TECHBRIEF

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Integrating NDE With Bridge Asset Management and Its Return on Investment in Complementing Bridge Safety Inspections

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INTRODUCTION

The Moving Ahead for Progress in the 21st Century Act (MAP-21) and Fixing America's Surface Transportation (FAST) legislation require that States develop data-driven asset management (AM) processes and plans (U.S. Congress 2012; U.S. Congress 2015). While traditional, largely visual inspections will continue to provide valuable information, owners have also turned to nondestructive evaluation (NDE) technologies as a means of acquiring additional information.

The use of NDE technologies to complement bridge inspection varies significantly from State to State. Some States use NDE as needed, while others have been reluctant to fully embrace such technologies based on their limitations and perceived value (i.e., cost and time to collect the data versus the information provided). Very few States deploy NDE technologies on a network wide basis.

Recently, several studies (e.g., Strategic Highway Research Program 2, Long-Term Bridge Performance (LTBP) Program have provided owners and decisionmakers with insight into the capabilities, reliability, strengths and limitations, benefits, and added value of using NDE tools and technologies to reliably manage their highway assets (Federal Highway Administration (FHWA) 2024; FHWA n.d.a.).

Research Synopsis

This research project investigates current State practices and policies for deployment-ready NDE technologies, presents two NDE return on investment (ROI) tools, provides NDE-to-AM integration strategies, and presents testing protocols for eight NDE technologies (Green, Nejad, and Walther Forthcoming).

Because this research is based on limited performance data and feedback from States, the ROI tools should be considered as a framework for further development.

Research Objectives

The primary goal of this study was to investigate the current use of NDE data to assess the condition of bridge and tunnel elements. However, based on interviews with personnel in Lead Adopter States and after consultation with engineers at FHWA, the research team focused on bridges and bridge decks. The researchers made the following efforts to achieve the primary objectives for this project:

- Studying current practices and policies of NDE application across State highway agencies examined through interviews with Lead Adopter States and a comprehensive literature review.
- Developing ROI tools, one focused on the network level (Network-Level Analysis (NLA) tool) and a second one focused on the project level (Project-Level Analysis (PLA) tool).
- Developing recommendations for integrating NDE technologies into AM.
- Reviewing available standards and guidelines for deployment-ready NDE applications in AM.
- Developing NDE guidelines by adopting and modifying existing protocols or the creation of new protocols.
- Solicitating industry feedback on the results of this research by hosting an NDE workshop (Azari et al. 2022).

CURRENT PRACTICE

Both MAP-21 and FAST emphasize the development and implementation of risk-based Transportation Asset Management processes to guide operational, maintenance, and repair strategies, particularly for bridges on the National Highway System (U.S. Congress 2012; U.S. Congress 2015). To that extent, this project focuses on how NDE can play a role in understanding the long-term performance of the bridge inventory.

The Role of NDE Data in Improved Decisionmaking

Virtually all data collected during routine inspections are from visual inspection. While this method has generally proven to be an effective condition assessment tool, it cannot identify internal defects. Most States use element-level condition states to make maintenance, repair, and restoration decisions. NDE techniques, such as ground-penetrating radar (GPR), half-cell potential (HCP) and infrared thermography (IT) are being used to supplement visual observations. Despite the proven value of NDE data in project-level assessments, integration into State AM systems has been slow, mainly due to high costs, the complexity of NDE technologies, and lack of platforms that correlate NDE data with AM practices.

FHWA NDE Selection Resources

The FHWA's InfoTechnology™ platform is designed to facilitate the transfer of NDE knowledge and technologies between researchers and practitioners (FHWA n.d.b.). This platform provides access to information about various NDE methods, their applications, and the types of defects they can detect. The platform serves as a valuable resource for engineers and asset managers seeking to enhance their understanding and use of NDE data in bridge, pavement, tunnel, and utility condition assessments.

Lead Adopter Interviews

Multiple interviews conducted with nine State departments of transportation (DOTs) revealed a diverse range of approaches to using NDE in bridge AM. While several DOTs have adopted NDE techniques like GPR and IT, these technologies are mostly used on a project-by-project basis. The primary barriers to wider NDE adoption are the high costs, slow processing and reporting time, specialized training requirements, and the lack of integration with existing bridge management systems (BMSs). Despite these challenges, the interviews highlighted growing interest in incorporating NDE data into long-term maintenance planning, with some States, such as Wisconsin and Utah, leading efforts to explore automated data collection and integration to improve lifecycle cost (LCC) analysis and asset performance tracking. Creating a framework within which NDE data can be collected, stored, and used in a systematic way will promote the use of NDE in AM.

