JOINT TRANSPORTATION
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INDIANA DEPARTMENT OF TRANSPORTATION
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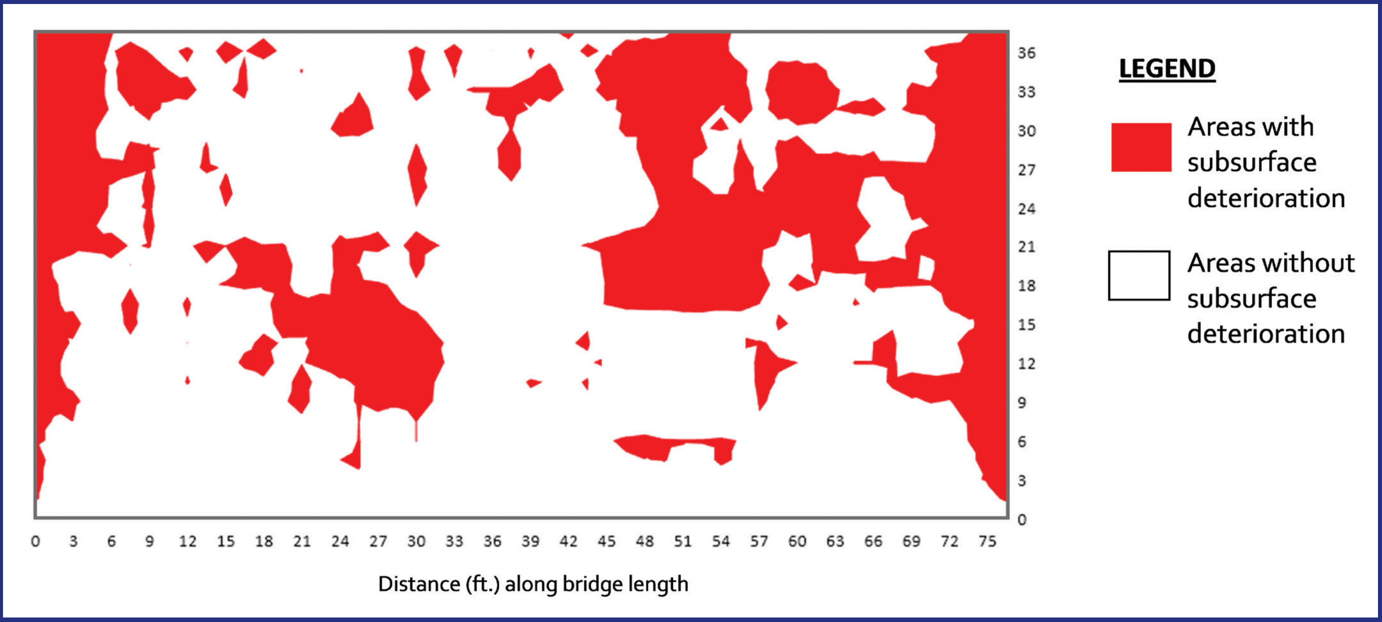
The Economic Impact of Implementing Nondestructive Testing of Reinforced Concrete Bridge Decks in Indiana



Benjamin R. Taylor

Yu Qiao

Mark D. Bowman

Samuel Labi

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AUTHORS

Benjamin R. Taylor
Yu Qiao
Graduate Research Assistants
Lyles School of Civil Engineering
Purdue University

Mark D. Bowman, PhD
Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-2220
bowmanmd@purdue.edu
Corresponding Author

Samuel Labi, PhD
Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-5926
labi@purdue.edu
Corresponding Author

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JOINT TRANSPORTATION RESEARCH PROGRAM

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16. Abstract

The deck is among the most expensive components of a bridge over its lifetime because of the frequent and costly maintenance and rehabilitation required. Currently, the Indiana Department of Transportation (INDOT) performs visual inspections of a bridge deck as the principal means of determining its condition, which enables the inspector to definitively document the surface condition while the unseen condition below the deck surface is left to the inspector's expert judgement. To compensate for this lack of data, INDOT supplements visual inspections with programmatic scheduling for major work actions, which is very effective for INDOT but costly. In this continuing era of funding shortfalls, INDOT commissioned this study to investigate nondestructive testing (NDT) methods to fill their data gap to inform its work action decision. The NDT methods have been shown to accurately locate corrosion and delamination and are a cost-effective alternative. A project level comparison between the NDT methods was performed to show which method, as well as which combination of methods, were the best choices from a cost perspective. A project level analysis of 30 bridge decks was performed, and those costs were compared to the costs of the current INDOT programmatic schedules. Finally, the analysis was expanded to the network level, which included the entire bridge inventory in Indiana. The results of this study indicate that implementing the NDT methods is cost-effective for INDOT at both the project and network levels.

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EXECUTIVE SUMMARY

THE ECONOMIC IMPACT OF IMPLEMENTING NONDESTRUCTIVE TESTING OF REINFORCED CONCRETE BRIDGE DECKS IN INDIANA

Introduction

Bridge decks require frequent maintenance and rehabilitation due to deterioration mechanisms such as corrosion of reinforcement and delamination of concrete. This makes the deck one of the most expensive components of a bridge over its lifetime. One major source of this damage is deicing salts applied in winter, which introduce chlorides to the deck surface and inevitably cause corrosion and cracking. Freeze-thaw cycles then exacerbate the cracks caused by corrosion, leading to delamination.

Currently the Indiana Department of Transportation performs inspections according to the federally prescribed two-year time interval for the state inventory of bridges. INDOT utilizes the findings from visual inspections as the main source of information regarding the condition of the deck, and the chain drag method occasionally is used in conjunction with the visual inspection. However, these methods do not provide a full picture of the condition. Due to this lack of quality data, INDOT has implemented a programmatic schedule for major work actions based on the age of the bridges in the network. Nondestructive testing (NDT) has been used extensively elsewhere to evaluate bridge decks, and it appears to be a more accurate alternative for deck inspections and programming decisions. This study was commissioned by INDOT to determine whether these methods will be cost-effective for the bridges in Indiana.

A thorough literature review and multiple interviews with INDOT personnel and NDT vendors provided the foundation for this study. The primary objective was to investigate the economic viability of using NDT methods for evaluating bridge deck condition to inform the decision-making process for work actions. The NDT methods were first evaluated to determine if they are more effective than INDOT's current practices. A project-level comparison between various NDT methods was conducted to show which method and combination of methods were the best choices from a cost perspective. This combination then was used in the project-level analysis, wherein their use and the resulting effect on agency costs were compared to the costs incurred using INDOT's current practices. At the network level, a combination of rapid-screening NDT methods was implemented and compared in a similar fashion to the current INDOT practices. Utilizing a consultant was also considered in place of establishing an in-house NDT option.

The comparison between the various NDT methods considered the following costs: equipment and software, maintenance, personnel salary, and traffic control. A project-level analysis then compared the use of the NDT methods to INDOT's current practices for 30 random bridge decks. A deterioration curve was created based on factored INDOT chain drag data. The project- and network-level analyses were conducted for a 100-year period, and the deteriorative curve was used to model the deck condition. An assumed decision matrix triggered work actions based on the percentage of deterioration and an associated probability of that work action. This analysis concluded that utilizing the NDT methods improved the deck condition overall. While the project-level analysis investigated only 30 bridge decks, the network level considered the entire Indiana bridge inventory. The network-level analysis assumed a leader of an in-house NDT group called the NDT expert, but at the project level there was no group leader and the costs for personnel were calculated based on an established hourly rate.

Findings

The past literature indicated that NDT methods can provide more accurate corrosion and deterioration detection than can visual inspections. With regard to the combination of NDT methods, several past studies concluded that such combinations also could accurately locate corrosion and deterioration to provide a better understanding of the different types of deterioration occurring in a deck.

When the costs at the project level were compared, infrared (IR) thermography was found to be the best alternative because of its low purchase cost and rapid data collection. The best combination of NDT methods was determined to be IR, chloride ion penetration (CIP), and ground-coupled ground penetrating radar (GPR), which then was used in the project-level analysis. The costs of the condition-based NDT methods represented the net present cost (NPC), and the equivalent uniform annual cost (EUAC) proved to be significantly less than the costs using INDOT's current programmatic schedules. The least expensive schedule was 23% more costly than the NDT methods, and the most expensive schedule increased the EUAC by 54%. When expanded to the network level, the costs were almost 1.5 times more using INDOT's current practices than using NDT methods. Although the average percentage of delamination was lower using the INDOT programmatic schedules, the costs to achieve those results were exorbitant.

Based on estimates from two consultants, the use of in-house network-level NDT was compared to use of a consultant for this work, and the results indicated a break-even point of $0.22 per square foot.Therefore, if a consultant offers services at less than $0.22 per square foot, then it would be more cost-effective to contract with them than to perform in-house NDT collection and analysis.

Because having more accurate data regarding the condition of the deck will allow INDOT to perform more appropriate work actions at the correct time, and thereby produce cost savings, this study concluded that using NDT methods for bridge deck inspection would be cost-effective for INDOT.

Implementation

Based on the results of this study, it is recommended that INDOT establish and fund a new NDT work group for network-level bridge deck condition assessment. The estimate for the startup costs and first year of funding for the group is $940,000. This estimate includes two sets of IR and air-launched GPR, two vans, two crews of two (four collectors), four analysts, and one NDT expert, as well as associated training, maintenance, and travel costs. High-priority bridges on the Interstates and NHS should be inspected first; if INDOT cannot afford to inspect every bridge in the state inventory, then these bridges should be the only ones inspected.

The crews will be able to inspect every bridge based out of the INDOT Research and Development Division in West Lafayette: Interstate bridges every two years, other NHS bridges every four years, and all other bridges every six years. INDOT should consider making use of a decision matrix similar to that of this study to aid in the decision-making process for bridge deck work.

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1. INTRODUCTION

1.1 Motivation

Bridge decks are among the most costly components of a bridge over the lifetime of the structure. They require more frequent maintenance and rehabilitation than the substructure and superstructure. During the winter months, deicing salts are applied to keep roads drivable, but they induce chlorides to the deck surface, which have the deleterious effect of accelerating corrosion and lead to delamination. Freeze-thaw cycles cause the cracks and delaminations to worsen and result in costly work actions.

