What innovative or developmental NDE methods has your agency experimented with for evaluation of bare decks?

5. What innovative or developmental NDE methods has your agency experimented with for evaluation of decks with overlays?

---

6. What proportion of NDE applications used by your agency are used for the following purposes? (In the provided space, please indicate an estimate percentage.)

- Screening condition assessment (prioritizing among a group of structures or preservation action decisionmaking) (percent) (1).
- Project-specific decisions (repair quantities) (percent) (2).
- Inspection NBI condition ratings or NBE condition state assignments (percent) (3).
- Other (percent) (4).

7. NDE testing of bridge decks for your agency is performed by which entities? (If the provider varies by method, please indicate in the comment box which methods apply and to what percentage of overall NDE testing (e.g., GPR 50 percent, IE 50 percent)

- In-house forces and equipment (1).
- Hired consultants/contractors (2).

8. What benefits does your agency see now, or potential for in the future, from NDE methods for bridge decks?

- To assess current condition (7).
- To assess future condition, rate of deterioration (8).
- To trigger specific preservation actions (9)._
- To differentiate between potential preservation actions (10).
- To determine accurate defect quantities for contract/construction purposes (11).
- Other (please elaborate): (12).

9. How often do you prescribe NDE tests of decks to be performed? Do you have defined thresholds for use of NDE based on age, condition, roadway, etc.? Please explain:

10. Do you specify spatial frequency (e.g., on a grid, distance between longitudinal scans, image resolution) for certain NDE tests? If so, please describe (If you have written specifications, please provide link or email[e-mail redacted]).

11. Do you have unit cost estimates/records for specific NDE techniques (e.g., $/SF deck area)? If so, please list the method and associated unit cost.

12. If you do not have NDE unit cost estimates, can you share bridge- or inspection-level costs? Explain or link:

13. How would you rate the maturity of adoption of NDE for bridge decks by your agency? What do you consider strengths and/or impediments to adoption? (Please differentiate by method as applicable.) Explain:

14. Has your agency validated the results you are getting from NDE methods? Explain:

15. Are there specific NDE methods your agency has stopped using? If so, why? Explain:

16. Does your agency have experience using Structural Monitoring (some form of in-place instrumentation) for bridge deck evaluation, preservation planning or condition tracking? If so, please elaborate.

17. Do you have any questions or comments regarding the questionnaire or to clarify your responses? Please share below.

If you would like to provide supplemental information in the form of documents, please email [e--mail redacted].

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