ROI ANALYSIS

The goal of an NDE ROI analysis is to evaluate how NDE affects decisionmaking processes, maintenance, repair, and replacement strategies, and ultimately the costs associated with managing infrastructure assets. Two tools were created as part of this project. The NLA tool focuses on strategic, long-term application of NDE over the entire network (Green, Nejad, and Walther Forthcoming). The NLA tool is intended to be a high-level review tool to determine if NDE is valuable for a particular population and, if so, what investment level produces the greatest returns. The PLA tool focuses on how the application of specific NDE technologies affects various AM strategies for individual assets (Green, Nejad, and Walther Forthcoming).

NLA

The NLA tool takes a top-down approach to assessing the value of NDE for an inventory of bridges. It helps answer two key questions: (1) Should bridge owners invest in NDE? and (2) What is the impact of NDE investment on the total cost of managing bridge inventories? The tool is designed to consider NDE technologies as a complementary suite rather than focusing on individual methods, with the aim of providing better overall information about asset conditions.

Fundamentals

The NLA tool supports strategic decisionmaking by incorporating both financial planning and performance measures in AM. The tool's outputs include budget projections, condition rating projections, and ROI. The calculation of ROI compares the costs of managing assets, with and without NDE, and quantifies the potential cost savings achieved by NDE-enhanced decisionmaking. Figure 1 illustrates how the funding is distributed between interventions, with a split between assets that are managed traditionally (figure 1-A) and those that use NDE (figure 1-B). By simulating different budget scenarios, the NLA tool allows decisionmakers to evaluate how various levels of NDE investment influence the network's overall condition.

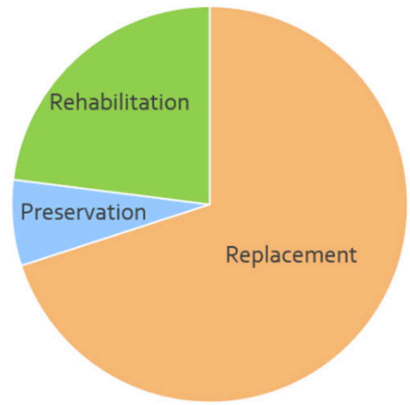
Focus on Bridge Decks

The NLA tool focuses heavily on bridge decks because they are among the most critical components of bridge structures, highly exposed to environmental factors and traffic, and costly to repair. The tool applies deterministic models (figure 2) to simulate bridge deck deterioration based on factors such as material type, traffic, and environmental exposure. The model predicts the lifecycle of bridge decks and aggregates the individual results over the inventory.

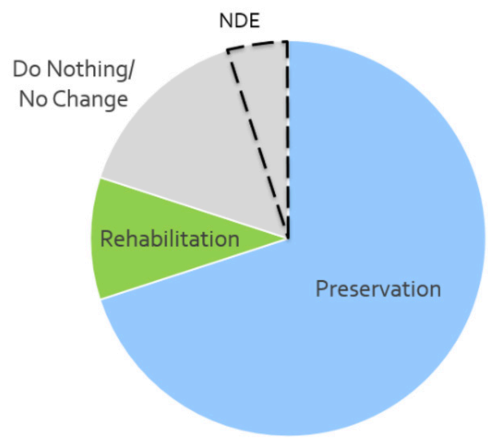
Cost Calculations and Budget Analysis

The NLA tool distributes user-defined, limited budget scenarios across various interventions (e.g., preservation, rehabilitation, and replacement). Replacement, rehabilitation, and maintenance costs are calculated based on deck area and the type of intervention needed, with NDE costs incorporated as a variable depending on the speed and complexity of the NDE technology selected. Higher-speed NDE methods like GPR and IT are more cost-efficient than lower-speed methods like impact echo (IE). The NLA tool can also include the impact of user defined agency and user costs.

Figure 1. Pie Charts. NLA budget distribution.



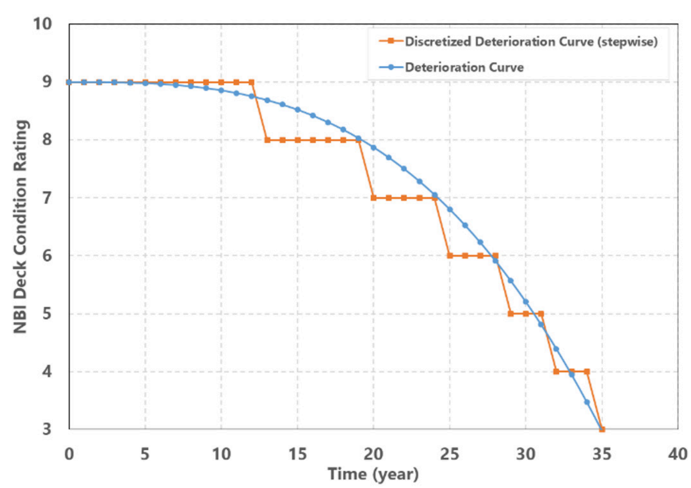
A. Budget A (no NDE).