To detect deterioration before excessive damage occurs, bridge decks must be inspected regularly. The Indiana Department of Transportation (INDOT) currently relies heavily on the information provided by visual inspection and occasionally, results from acoustic methods such as chain drag. However, these current inspection methods do not fully reveal the condition of the deck. Due to this lack of quality data, INDOT follows a programmatic schedule for major work actions based on the age of the bridge. A more accurate alternative for deck inspections, nondestructive testing (NDT), is a viable option for obtaining a better understanding of what is happening beneath the deck surface to inform the scheduling decision process. This study was commissioned by INDOT to explore the suitability of NDT methods for INDOT as well as their cost-effectiveness.

1.2 Scope and Limitations

A literature review as well as interviews with INDOT personnel and vendors provided the foundation for this study. The deterioration curve used in the analysis was based on chain drag data collected by INDOT personnel for bridge inspection reports. This study also utilized data from the NBI database for the Indiana bridge inventory.

1.3 Objectives

The first objective of this study was to determine if the NDT methods are effective in locating deterioration. Secondly, if the NDT methods were found to be effective, the question became whether or not INDOT could potentially realize substantial cost savings by making optimal perform/delay decisions informed by more complete deck condition data. Therefore, the various NDT methods were compared at the project level in order to determine the optimal cost-effective choice. Then, the optimal combination of NDT methods was compared to INDOT's current practices at both the project and network levels. Finally, the option of utilizing a consultant was considered instead of in-house data collection and analysis.

2. LITERATURE REVIEW

2.1 Deterioration Mechanisms in Concrete Bridge Decks

Corrosion is one of the leading causes of damage in reinforced concrete bridge decks. Chlorides from deicing salts are known to permeate sound concrete slowly and then quickly seep through cracks to reach the rebar (Weyers, Prowell, Sprinkel, & Vorster, 1993). If the steel is bare (i.e., no epoxy coating), then corrosion will begin once the passive layer dissolves. The passive layer is formed naturally as a result of the alkaline environment the concrete provides (Jones, 1996). Epoxy-coated rebar ideally does not succumb to corrosion; in practice, however, the epoxy layer can be damaged during manufacturing or construction, leading to vulnerabilities where corrosion can occur.

As corrosion continues, rust is produced, which leads to an increase in volume that causes cracks to form. These cracks grow and propagate to cause delaminations, spalls, and popouts over time, which can jeopardize driver safety if they are not addressed (Gucunski et al., 2013).

Although reinforced concrete bridge decks exhibit a variety of deterioration mechanisms, this study chose to focus on two major mechanisms in concrete bridge decks: corrosion of rebar and delamination in concrete.

2.2 Nondestructive Testing Methods for Concrete Bridge Decks

This section describes the NDT methods investigated in this study. A more detailed description of their capabilities and limitations can be found in Appendix A.

2.2.1 Chain Drag and Hammer Sounding

Acoustic methods such as chain drag and hammer sounding are commonly used by inspectors to locate delaminations in bridge decks. Chain drag involves dragging a chain or set of chains on the surface of the deck and listening for a change in the sound. Hammer sounding involves tapping a hammer to more clearly delineate the boundaries of the delaminations.

One limitation of chain drag is that it can only find advanced and severe delaminations. Incipient delaminations generally do not produce a distinguishable sound (Clemeña & McKeel, 1977). Chain drag is inherently subjective since it relies on the operator's experience and hearing ability (e.g., high traffic volume can make hearing the sounds difficult) (Oh, Kee, Arndt, Popovics, & Zhu, 2013). The collection speed depends on the amount of delamination (e.g., a highly delaminated deck will take significantly longer to inspect than one in good condition) (Gucunski et al., 2013).

2.2.2 Infrared Thermography

Infrared (IR) thermography is a NDT method used to locate voids and delaminations beneath the deck surface. An IR camera can capture the thermal radiation emitted from the objects in sight (Gucunski et al., 2013). Variations in temperature caused by a different transfer of heat at delaminations are seen as changes in color. One study found that IR was capable of locating 88% of delaminations at a depth of 2.5″ or less (Yehia, Abudayyeh, Nabulsi, & Abdelqader, 2007).

IR cameras can be handheld or mounted on vehicles and are operable at highway speeds. A majority of the past studies showed that IR can collect reliable data only at depths up to two to three inches; deeper applications will yield faint images or nothing at all (Yehia et al., 2007). IR is highly dependent on the conditions at the site (i.e., it must be a clear sunny day, dry for the previous 24 hours, and calm winds) (ASTM D4788, 2013). If crawling speed or handheld cameras are being used, then lane closures are required. Because of its high-speed capability, IR is a good choice as a screening tool.

2.2.3 Chloride Ion Penetration

The chloride ion penetration method (CIP), also known as the chloride ion concentration profile, can be used either to determine if the environment is suitable for corrosion or to predict when corrosion will begin. The concrete is tested at varying depths to determine when the concentration of chlorides exceeds the threshold for initiation of corrosion. Powder samples are collected from the deck and analyzed. The collection and analysis methods are detailed in AASHTO T260-97 (2011) and ASTM C1218 (2008).

The thresholds used by INDOT Research and Development Division ranged from 1.4 kg/m^3 to 2.8 kg/m^3. NCHRP Report No. 558 recommended threshold ranging from 0.025 to 0.033% by the weight of the concrete (Sohanghpurwala, 2006). Above these thresholds, corrosion is expected to occur. Since CIP testing takes a relatively long period of time, lane closures are required. It is recommended that this method be used only on decks with uncoated rebar unless INDOT assumes a different threshold for epoxy-coated rebar.

2.2.4 Half-Cell Potential

Half-cell potential (HCP) is a method used to determine the probability of active corrosion at discrete locations. HCP utilizes a galvanic system that includes a voltmeter, a reference electrode, and the reinforcing steel bars of interest. Corrosion causes a potential difference to build up in the concrete; and a greater amount of corrosion corresponds to a larger potential difference.

To perform HCP, the rebar must be checked to ensure that the mat is continuous so that the current can flow throughout. A grid is marked on the surface, and each point is wetted before the portable half-cell is put in contact with the surface to measure the potential difference.

ASTM C876 (2011) sets the following thresholds: -0.35 V or less correlates to a 90% probability of corrosion, and -0.20 V or greater correlates to a 90% probability of no corrosion. HCP is one of the most time-consuming methods for collection because of the long set-up time and point-by-point application; also, lane closures are required. ASTM C876 states that only uncoated carbon steel reinforcing bars should be tested since epoxy can disturb the electrical connection.

2.2.5 Ground-Penetrating Radar

Ground-penetrating radar (GPR) is considered a very reliable method for locating rebar, determining concrete cover, and identifying the locations of corrosion and delamination. Electromagnetic radar signals are sent into the deck, pass through the concrete until a change in dielectric properties is detected and then reflect. The rebar, corrosion by-products, voids, and the bottom of the deck have dielectric properties that differ from those of the concrete. It should be noted that GPR detects delaminations not directly but by identifying finding corrosion by-products (Donnelly et al., 2012). The analyst calibrates the data from a known standard, such as ground truths or the evaluator's experience (Gucunski, Feldmann, Romero, Kruschwitz, & Parvardeh, 2010). Bare decks and decks overlaid with concrete or asphalt can be inspected using GPR (ASTM C1218, 2008).

Ground-coupled GPR requires direct contact or very near proximity with the deck, and must be performed at a walking pace. Air-launched horn GPR can be performed at two feet off the deck and at highway speeds up to 50 mph. Ground-coupled GPR can measure the deterioration at each individual rebar, while air-launched horn GPR yields a "condition smear" that shows the general condition near several rebar. One study found that the difference in the quality and accuracy of the data was noticeable but small as the deterioration quantities were found to only have a 4% difference (Maser, Guarino, & Martino, 2014). Moisture and chlorides from deicing salts can affect the readings significantly (Gucunski et al., 2010); therefore, data collection is not recommended during the winter months (Gucunski et al., 2013). Lane closures are required for ground-coupled GPR.

2.2.6 Impact Echo

Impact echo (IE) is another method that can locate delaminations and rebar by introducing an impact to the deck, which causes a wave to propagate through the thickness of the deck until it hits an acoustic impedance, such as a delamination or the bottom of the deck. The frequency response is obtained through Fourier transformations. The deck is considered to be sound concrete without delaminations when the dominant frequency correlates to the thickness of the deck.

When anomalies are present, the thickness will vary and several peaks will appear in the data.

IE can be performed on bare decks, concrete overlays, and even asphaltic overlays when the temperature is low enough to make the surface hard (Gucunski et al., 2013). The SHRP2 R06A study stated that IE is the best NDT method for locating delaminations when considering accuracy and reliability (Gucunski et al., 2013). The IE system consists of an impactor, sensors, and a control unit. Both handheld units and faster, rolling units are available. Significant limitations are associated with IE: (1) data collection and data analysis both take a great deal of time to perform correctly, and (2) it is the slowest method with regard to collection and analysis.

2.3 Benefits of Using Complementary Nondestructive Testing Methods

Several past studies compared the results gathered by different NDT methods in addition to testing the capabilities of each method. The results varied from study to study. Some studies found good correlation between the NDT methods being tested (Gucunski et al., 2010; Oh et al., 2013), while other studies found that the results from the different methods varied significantly (Donnelly et al., 2012; Scott et al., 2002), which of course shows that no one method is perfect in every application. The findings from these studies collectively suggest that using multiple NDTs is a better approach to correctly characterize the deterioration in the deck. Using complementary NDT methods can determine the condition in the deck more accurately while at the same pinpoint the causes of the deterioration since each NDT method specializes in detecting certain deterioration types.

Table 2.1 displays the collection speed and analysis speed for each method. The estimated values were provided by either INDOT personnel, vendors, or manufacturers of the equipment. The chain drag collection speed was highly variable and therefore was estimated based on experience. The air-launched GPR analysis speed was assumed to be the same as the ground-coupled GPR. Chain drag and rapid CIP can both produce results on-site quickly; a value of 10,000 square feet per hour was assumed for analysis purposes.