B. Budget B (with NDE).

Source: FHWA.

Figure 2. Graph. Examples of calculated and discretized deterioration curves.



Source: FHWA.

Asset Prioritization

One of the key features of the NLA tool is its ability to prioritize assets for interventions based on several factors, including deck condition rating (CR), bridge age, traffic volume, and environmental exposure. In general, assets with higher CRs are deferred, while those with lower CRs are prioritized for intervention. This prioritization ensures that the most critical assets receive attention first, optimizing the use of limited budgets. The NLA tool allows managers to allocate funds between Budget A (assets that do not undergo NDE) and Budget B (assets subjected to NDE).

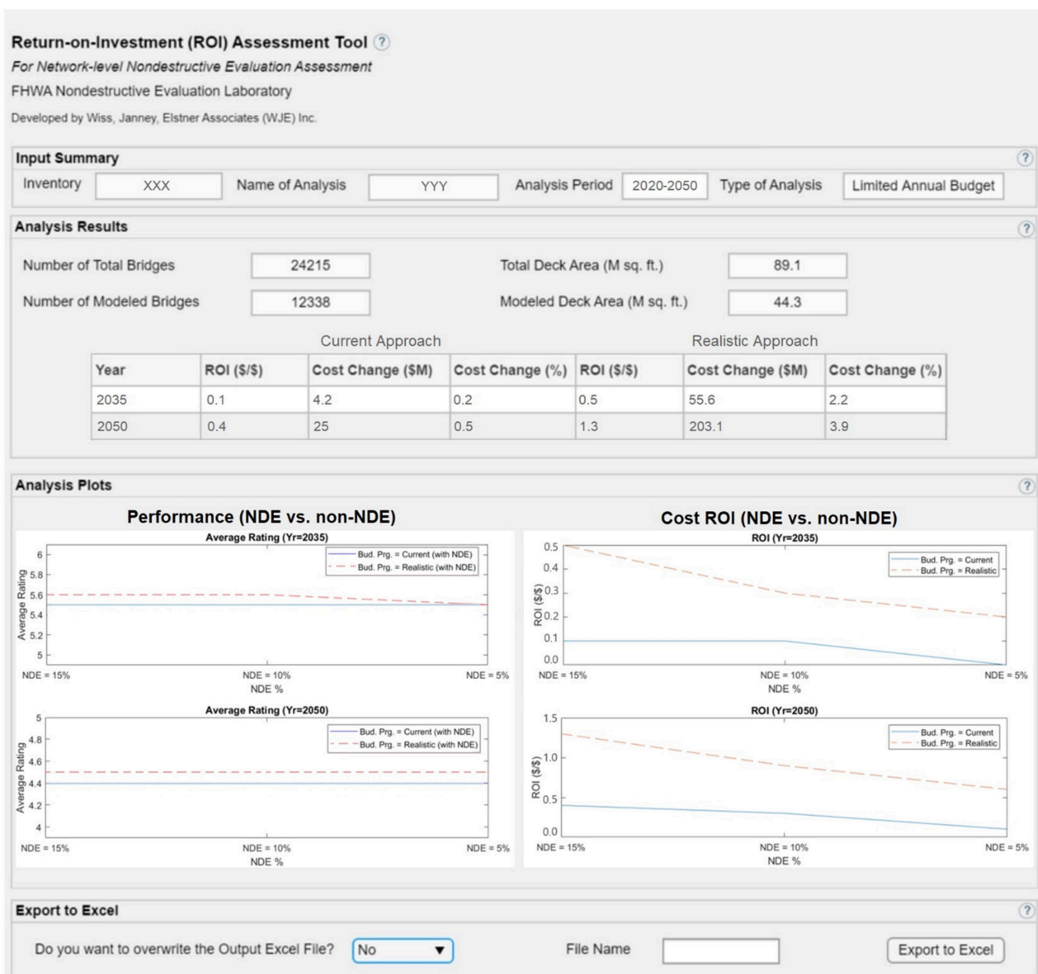
ROI Tool

The NLA tool executes ROI analysis by comparing the cost of managing assets with and without NDE. The execution process begins with user inputs, such as bridge inventory data, funding levels, and intervention strategies. Users can define the analysis period, intervention types, and NDE implementation scenarios. The NLA tool then generates deterioration models, distributes budget allocations, and service life extensions. After processing, the tool presents the results in both numerical and graphical formats, showing the changes in cost, CR, and ROI over time (figure 3). This output allows decisionmakers to visualize the long-term financial and operational benefits of investing in NDE.

Validation

Case studies with two Lead Adopters: Pennsylvania DOT (PennDOT) and Indiana DOT (INDOT) validated the NLA tool (Green, Nejad, and Walther Forthcoming). These validations involved applying the NLA tool to real-world bridge inventories and testing how it could simulate different NDE investment scenarios at the network level. For PennDOT and INDOT, the results demonstrated that even moderate investments in NDE resulted in positive ROIs, with cost savings ranging from 0.1 to 7.1 percent depending on the level of NDE implementation. The results showed that NDE can delay costly interventions by identifying bridges in better-than-expected condition, thereby optimizing

Figure 3. Screenshot. Summary screen of the NLA platform.



Source: FHWA.

maintenance schedules. The tool demonstrated its potential value in guiding strategic investment decisions by showing how NDE could be used to allocate resources more efficiently across an inventory.

PLA

The PLA tool provides asset managers with data-driven insights into the deterioration of bridge components, incorporating NDE Factors that modify transition times between condition states (CSs). By adjusting these factors, managers can visualize changes in service life based on various interventions. The tool presently focuses on concrete bridges and bridge decks in particular.

Fundamentals

The PLA tool uses CS values, user-defined transition times, and Markov chain calculations to develop the Health Index (HI) of individual bridge components (Markov 1906). CS transition times are modified by various factors that incorporate the element's environment, the level of protection, and NDE results. A new transition time modification factor, called the NDE Factor, incorporates the impact of NDE results.

Element-Level Approach

The tool uses element-level CS quantities to calculate HI. For reference, the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Bridge Element Inspection* defines CS1 as good, CS2 as fair, CS3 as poor, and CS4 as severe (AASHTO 2019). When viewed in terms of an entire bridge, multiple different elements may need to be assessed to determine the best overall AM approach.

Deterioration Modeling

The user defines a series of input values including CS transition times, CS distribution, the protection factor, and the environment factor. Deterioration curves are created using Markov modeling relationships. The HI curve is a weighted representation of the CS deterioration curves. AASHTOWare™ Bridge Management (BrM) uses a Weibull based deterioration model for CS1 to CS2, and a Markov-based deterioration model for the other CSs, whereas the PLA tool only uses Markov calculations (AASHTO, n.d.; Weibull 1951). This calculation difference may result in earlier predicted deterioration, but this result is acceptable for the tool's purpose.

Modification of Transition Times

Within BrM, three factors are currently used to modify the deterioration curve: the environment factor, the combined protection factor, and the formula factor. The environment factor captures the asset's environment and agency's operating practices (e.g., weather conditions or use of deicing salt). The combined protection factor summarizes the effectiveness of any protective systems, like coatings, on element performance. The formula factor is an optional, nonpredefined feature present in BrM that can be customized by the user. These three factors are multiplied together (equation 1) to provide a single transition time modification factor (F).

$$F = f^E * f^F * f^M \tag{1}$$

Where:

F = transition time modification factor.

f^E = environment factor - 2 (benign), 1.5 (low), 1 (moderate), and 0.7 (severe).

f^F = formula factor - user customized formula.

f^M = combined factor for all protective systems.

Actions

The PLA tool further modifies the deterioration curve or curves using two basic actions: NDE and interventions.

NDE

NDE can help quantify visually observable conditions, identify potential issues that are hidden from view, or quantify attributes that are known to contribute to shortened service life. For example, GPR surveys can help determine concrete cover over embedded reinforcing bars. Identifying cover that is greater than expected can increase the estimated life of a structure. Conversely, identifying cover less than expected can reduce the life expectancy of a structure. By knowing the concrete cover, owners can better predict when interventions may be needed.

The PLA tool includes both higher and lower speed NDE techniques. The techniques in *italics* can be used to quantify or correct CSs, while techniques not in *italics* are considered predictive of future performance:

- GPR: Used to locate reinforcing, voids, and delaminations.
- *IT: Used to locate and quantify delaminations*.
- Half Cell Potential (HCP): Used to assess the probability of active corrosion.
- Chloride ion concentration testing: Not typically thought of as an NDE technique but it is commonly used by States to provide information about the potential for corrosion, and therefore, is included in the PLA.
- Electrical Resistivity (ER): Used to provide information about corrosion rate.