TABLE 2.1
Data Analysis and Collection Speeds for NDT Methods

Type of NDT	Collection Speed (ft^2/hr)	Analysis Speed (ft^2/hr)
Chain drag	2,000	–
Infrared thermography	48,000	3,000
Chloride ion penetration	3,000	–
Half-cell potential	3,000	3,500
Ground-coupled GPR	4,800	3,200
Air-launched horn GPR	12,000	3,200
Impact echo	1,500	900

3. ANALYTICAL METHODOLOGIES FOR NDT EVALUATION

This section briefly describes the methodologies utilized for the NDT evaluation in this study. Additional details are provided in Appendix B.

3.1 Estimation of Costs

3.1.1 Costs Associated with NDT Inspections

The estimated purchase costs of the NDT equipment and software are shown in Table 3.1. These estimates were provided by the equipment vendors. The annual maintenance cost was estimated as 5% of the original cost. For the NDT methods that require a vehicle, $30,000 was estimated for a large van. The life of the NDT equipment and software was assumed to be five years because technology changes so rapidly.

The personnel recommended for the NDT operations include a team leader hereinafter referred to as the NDT expert, data collectors, and data analysts. The cost of initial training for the NDT expert was estimated to be $15,000, which includes training by manufacturers, attending conferences, and other events that will familiarize the NDT expert with the methods; this cost estimate was obtained from a South Dakota Department of Transportation report (2006).

Although the data collectors and analysts are treated separately in the analysis, they are likely to perform duties that overlap. Therefore, their salaries are assumed to be the same. The initial training for these personnel would be performed in-house by the NDT expert. In addition to the initial training, an annual amount for periodic training is expected for the NDT expert and the analysts, which is assumed to be 5% of their base salary. Finally, the base salary was increased by 30% to estimate the benefits each employee receives. Table 3.2 summarizes the assumed salaries and training allowances.

The cost of travel was calculated by estimating the distance traveled. This distance then was multiplied by the rate of $0.575 per mile (IRS, 2014). Maintenance of traffic (MOT) is a consideration only for the NDTs which require lane closures and includes the costs for the personnel, vehicles, and equipment and varies by the number of lanes. INDOT's MOT hourly cost is based on the number of lanes:

TABLE 3.1
Purchase Cost of NDT Equipment

Type of Nondestructive Method	Combined Cost of Equipment and Software
Infrared thermography	$10,000
Chloride ion penetration	$12,150
Half-cell potential	$14,650
Ground-coupled GPR	$25,350
Air-launched horn GPR	$78,960
Impact echo	$82,500

TABLE 3.2
NDT Personnel Salaries and Training Expenses

Personnel Type	Annual Salary	Salary Including Benefits	Annual Training Allowance
NDT Expert	\$70,000	\$91,000	\$3,500
Data Analyst and Data Collector	\$55,000	\$71,500	\$2,750

two-lane bridges cost \$112 per hour, and multilane (three or more) bridges cost \$150 per hour.

3.1.2 Costs Associated with Deck Work Actions

Four work actions were considered in this study: patching, epoxy overlay, latex-modified concrete (LMC) overlay, and deck replacement. The main assumption regarding work actions was that the decisions were controlled only by the deck itself. In other words, deck work actions occurred because they were needed, independent of work being completed on the substructure or superstructure.

The estimated cost per area is provided in Table 3.3. Patching was measured per square foot of delaminated area, while the other treatments were applied to the whole deck area. The cost of a second overlay was slightly more (\$67 per square foot) because the first overlay must be removed via hydrodemolition.

3.2 Construction of the Deterioration Curve

The deterioration curve used to model the spread of deterioration in the deck was a key aspect of the analysis because planning decisions are to be made based on the percent deterioration.

The data utilized for the deterioration curve were obtained from bridge inspection reports provided by Dr. Victor Hong of INDOT Research and Development Division. Twenty-seven bridge decks were surveyed, and chain drag was conducted on 21 of them. No delaminations were found in five of the decks, and 16 decks had meaningful data. The ages of the decks were obtained from the NBI database.

Since chain drag is known to be capable of detecting only severe delaminations, a factor was necessary to account for incipient delaminations. One study in Iowa researched various NDT methods and compared their results to chain drag results (Donnelly et al., 2012). The quantities of detected delaminated concrete were calculated for each NDT method; and the delamination quantities obtained using IE were divided by the quantities found using chain drag, which yielded a factor of 1.79. The current study therefore assumed 1.79 as a reasonable representative value for the true amount of delaminations versus the chain drag results.

The best fit curve for the factored data was established using Microsoft Excel. An exponential equation was assumed based on knowing that deterioration spreads slowly at first in bridge decks but then accelerates as it spreads. Using nonlinear regression, the best fit curve was determined as shown by Equation 3.1.

TABLE 3.3
Unit Cost of Deck Work Actions

Type of Work Action	Cost per Square Foot
Patching	\$45
Epoxy overlay	\$15
LMC overlay	\$60
Replacement	\$95

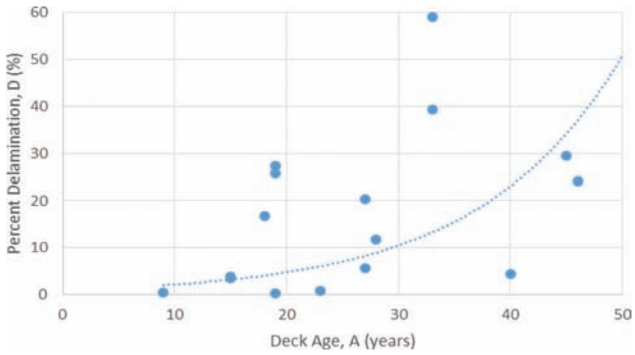


Figure 3.1 INDOT chain drag data and deterioration curve.

$$D = 0.98\, e^{0.079\, A} \tag{3.1}$$

where A is the age of the deck, which is explained in Section 3.3.2, and D is the percentage of delamination in the deck. Figure 3.1 shows the discrete factored chain drag data points and the curve from Equation 3.1. In reality, there is no delamination at age 0. Thus, a correction was added to make the deterioration 0 when the deck is new; Equation 3.2 shows the final deterioration curve.

$$D = 0.98\, e^{0.079\, A} - 0.98 \tag{3.2}$$

3.3 Cost-Benefit Analysis Approach

3.3.1 Explanation of Economic Variables and Calculations

The cost-benefit analysis (CBA) in this study was unique in that it did not consider benefits as such, but rather determined the best option with the least costs over the analysis period. The commonly used conservative discount rate of 4% was used in this study.

The NPC is the present worth of all future costs discounted according to their respective year (MnDOT, n.d.). The NPC calculation is shown in Equation 3.3, where C represents the capital costs, annual costs, and any other future costs that arise; i represents the discount rate; and n is the year corresponding to C.

$$NPC = \sum_{t=o}^{n} \frac{C}{(1+i)^n} \tag{3.3}$$

The NPC can be converted to the equivalent uniform annual cost (EUAC) using Equation 3.4. Using the interest rate i, the future worth of the NPC is spread out in equal annual amounts. The interest rate is the same value as the discount rate; the changed name relates only to its usage. The discount rate decreases the value of the future costs when converted to present values, while the interest rate compounds the costs when converting present costs to future costs. The EUAC is important because of its ability to compare the costs of projects with differing lifetimes or analysis periods. Since the EUAC is not the actual amount that will be spent per year but rather a representation of the capital and future costs, its output is more conceptual than meaningful, which makes it useful for comparing alternatives. The option with the lowest EUAC thus is the best cost-effective choice.

$$EUAC = NPC \frac{i(1+i)}{(1+i)^n - 1} \tag{3.4}$$

3.3.2 Description of Network-Level Analysis and Assumptions Made

Many aspects of the analysis in this study apply to the project-level comparisons, which are discussed in Section 3.3.3. Every bridge in the entire Indiana bridge inventory was inspected and maintained throughout its lifetime or until the analysis simulation ended. It was assumed that a bridge's service life ended at 100 years or when certain criteria were met based on the work actions on the bridge deck. The NDT methods used for the network-level analysis were IR and air-launched GPR since they are the only methods capable of operating at highway speeds. One crucial aspect of this study was the decision matrix, which indicated the percentage of chance that work actions would occur on a bridge deck given the percentage of delamination detected. Table 3.4 shows the decision matrix used in this study.

The simulation was probabilistic because of the decision matrix. Each action had a percentage of likelihood of occurrence based on the percentage of delamination of the deck found by inspection. For example, if a deck had 13% delamination, then there was a 10% chance of no work action, a 15% chance of patching, a 40% chance of LMC overlay, and a 25% chance of replacement. Each probability was based on expert judgment. A range of deterioration limits, shown in the left column of Table 3.4, was also assumed. When delamination was above 25%, the deck likely would need to be replaced because of serious degradation of the surface. Two other decision matrices were used in the simulation in certain instances to prevent unrealistic sequences of work actions. When a replacement occurs on a deck, the next major work action cannot be another replacement. Similarly, when two overlays have taken place, the next major work action cannot be an overlay.

The analysis start year was 2015, with inspections and decisions made annually. The life of the bridge system – deck, superstructure, and substructure – was assumed to be 100 years based on INDOT initiatives and expert judgment. The analysis period therefore was 100 years, which was the maximum value. The service lives of bridges that were built before 2015 ended when the bridge reached 100 years. Additionally, the bridge's service life ended if three major actions occurred in the analysis period. Three major actions of either two LMC overlays or a deck replacement were a limiting factor in the analysis because of INDOT's programmatic procedures assume that after an overlay, a replacement, and another overlay are performed, no further work is assumed to be cost-effective. Therefore, the bridge's service life is assumed to end based on the remaining life provided by the third work action. This study assumed that the bridge was taken out of service 10 years after an LMC overlay and 20 years after a replacement. For example, if a bridge had a replacement for its third major action at age 70, then the analysis ended when the

TABLE 3.4
Decision Matrix

Deterioration Limits (Percent Delamination)	Work Action				
	Do Nothing	Patching	Epoxy Overlay	LMC Overlay	Replacement
0–2.5	90	10	0	0	0
2.5–5	70	20	10	0	0
5–10	35	25	5	25	10
10–15	10	15	0	40	25
15–20	5	10	0	35	50
20–25	0	5	0	10	85
>25	0	0	0	0	100

bridge age reached 90. These remaining lives are conservative and are based on expert judgment.