- *IE: Used to locate delaminations and determine thickness.*
- *Automated Sounding (AS): Used to locate and quantify delaminations.*
- *High-resolution Imaging (HRI): Used to document existing surface conditions including cracking, spalling, and delaminations.*

NDE Factor

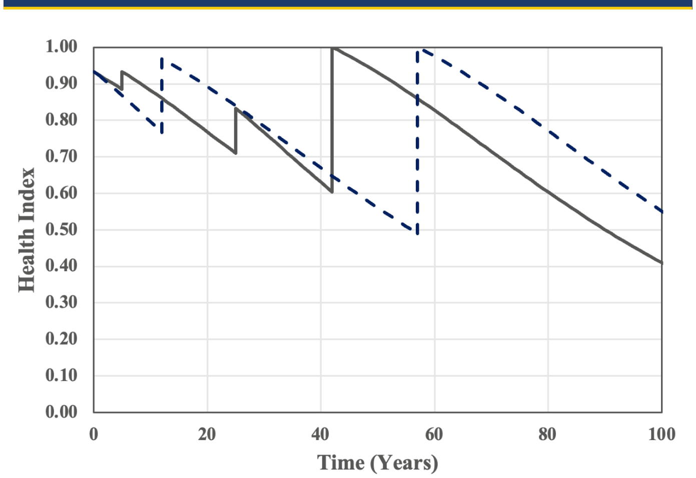
Ideally, a unique NDE Factor is used for each NDE technique-CS-test result. However, well defined, independent relationships do not exist and require additional research. Furthermore, when multiple NDE techniques are used, they must be combined into a single NDE Factor. This combined NDE Factor, possibly using the formula factor, is then combined with other factors to calculate the transition time modification factor (F).

While the PLA tool includes a framework for the more sophisticated NDE Factor formulation, certain challenges associated with its implementation are recognized. Therefore, at present, the use of a simplified NDE Factor is recommended. The simplified NDE Factor categorizes the NDE results as good, moderate, or poor based on general indicators of performance. The multipliers for each of the simplified categories can be user-defined, but they are currently set at 1.25 (good), 1.00 (moderate), and 0.75 (poor), or 1.00 for unknown.

Interventions

The effect of each intervention can be customized by the user. For replacement, the default is to modify all CSs to CS1. For repair or rehabilitation, the default is to modify CS3 and CS4 to CS1. For patching, the default is to modify CS4 to CS2.

Figure 4. Graph. HI versus time.



Source: FHWA.
Note: The solid line is Action Plan 1 (no NDE), and the dashed line is Action Plan 2 (with NDE).

Action Plans

Action plans combine the application of NDE and interventions over time. For example, a bridge deck may be subjected to patching at year 10, NDE at year 15, and replacement at year 35. Up to three Action Plans can be used to compare different AM strategies.

Costs

Costs associated with various interventions are included in the tool or can be defined by the user. NDE costs for each NDE technique are also included in the tool. Other costs like traffic management can be defined by the user.

ROI

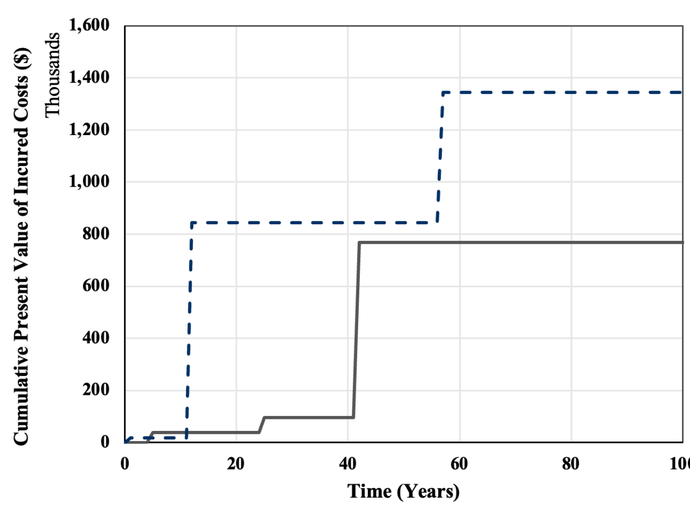
The PLA and NLA define ROI as the cost of managing the asset without NDE minus the cost of managing the asset with NDE divided by the cost of the NDE. Therefore, AM savings with NDE results in a positive ROI, while additional AM costs with NDE results in a negative ROI. The cost of the NDE scales the final ROI value.

ROI Tool

The PLA tool is implemented in Microsoft® Excel™, making the tool accessible and customizable to users. The PLA's advantages are that it is a relatively simple spreadsheet-based tool that can be modified by the user, uses actual NDE data, and can likely fit within existing AM platforms.