The age of the bridge deck was crucial to this study because age was an input for the deterioration curve. The NBI data used in this study did not provide detailed information on the history of past work actions, but it did indicate when the last reconstruction occurred. Since this was assumed to be a major action, the deck age started at zero in that year. If there was no information about the last reconstruction, then the deck age was assumed to start in the year the bridge was built, which led to some very old decks remaining in service with unacceptable delamination levels. This is an unfortunate consequence of the lack of detailed data. Replacements were performed on these decks after the first inspection.

Each bridge was placed in a loading category based on its annual daily truck traffic (ADTT) rating: 1 indicates an ADTT less than 100, 3 is an ADTT greater than 500, and 2 is in between the previous two ratings. ADTT ratings of 2 and 3 require more frequent inspections. The ADTT category values in this study are the same as those used in a University of Nebraska study (Hatami & Morcous, 2012).

The inspection frequency was an assumed value based on the ADTT category and the age of the deck. Table 3.5 shows how this was determined. The traffic on the bridge combined with the load environment reflects the importance of these bridges and their likelihood for significant damages. INDOT proposed a simpler method for assigning frequency that reflects the importance of Interstate and NHS bridges: bridges on the Interstate system are inspected every two years, bridges on the other National Highway System (NHS) roads are inspected every four years, and all other bridges are inspected every six years.

Each work action had a corresponding effect on the assumed deterioration level. Patching and epoxy overlay were considered minor actions so they simply reduced the degree of deck delamination, as shown in Table 3.6. These actions are more effective when the deterioration levels are low and are less effective when the levels are high. If this were not the case, then minor actions more often than not would likely be more cost-effective than a LMC overlay. A deck that requires 3% patching will leave 1.2% delamination after the action takes place, while a deck requiring 22% patching will leave 19.8% delamination.

Major actions have a more lasting effect than minor actions in the real world. As such, the simulation in this study used a conceptual variable called "modified age" to achieve this distinction. When a major action was triggered, the actual deck age was reduced to yield the modified age due to the rejuvenating effects of the action. Age and deterioration are linked; by reducing the age, the deterioration also was reduced. Additionally, the deterioration rate was reduced when the age was decreased. Figure 3.2 illustrates the difference between the bridge age, actual deck age, and modified deck age. Figure 3.3 shows the different effects that work actions have on deterioration (Sinha & Labi, 2017).

For analysis purposes, a deck replacement resets the modified age to zero. A LMC overlay decreases the modified age by a certain percentage. For decks that have modified ages of less than 50 years, a LMC overlay decreases the modified age by 80%; if the deck is 50 years or older, then it will decrease the modified age by 60%. This decrease will change if the last major action was also an overlay because a second consecutive overlay is typically not as effective as the first. The modified age reduction for decks younger than 50 years

TABLE 3.5
Frequency of Inspections Determination (Years)

	Deck Age, A (years)			
ADTT Loading Category	**$A < 25$**	**$25 < A < 50$**	**$50 < A < 55$**	**$A > 55$**
1	7	6	5	2
2	6	5	4	2
3	5	4	3	2

TABLE 3.6
Percent of Delaminated Area Repaired by Minor Work Actions

	Delamination Reduction by Action Type	
Deterioration Limit (Percent Delamination)	**Patching**	**Epoxy Overlay**
0 – 2.5	80	99
2.5 – 5	60	80
5 – 10	40	60
10 – 15	20	40
15 – 20	10	30
20 – 25	10	30
>25	10	30

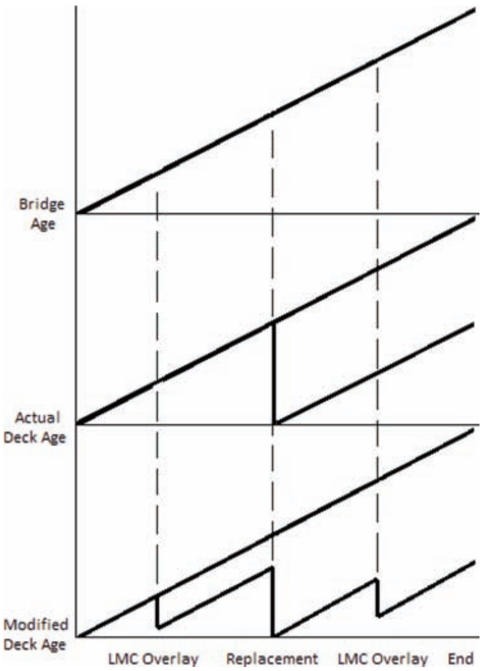
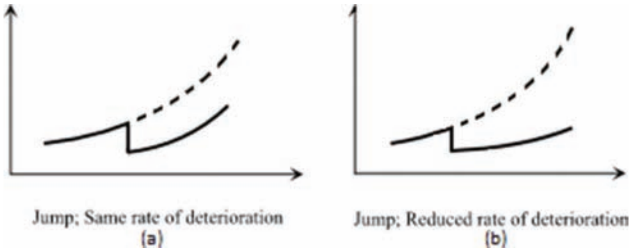


Figure 3.2 Effect of work actions on age variables.



Jump; Same rate of deterioration (a)

Jump; Reduced rate of deterioration (b)

Figure 3.3 Differing effect of work actions on deterioration. (Modified from Sinha & Labi, 2015.)

old is 40% while that for decks 50 years or older is assumed to be 30%.

The NDT collection crews were assumed to spend four hours per day collecting data and four hours per day in transit to the sites. Analysts were assumed to spend eight hours per day analyzing the results and preparing reports. The number of days spent collecting data was assumed to be 140 based on the limitations of IR, which can be used only on sunny days, and there are approximately 200 sunny days per year in Indiana (NOAA, 2012); then, adjusting for the perceived work week therefore left only 140 work days. The office location was assumed to be INDOT Research and Development Division in West Lafayette. The distance traveled and the required number of crews were calculated based on the assumption that the areas of the decks that require annual inspections were inspected. In other words, the area of the deck that must be inspected was calculated first, then the distance traveled and the number of crews needed to inspect the deck area was calculated.

Assuming a collection crew takes one trip per day, the area per trip was calculated by multiplying the NDT collection speed by four hours. The required trips is the area of inspection required divided by the area per trip. The number of crews needed to inspect that required area was calculated based on the required trips and the number of days the crew is collecting. The average latitude and longitude were known for the decks being inspected on each trip, and the distance between these averages and the office latitude and longitude is the total distance for each trip. Knowing the number of trips, the distance traveled was calculated.

3.3.3 Description of Project-Level Analysis

The project-level analysis was conducted in two parts: a comparison of the strengths and weaknesses of the various NDT methods and a comparison of the NDT methods to INDOT's current practices. Both of these analyses included a simulated inspection of 30 bridges.

The purpose of the comparison of the NDT methods was to determine which NDT method was the best choice from a cost standpoint as well as to determine the best combination of NDT methods to meet INDOT's needs. The costs considered included equipment and software, maintenance, MOT, and inspectors' wages. The costs first were represented as the annual cost of inspecting 30 bridges for the lifetime of the bridge decks. The inspector costs and MOT costs were determined by calculating the time spent collecting and analyzing data, which were then multiplied by the hourly wage of the analyst or the hourly rate for the MOT. The purchase cost of the equipment and software was divided by the assumed life of the NDT equipment. This cost then was added to the inspection, MOT, and annual maintenance costs. The second way the costs were represented was simply as a per-bridge cost. The sum of the equipment, maintenance, inspection, and MOT costs was divided by the number of bridges being inspected. The least costly NDT method and combination of NDT methods were selected by comparing both of these representative costs.

The project-level comparison of the NDT methods to INDOT's current practices was similar to the network-level comparison in most regards. One difference was that the inspection cost did not account for the annual salaries of data collectors and analysts; instead, the hourly wage equivalent of their salaries was multiplied by the hours spent analyzing and collecting data. In addition, while a NDT expert position was not included in the project-level analysis, the network level does include this expert because a large-scale NDT operation requires the coordination and supervision of a project team. The other difference was that only a small portion of the bridge inventory (30 bridges) was investigated at the project level.

3.4 Visual Inspection and Programmatic Planning of Work Actions

Two approaches to bridge deck management were considered in this study: the current INDOT programmatic scheduling of work actions and the condition-based NDT evaluation of deck deterioration upon which the planning and execution of appropriate work actions are based.

The current scheduling of work actions is based primarily on the age and general condition of the bridge. The problem with doing work actions programmatically, such as by age, without thorough condition-based assessment is that the work that should be undertaken is not always the work that is chosen. One study found that using NDT methods versus programmatic actions led to a different action in 53% of the cases (Carmichael, Maser, Stevenson, & Halloran, 2014).

INDOT provided a general schedule followed in the past, and three more schedules also were considered in this study. Work Schedule 1 involves performing an overlay at 20 years, a replacement 20 years thereafter, a second overlay after another 20 years, and 20 years later the bridge is taken out of service at age 80. This schedule is shown in Table 3.7. The frequency of patching was assumed to be halfway between each major action. The other work schedules are displayed in Tables 3.8, 3.9, and 3.10. Origin refers to year 0.

TABLE 3.7
Programmatic Schedules for Major Work Actions, Schedule 1

Action	Years After Origin
Overlay	20
Replacement	40
Overlay	60
End of Bridge Life	80

TABLE 3.8
Programmatic Schedules for Major Work Actions, Schedule 2

Action	Years After Origin
Overlay	20
Replacement	40
Overlay	60
Replacement	80
End of Bridge Life	100

TABLE 3.9
Programmatic Schedules for Major Work Actions, Schedule 3

Action	Years After Origin
Overlay	22
Overlay	40
Replacement	53
Overlay	75
Overlay	93
End of Bridge Life	106

TABLE 3.10
Programmatic Schedules for Major Work Actions, Schedule 4

Action	Years After Origin
Overlay	22
Overlay	40
Replacement	53
Overlay	75
Overlay	93
Replacement	106
End of Bridge Life	128

3.5 Consultant Data Collection and Analysis

Performing data collection and analysis in-house has been the assumption thus far; however, there are many consultants available to collect, analyze, and present deterioration data for bridge decks. Two consultants participated in this study: one provided a cost estimate of $0.08 per square foot while the other submitted a similar estimate. Consultants' estimates can vary based on the scale and proximity of the bridge decks as well as the extent of the investigations. The price ranges are described in more detail in Section 4.2.2. These cost estimates provided a cost figure with which to calculate the cost of consultant-based inspection and to conduct the comparison to the in-house inspection option.

4. ANALYSES RESULTS AND DISCUSSION

The results from the project- and network-level analyses are discussed in this section. A more detailed discussion is provided in Appendix C.

The base case for the condition-based inspection and work action cost is the set of variables that are most representative of the true conditions in the field. This set of variables will produce simulations of the NDT inspection and work action costs that are as realistic as possible. The key variables in the network-level base case include 140 days of NDT inspection per year, 200 days of NDT analysis annually, a discount rate of 4%, a 20 year remaining life following the final work action if that work action was a deck replacement, and a 10 year remaining life following an LMC overlay as the final work action. These variables were used for the majority of the simulations, but two additional cases were also explored to evaluate the sensitivity of variations of the base variables.

The simulations are probabilistic in nature, and the results vary somewhat each time the simulation is run. For a given bridge deck, different decisions can be made each time the simulation is run, which would produce a slightly different cost. To evaluate the analysis routine, the base case was run one hundred times for the entire inventory of bridges in the system using the network-level simulation. It was found that very small variations in the results occurred with correspondingly low coefficients of variation. Consequently, it was concluded that it was sufficient to run five simulations when investigating the effect of each variable.

4.1 Project-Level Usage of Nondestructive Testing Methods

4.1.1 Comparison of NDT Methods with Each Other

Since it was not within the scope of this study to use NDT methods first-hand to quantitatively estimate accuracy, it was assumed that each NDT provided the same accuracy in locating deterioration. The only difference in this comparison is that the cost incurred by each was related to equipment, maintenance, inspection, and MOT.

Table 4.1 shows the results gathered applying each NDT method on 30 bridge decks randomly selected from Indiana's inventory. The least expensive method was IR for both the one-year cost and the cost per bridge because the equipment cost is the least expensive and the collection and analysis speeds are relatively fast. It should be noted that the collection speed was reduced by a factor of five for project-level inspection to ensure that the best quality photographs were collected. The most expensive option was IE by far because of the high equipment cost and the slow collection and analysis speeds.

The best methods from the annual cost only perspective were IR, ground-coupled GPR, and CIP, which also constitute one of the combinations considered in this study and is discussed below. Two other sets of NDT methods were part of the cost comparison as well. As mentioned in Section 2.3, it is prudent to use a combination of NDT methods capable of locating different types of deterioration. Table 4.2 shows the costs from these three combinations.

The combination of CIP, IR, and ground-coupled GPR was the least expensive option and was used for the comparison of the NDT methods to current INDOT programmatic scheduling in the next section. Using a combination of NDT methods that can locate corrosion and delamination in practice makes the inspection more robust than any one method. In the simulation, however, only delaminations were considered. It was therefore assumed that one NDT method collectively located deterioration in the bridge deck, which allowed for the use of one deterioration equation even though it is not representative of reality but is considered acceptable to allow for a simpler analysis.

4.1.2 Comparison of Condition-based and Programmatic Scheduling of Work Actions

The base case variables described earlier were used for the five sets of 30 bridge decks investigated in the simulations. Table 4.3 shows sample results from one of the sets. In contrast, Table 4.4 shows the results from each of the schedules that implement the INDOT programmatic planning of work actions.

The NPC is the sum of each cost incurred during the analysis normalized to present day value through the discount rate. The EUAC is the representation of the NPC as equal annual payments, which is conceptually used to compare analyses within different time periods. Since no inspection cost was associated with

TABLE 4.1
Comparison between Costs of NDTs on the Project Level

Type NDT	Cost for One Year ($)	Cost per Bridge ($)	Annual Cost ($/sq. ft.)	Cost per Bridge ($/sq. ft.)
GPR (ground)	16,600	1,230	0.08	0.01
IR	8,900	560	0.04	<0.01
CIP	16,570	880	0.08	<0.01
HCP	18,530	1,010	0.09	0.01
IE	54,250	4,010	0.27	0.02
Chain drag	19,970	670	0.10	<0.01

TABLE 4.2
Combinations of NDTs and Their Respective Costs of Inspection

NDT Combinations	Cost for One Year ($)	Cost per Bridge ($)	Cost for One Year ($/sq. ft.)	Cost per Bridge ($/sq. ft.)
GPR, HCP, and IR	45,330	2,840	0.23	0.01
IE and CIP	71,100	4,900	0.35	0.02
CIP, IR, and GPR	43,040	2,700	0.21	0.01

TABLE 4.3
Sample Results from NDT Usage on Bridge Set 1, Project Level

EUAC ($)	NPC ($)	Inspection NPC ($)	Repair NPC ($)	Average Service Life (years)	Average Percent Delamination
627 K	15.4 M	816 K	14.5 M	99.5	5.3

TABLE 4.4
Sample Results from Four INDOT Programmatic Planning Schedules on Bridge Set 1, Project Level

	EUAC ($)	NPC ($)	Average Service Life (years)	Average Percent Delamination
Schedule 1	771 K	18.4 M	80	2.5
Schedule 2	950 K	23.3 M	100	1.9
Schedule 3	883 K	21.7 M	106	2.1
Schedule 4	960 K	23.9 M	128	1.8

TABLE 4.5
Results from Four INDOT Programmatic Planning Schedules and Results from Base Case, Network Level

	EUAC ($)	NPC ($)	Age (years)	Average Percent Delamination
Schedule 1	203 M	4.86 B	80	1.8
Schedule 2	245 M	5.99 B	100	1.5
Schedule 3	212 M	5.21 B	106	2.1
Schedule 4	227 M	5.64 B	128	1.8
NDT Option	136 M	3.33 B	99.0	7.6

the INDOT programmatic schedule, its NPC was shown as only the costs of the work actions. The average bridge service life is the average value representing the average time at which the serviceable life of the bridges ends. The average percentage of delamination is the average condition of each bridge from each year of its life during the analysis. A higher average percentage of delamination indicates poor condition.

In the example bridge set shown, the disparity in costs between the inspection NPC and the work action NPC was remarkable in that the inspection costs only accounted for 5% of the overall NPC while the work action costs accounted for 95%. The NDT inspection led to an EUAC of $626,000, and the overall NPC was $15.4 million. Every programmatic schedule implemented by INDOT resulted in a higher EUAC and NPC. Schedule 1, the least expensive option, was about 23% more expensive than the NDT option. The most costly option was about 53% more expensive. These options cost more because work actions were performed earlier than necessary. By utilizing NDT methods, the correct work action can be performed at a later, more appropriate time.

Most of the INDOT programmatic schedules recommended taking bridges out of service at the same time or earlier than the NDT methods. A better average condition was maintained using the INDOT programmatic schedules; however, the better condition and longer life were achieved at a higher cost because more actions were performed throughout the life of the structure to obtain a much lower percentage of delamination. On average, the costs were about 52% higher when the INDOT programmatic schedules. Based on these results, it was determined that, on the project level, the use of NDT methods is not only feasible, but is more cost-effective than the INDOT programmatic scheduling.

4.2 Network-Level Usage of Nondestructive Testing Methods

4.2.1 Comparison of Condition-based Scheduling and Programmatic Scheduling

Table 4.5 shows the results when NDT methods were used to determine the condition of a bridge deck and to make work action decisions. When compared to the current INDOT programmatic schedules, once again, implementing the NDT methods was more cost-effective in the long run. The EUAC and NPC for each programmatic schedule were at least 40% more expensive compared to the NDT methods. In addition, the average bridge age when taken out of service was generally higher using INDOT's programmatic schedules, and the average delamination was about five times less. This increase in longevity and decrease in delamination was made possible by more major actions and, consequently, expending more funding.

The least costly INDOT programmatic schedule had an EUAC 49% higher and a NPC 46% higher than the NDT option. Both the EUAC and NPC were significantly less using the NDT methods, making them a more cost-effective choice. Also, it is apparent that when an inspection NPC of $19.6 million was compared to a work action NPC of $3.31 billion, the inspection cost was dwarfed by the work action cost, which was only 1% of the work action NPC. The funding required to initiate and maintain an active, functional NDT inspection and analysis team is not trivial. However, the savings realized by reducing the work action costs is a worthwhile investment for INDOT. Using NDT methods at the network level also appear to be cost-effective.

4.2.2 Comparison of In-house NDT Usage to Contracting a Consultant

The previous options considered in-house NDT by INDOT. This section looks into the possibility of contracting with a consultant for data collection and analysis. Two consultants were contacted, both of which utilize IR and air-launched GPR for inspection. The estimated cost ranges are shown in Table 4.6.

Prices of $0.10, $0.20, and $0.30 per square foot were selected for the analysis of how the costs compare to the in-house option. The area of decks needing inspection was multiplied by the cost per square foot. At $0.20 per square foot, the cost was less than the base case inspection NPC of $19.57 million, while the upper limit was more expensive. Using a simple linear interpolation, the break-even consultant cost was set at $0.22 per square foot. Thus, when a consultant is able to do the work for less than this value, it would be more cost-effective to hire the consultant than perform the NDT operation in-house. It should be noted that this recommendation was based strictly on the cost of the work and did not consider the technical merits of the consultant.