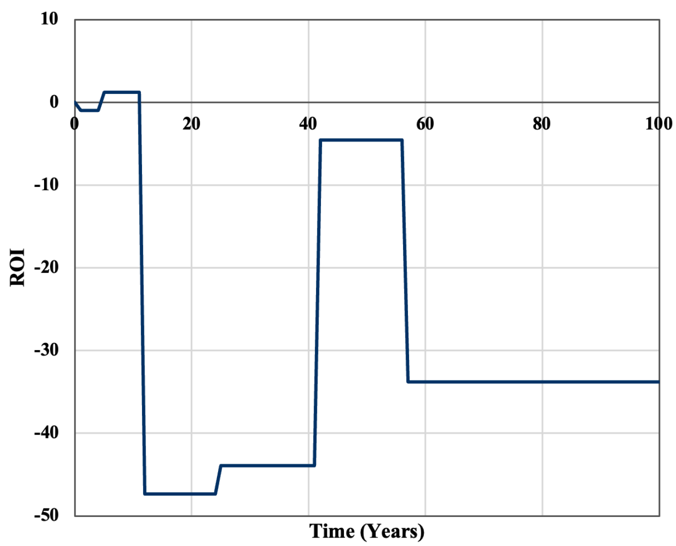
Figure 4 illustrates HIs over time. Figure 5 illustrates the cost over time. Figure 6 illustrates ROI over time for two Action Plans. When comparing Action Plan 1 (no NDE) to Action Plan 2 (with NDE) at 100 yr, Action Plan 2 results in an improved HI but at a higher cost. As such, ROI for

Figure 5. Graph. Action Plan costs versus time.



Source: FHWA.
Note: The solid line is Action Plan 1 (no NDE), and the dashed line is Action Plan 2 (with NDE).

Figure 6. Graph. ROI versus time.



Source: FHWA.

this set of variables is negative indicating that the Action Plan that uses NDE does not minimize LCC.

Validation

The PLA tool was validated through case studies with Lead Adopter States, including PennDOT, Utah DOT, and Virginia DOT (Green, Nejad, and Walther Forthcoming). Case study results indicated that NDE investment combined with sound intervention strategies can lead to better AM decisionmaking.

NDE INTEGRATION WITH AM

The project focused on four key areas of integration: technology and research, AM systems, codes and policies, and outreach and training (figure 7).

Technology and Research

The application of NDE for wholesale replacement of visual inspection is not cost-effective and would not be accepted by the industry or public. However, if the bridge population is parsed into different categories of risk (both safety and economic), then NDE may be studied as a cost-effective alternative for high-risk bridges where more accuracy and quantitative data are required. Alternatively, it could be used to completement visual inspection on high-risk bridges. To that extent, the following actions are recommended:

- Continue to leverage existing NDE techniques to solve specific challenges and concerns. Perform research that links NDE results to conventional performance indicators like CR and CS.
- Focus research efforts on high-speed, robotic, and noncontact NDE techniques because these could offer faster data collection, lower maintenance of traffic costs, and inspection personnel safety advantages.
- Develop methodologies to reduce data collection and processing time while maintaining quality.
- Continue full-scale accelerated testing to gather objective and quantitative data on durability of new designs and materials. Couple that information with NDE data.

Integration With AM Systems

Quantifying bridge condition plays a pivotal role in AM. Bridge condition can be expressed in several ways—NBI component-level CR, element-level CS, or HI. Researchers do not envision these metrics being superseded anytime soon. Therefore, NDE data need to be complementary to the CR or CS systems that are currently in use. The following steps are recommended to integrate NDE data with the current AM systems:

- Leverage existing NDE techniques like AS, HRI, and IT to adjust CRs and CSs. This integration should also provide better data for repair contract quantities.
- Use predictive NDE techniques like GPR, HCP, ER, and chloride content testing to identify assets that may deteriorate faster or slower than expected.
- Develop relationships between commonly used NDE techniques and conventional performance indicators. This development is likely to require long-term data collection using in-service bridges, and full-scale accelerated testing.
- Develop an “NDE Factor” that can be used to modify asset transition times as it relates to BrM and other similar AM systems (AASHTO n.d.). Calibrate this factor using data from in-service bridges and possibly from additional research.
- Consider using NDE data to calculate an “Integrated Condition Index” if development of an “NDE Factor” is not feasible. The Integrated Condition Index defines service life stages (protected, exposed, vulnerable, attacked, and damaged) with NDE helping to define which stage the asset is in (Hearn and Shim 1998).
- Expand scenario modeling capabilities for high-level decisionmakers so that connections between NDE usage and implementation costs over the inventory can be investigated.