TABLE 4.6
Consultant Price Ranges

Consultant Number	Low End of Price Range ($/sq. ft.)	High End of Price Range ($/sq. ft.)
1	$0.08	$0.20
2	$0.07	$0.30

4.3 Sensitivity Analysis to Changing Variables on the Network Level

A sensitivity analysis was performed to investigate the variation in the collective costs, age, and condition of the bridge inventory in response to changes in the input variables. The decision matrix, number of inspection and analysis days, NDT equipment life, remaining life of final treatment (replacement or LMC overlay), deterioration limits, discount rate, and inspection frequency all varied and the outputs are shown below.

When the decision matrix was changed to make more invasive actions, such as a LMC overlay and a replacement, the EUAC increased by almost 4%. Accordingly, when less invasive actions such as patching and epoxy overlay were made, the EUAC was likely to decrease nearly 4%. When the less invasive matrix was used, minor actions were undertaken sooner. This approach delayed major actions from occurring, but only a minor decrease in costs. Figure 4.1 shows the results.

The number of inspection and analysis days in the base case were increased and decreased. The overall costs did not change significantly, but the inspection costs did. By increasing the number of days available for inspecting and analyzing, the number of collectors and analysts required decreased; similarly, when inspection was conducted in a smaller timeframe, the required personnel increased, which directly affected the inspection costs due to increased personnel salaries. The results can be found in Figures 4.2 and 4.3.

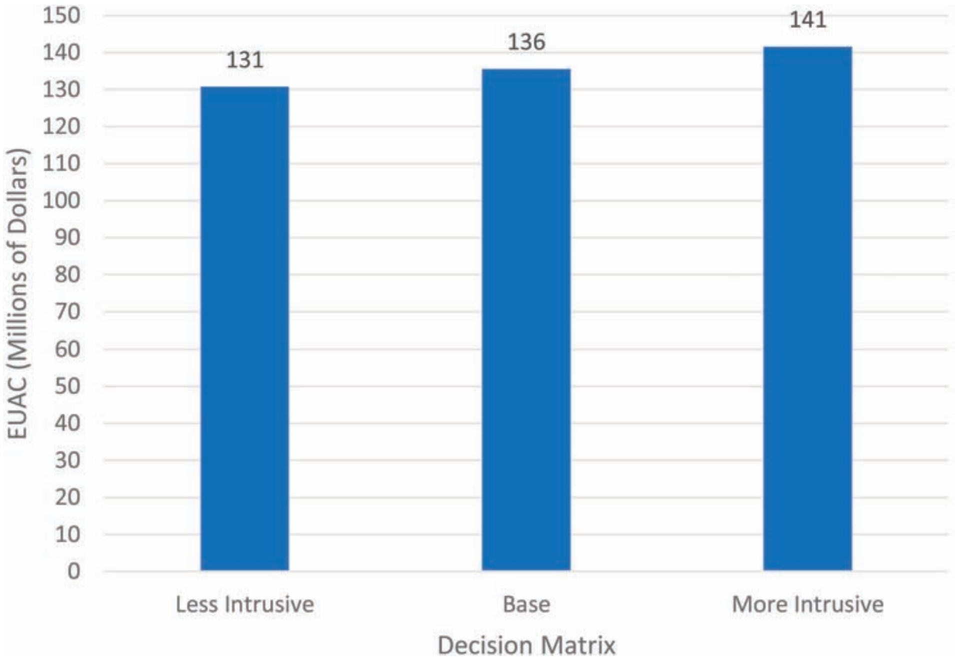


Figure 4.1 Impact on EUAC by changing the decision matrix.

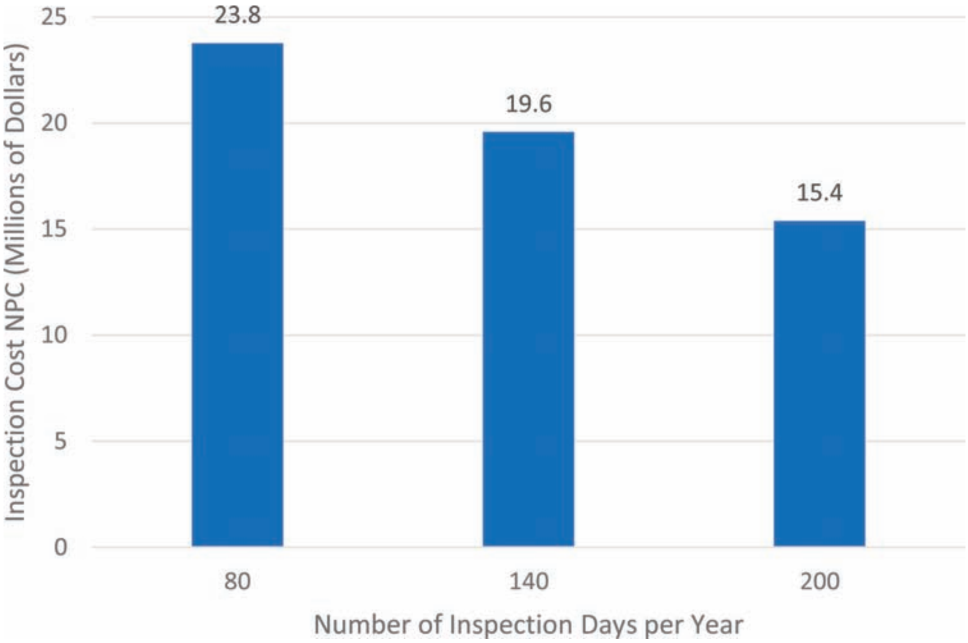


Figure 4.2 Impact on inspection NPC by changing inspection days.

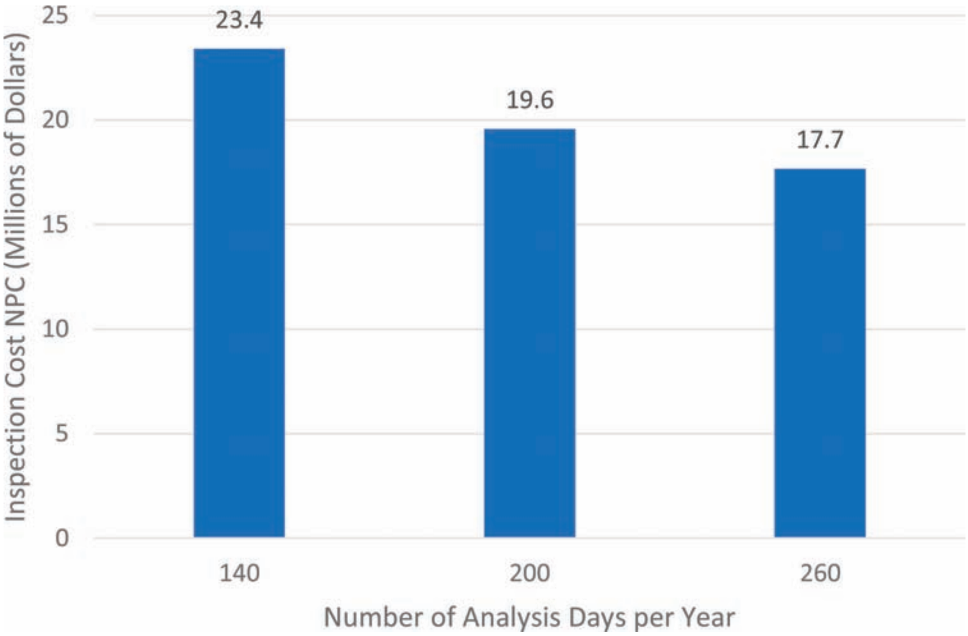


Figure 4.3 Impact on inspection NPC by changing the number of analysis days.

Changing the NDT equipment life led to negligible changes in all of the costs, indicating that NDT equipment life has only a minor impact on the analysis outcomes.

The remaining life of the last major action (LMC overlay or replacement) was altered to add more years and fewer years. Figure 4.4 displays the results. The only affected variable was the average service life of the bridges. It is no surprise that increasing the remaining life of the last action also increased the average age of the bridges.

The deterioration limits had perhaps the greatest impact on the outcomes. Stricter limits (Table 4.7) resulted in increased costs, improved conditions, and decreased service lives. This result makes sense because spending more money improves condition, and having stricter limits means ending service lives sooner before the conditions of bridges markedly deteriorate. The results are presented in Figures 4.5, 4.6, and 4.7.

Changing the discount rate and interest rate led to predictable changes in the NPC and EUAC. Increasing the discount rate led to a lower NPC, while increasing

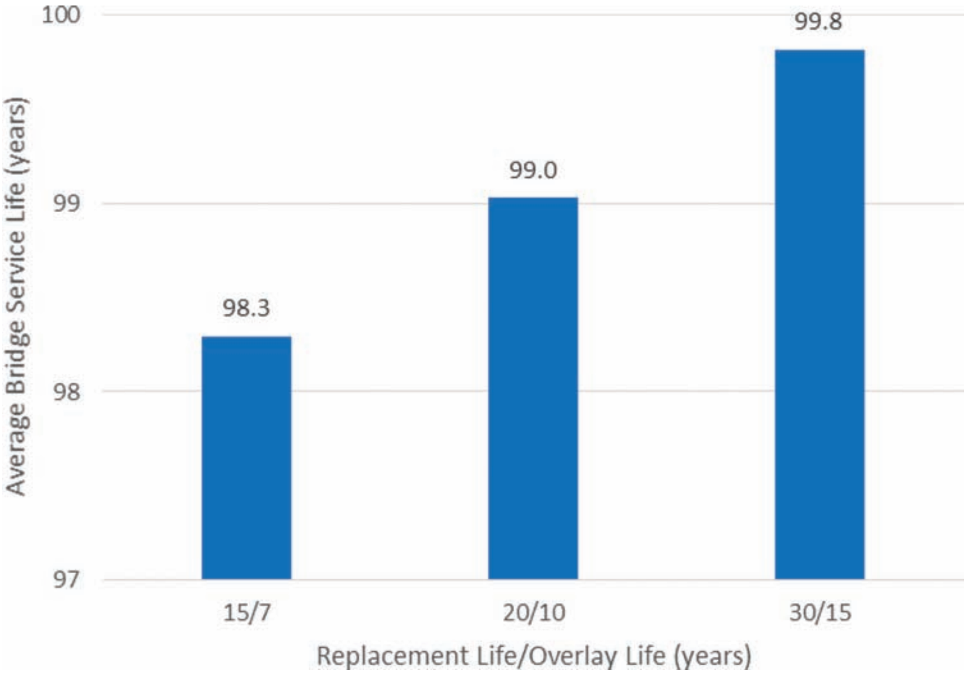


Figure 4.4 Impact on bridge service life by changing remaining life of replacement and LMC overlay.

TABLE 4.7
Deterioration Limits of Percent Delamination Used in the Decision Matrix

Stricter	Base Case	More Lenient
0–1	0–2.5	0–5
1–2.5	2.5–5	5–10
2.5–5	5–10	10–20
5–7.5	10–15	20–30
7.5–10	15–20	30–40
10–15	20–25	40–50
15 +	25 +	50 +

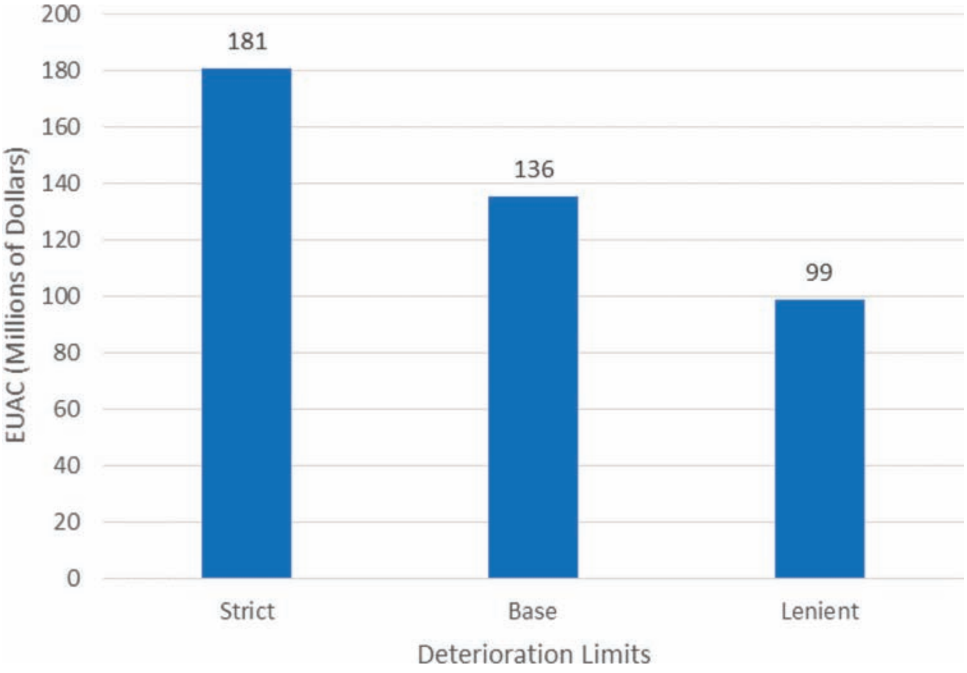


Figure 4.5 Impact on EUAC by changing the deterioration thresholds for intervention.

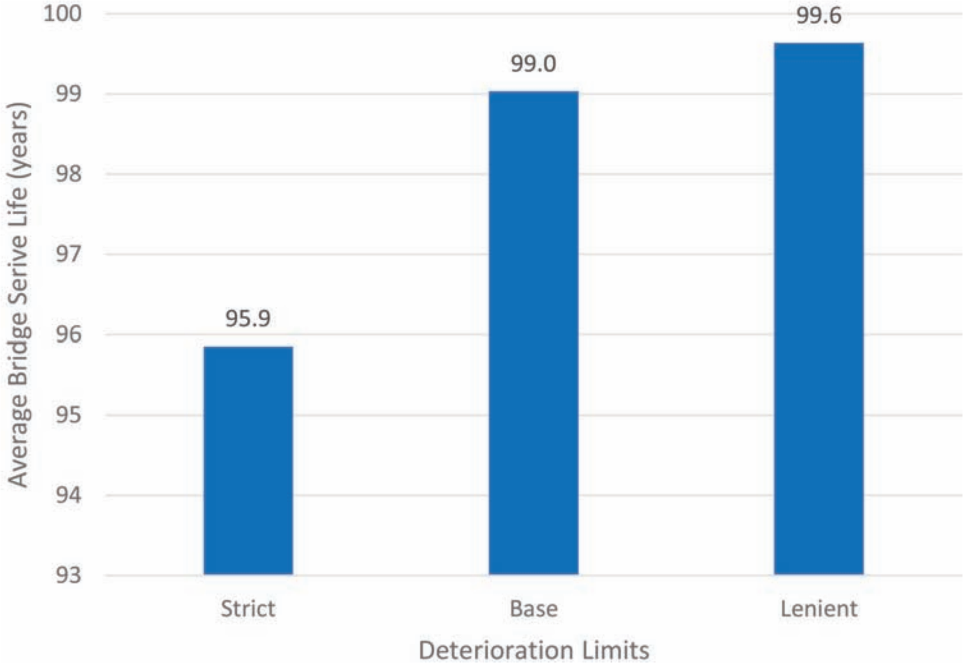


Figure 4.6 Impact on average bridge service life by changing the deterioration limits.

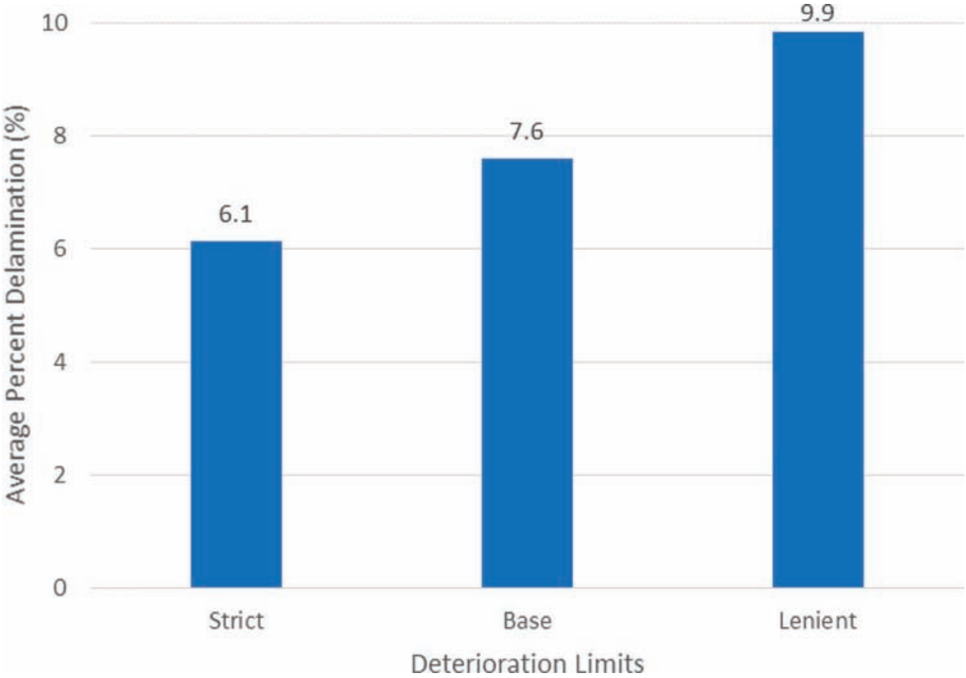


Figure 4.7 Impact on average percent delamination by changing the deterioration limits.

the interest rate led to a higher EUAC. The opposite was true when the rates were decreased. These trends were expected and are shown in Figures 4.8 and 4.9.

Inspection frequency was determined by highway classification instead of ADTT and age, and as a result, the costs changed. Inspection costs increased by more than 40%; and because the bridges were inspected more often, more inspectors and analysts were required. However, the EUAC only increased by 6%, further reinforcing the conclusion that inspection costs do not impact the overall cost significantly. Table 4.8 shows the results.

Restricting the size of the area inspected and the number of bridges inspected could potentially lead to a decrease in costs. It was shown that only inspecting travel lanes did not significantly impact the inspection

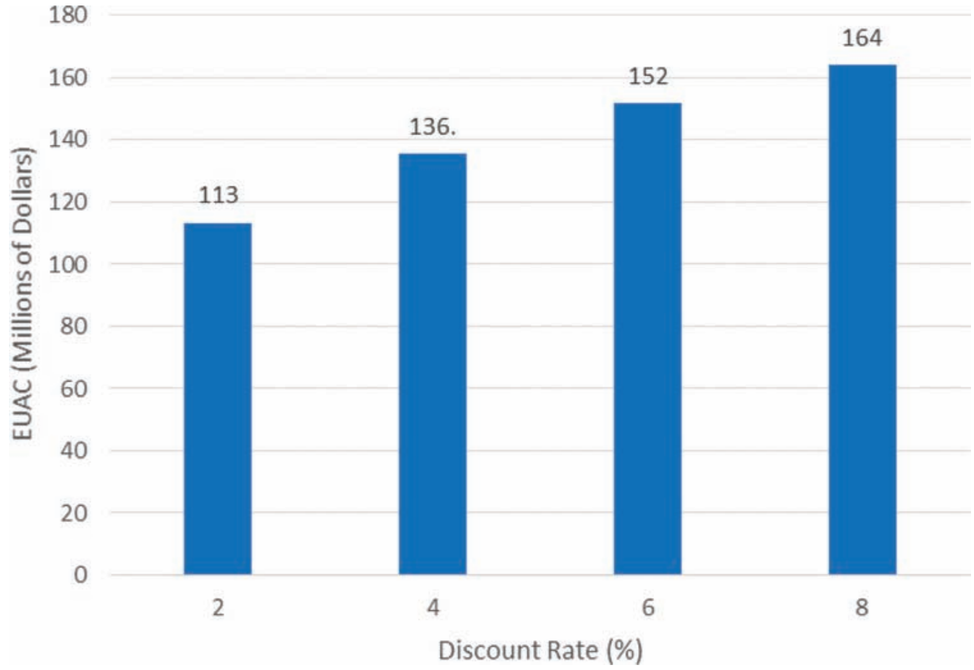


Figure 4.8 Impact on EUAC by changing the interest rate.