Codes and Policies

State and nationwide policies could play a vital role in enhancing NDE usage. These policies could provide a consistent and unified approach to NDE practices, including the following:

- Use NDE to complement visual inspection results and to act as "flags" when evaluating those findings.
- Establish statewide policies for NDE within inspection manuals, defining the selection of and procedures for NDE usage.
- Establish nationwide policies for NDE data collection and create standards that summarize raw NDE data into concise indicators consistent with existing database limitations.

Outreach and Training

Training, workshops, conferences, and outreach efforts are vital for promoting the wider adoption and application of NDE techniques in bridge engineering, including the following:

- Provide training for State DOT staff and industry engineers. This training should include technical information about the NDE techniques, hands-on use of the equipment, data processing logistics, and reporting basics.
- Provide training for leadership and decisionmakers. This training should focus on different AM strategies rather than specifics related to the individual NDE techniques.
- Provide workshops, conferences, and outreach designed to enhance the application of NDE techniques in bridge condition assessment.

NDE TECHNOLOGIES AND TESTING PROTOCOLS

The research team identified eight deployment-ready NDE technologies. They modified existing protocols to align with the project goals, and the team developed new protocols where no protocols existed.

Identification of Relevant NDE Standards and Guidelines

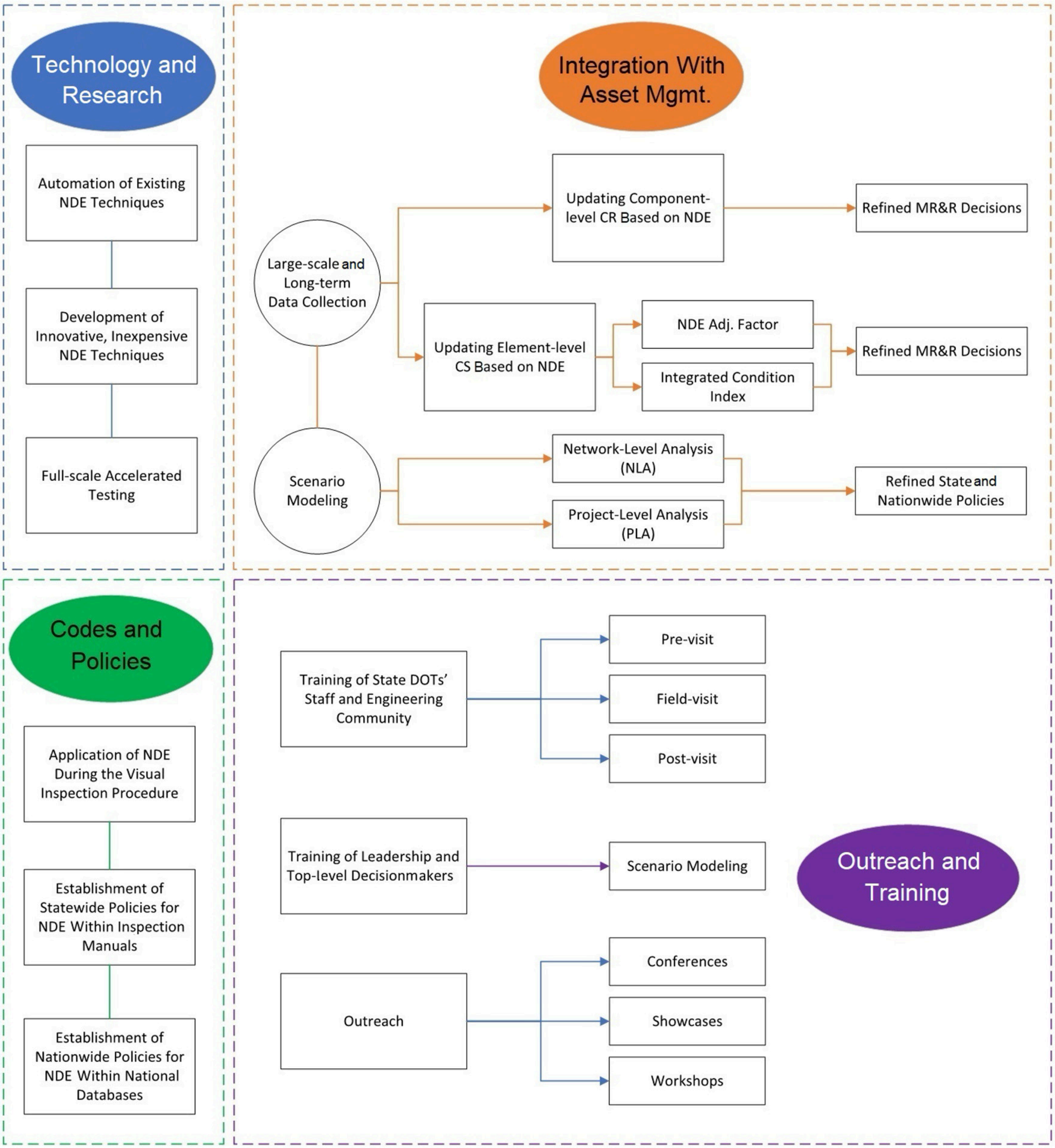
Several organizations provide relevant standards for the eight selected NDE technologies:

- ASTM standards: These standards, such as ASTM C876 for HCP and ASTM D6432 for GPR, provide detailed guidance on equipment and testing methods but lack comprehensive information on data collection and interpretation (ASTM International 1999; ASTM International 2020).
- The American Concrete Institute (ACI) standards: The ACI's report 228.2-13 presents basic principles and testing procedures for a range of NDE techniques, but it does not offer specific guidance on the extent of testing or follow-up actions (ACI Committee 2013).
- American Society of Civil Engineers® (ASCE) standards: ASCE standards include books, proceedings, and approximately 1,000 articles on NDE methods, covering technologies like GPR, IT, and unmanned aerial vehicle-based surveys. However, these materials do not provide comprehensive standards or detailed guidelines for testing or data interpretation (ASCE 2024; Green, Nejad, and Walther Forthcoming).
- International Guidelines: The German Society of Non-Destructive Testing (DGZfP) is an association for research, development, application, and dissemination of information related to NDE (DGZfP n.d.). DGZfP guidelines include technical documents related to cover measurement, HCP, ultrasonics, IT, GPR, and IE. These codes offer practical advice but lack global standards for NDE testing and interpretation.
- LTBP Program Protocols: FHWA's LTBP Program has developed protocols for several NDE techniques, including GPR, HCP, ER, and IE (FHWA n.d.a.).

Selection of Deployment-Ready NDE Techniques

The eight NDE technologies identified for bridge deck AM were GPR, HCP, ER, IE, HRI, IT, and AS. Five of the identified NDE technologies already have well-established protocols through the LTBP Program, while three techniques—IT, AS, and HRI—did not have existing protocols so new testing protocols were created.

Figure 7. Organizational Chart. Flowchart depicting how NDE can be integrated with an AM system.



Source: FHWA.
Adj. = adjustment; Mgmt. = management; MR&R = maintenance, preservation, rehabilitation, and replacement.

NDE WORKSHOP

The NDE and Structural Monitoring (SM) Workshop, hosted by FHWA on October 26–28, 2022, gathered key stakeholders and subject matter experts from the NDE and SM communities to explore the integration of NDE technologies into AM systems (Azari et al. 2022). The discussions highlighted the added value of NDE in AM and identified the following opportunities for future research and development:

- Collecting data over many bridges may reduce the time required to inspect each bridge. This change could reduce overall inspection costs.
- Using an NDE Factor to integrate NDE data into AM represents a promising approach at the project-level, however, research over 10–20 yr would be required to collect the data needed to calibrate the NDE Factor, especially when multiple technologies are used. Efforts such as the LTBP Program are poised to support this type of future research.
- Developing a data standard for raw NDE data and simplified NDE metrics. Collect and process data from a large population over a sustained period of time to validate the feasibility of a network-level NDE approach.
- Performing network-level analysis tool trials over time to assess their usefulness for high-level decisionmakers.
- Advancing efforts to develop NDE equipment capable of network-level data collection that are automated, low-cost, and can be executed at highway speeds or with minimal traffic disruption.

KEY RESEARCH FINDINGS

Document review and Lead Adopter interviews revealed that while NDE offers significant potential in providing more accurate data on infrastructure conditions, its integration into AM systems remains limited. Only a few States, like Wisconsin, have started using NDE on a network-wide level. Most States still rely on traditional visual inspections.

ROI tools developed allow decisionmakers to model how NDE impacts maintenance costs and bridge performance over time. However, challenges such as high NDE costs, NDE data complexity, and the need for further research into NDE-to-CS relationships limit widespread adoption.

Key recommendations include creating standardized NDE data collection frameworks, refining the integration of NDE results with existing BMSs, and continuing research to develop long-term strategies for higher-speed, lower cost NDE methods. Finally, this project highlights the need for a clearer ROI definition—ideally one that incorporates both cost and asset performance.

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