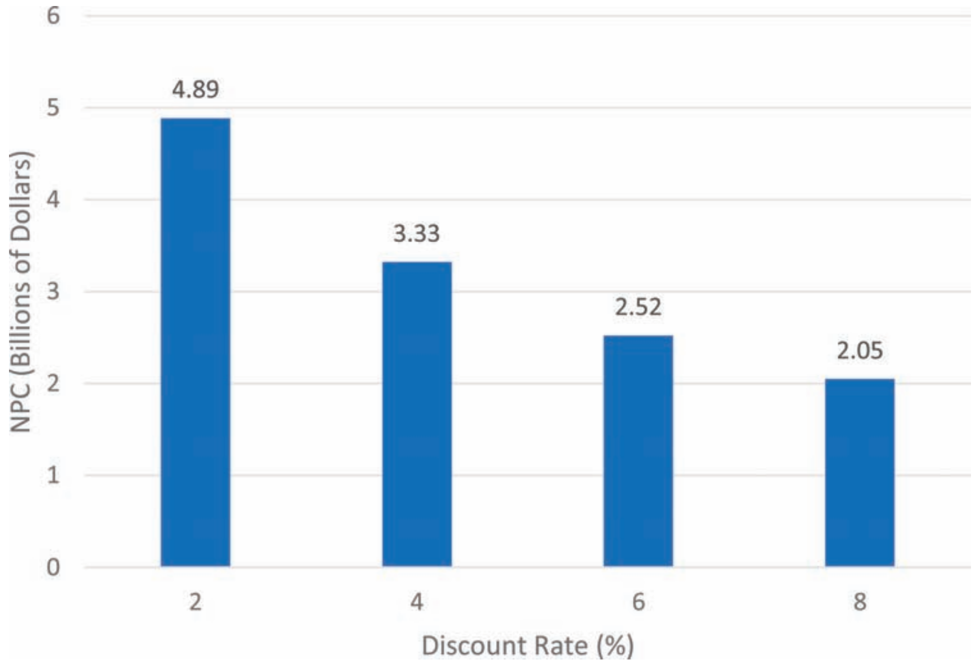


Figure 4.9 Impact on NPC by changing the discount rate.

TABLE 4.8
Comparing Results between Different Frequencies of Inspection Options

	EUAC ($)	NPC ($)	Inspection NPC ($)	Repair NPC ($)	Age (years)	Average Percent Delamination
Base Frequency	136 M	3.33 B	19.6 M	3.31 B	99.0	7.6
Alternate Frequency	145 M	3.54 B	27.8 M	3.51 B	99.1	7.4

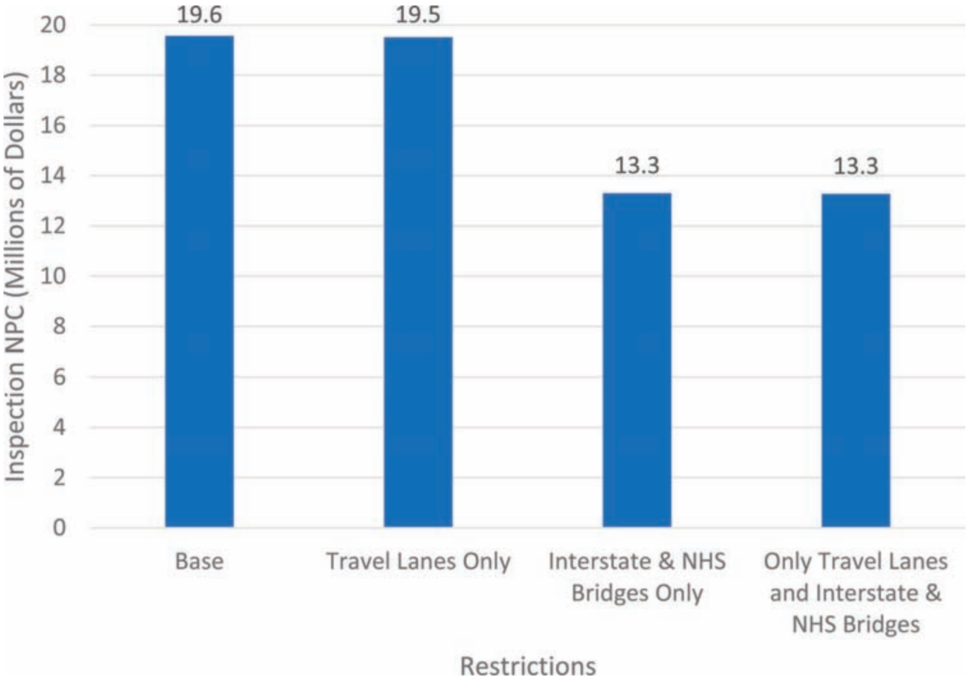


Figure 4.10 Impact on EUAC by adding restrictions to area and bridge highway classification.

costs, but inspecting Interstate and NHS bridges only did have an impact. The costs decreased by 32% when only the high-priority bridges were inspected. The results from these simulations are presented in Figure 4.10.

5. CONCLUSIONS

5.1 Summary and Conclusions

The coordination and planning for bridge deck work actions can be vastly improved by acquiring as much information as possible about the deck's condition. The main objective of this study was to investigate whether or not implementation of NDT methods would be more cost-effective for INDOT than its current practices.

The literature review revealed that past studies concluded that the NDT methods investigated in this study are capable of locating a great deal more information about corrosion and delaminations than visual inspection only. Several studies also confirmed the value of using complementary NDTs, which was also a part of this study.

The data collection and analysis for the simulations of the economic impact of NDT inspections were assumed to be performed in-house by INDOT; and cost estimates for conducting NDT inspections and the ultimately recommended work actions were provided by INDOT personnel and equipment vendors. The deterioration curve in our simulations was based on chain drag data collected by INDOT, which was factored to account for the incipient delaminations typically not found using chain drag. The ultimate assumed decision matrix relied on probability to determine the timing and type of work actions that should be performed.

The first project-level analysis compared the individual costs of the NDT methods being considered. The least expensive method was IR thermography, and the best combination of NDT methods from a cost perspective consisted of CIP, IR, and ground-coupled GPR. The second project-level analysis involved simulations of the inspection and work action of random decks throughout their assumed lifetimes. Five sets of 30 bridge decks were investigated utilizing the CIP, IR, and ground-coupled GPR combination for inspections. The NPC and EUAC were calculated for the condition-based NDT inspection program and the current INDOT programmatic schedules. The least expensive INDOT programmatic schedule was 23% more than the NDT alternative, and the most expensive INDOT schedule increased the EUAC by 54%.

The analysis was then expanded to network-level inspections and work actions for the entire bridge inventory in Indiana, which produced the following similar results. Using the NDT methods led to a decrease in the EUAC by at least 45% when compared to the INDOT schedules. The average percentage of delamination was lower when the INDOT schedules were in place; however, the improvement was achieved by performing more work actions, which increased the costs.

Hypothetically, performing major work actions every few years would assure that bridge decks are continually in excellent condition, but it cannot happen without exorbitant costs. The primary advantage of using the NDT methods, based on the quality of the condition data they produce, is that major actions are performed on bridge decks as needed rather than as scheduled. Therefore, the cost savings generated by using NDT methods far outweigh the improved condition achieved by using the INDOT schedules.

INDOT's establishment of an in-house network-level NDT group was compared to contracting NDT services through a consultant. The break-even point was determined as $0.22 per square foot based on cost estimates from two consultants. Therefore, if a consultant can provide its services for less than $0.22 per square foot of deck area,its services would be more economically feasible than in-house data collection and analysis.

Using the NDT methods will allow INDOT inspectors to more accurately reveal deteriorations that otherwise are undetectable by visual inspection. The improved data will help INDOT decision-makers plan work actions that are more condition-based and thereby appropriate funds more efficiently. Both the project-level and network-level analyses showed that INDOT could realize significant cost savings by implementing NDT methods. The simulations in this study also showed that every INDOT schedule was more expensive than a condition-based NDT work program. It is therefore concluded that implementing the NDT methods would be cost-effective and beneficial to INDOT's bridge program.

5.2 Implementation and Recommendations

It is recommended that INDOT implement NDT methods for network-level bridge inspection. The initial startup cost is estimated to be $940,000, which includes the necessary equipment and vehicles, training for the INDOT NDT expert, one year of salary for the required NDT personnel, and one year of maintenance and travel costs. Once the NDT program commences, high-priority bridges, such as Interstates and NHS, should be inspected first. If INDOT cannot afford to inspect the entire inventory, then only the aforementioned priority bridges should be inspected.

Two collection crews are recommended for the entire bridge inventory with each having two collectors in one vehicle equipped with an air-launched horn GPR and IR. The two crews should be based at INDOT Research and Development Division in West Lafayette, from which the crews should be able to inspect every bridge at the following recommended intervals: two years for Interstates, four years for NHS, and six years for all other bridges. A total of four analysts should be able to process and analyze the data provided by the crews. A NDT expert is needed to manage the group and supervise the collectors and analysts. Therefore, the INDOT personnel should include one NDT expert, four collectors, and four analysts.

After the first year, the total cost for the NDT bridge deck inspection team will be somewhat less than the initial cost, but not significantly. The recurring expenses would include salaries for the inspection personnel, equipment maintenance ongoing training, and amortized costs for equipment replacement approximately every five years.

In practice, INDOT likely would not use a decision matrix as rigidly as this study for the simulations since their decisions are made on a case-by-case basis. It would be beneficial, though, for INDOT to use this matrix or to design one of their own as a tool to inform the decision-making process.

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APPENDICES

APPENDIX A: LITERATURE REVIEW OF NDT METHODS

Corrosion and delamination can lead to extensive deck surface distress even though they are not fully visible to the human eye. Figure A.1 depicts the effect of corrosion and how it spreads within the deck.

INDOT currently relies on visual inspection as the primary means of assessing the condition of bridge decks. There are several NDT methods that can supplement visual inspections which are capable of locating such deteriorations. This study considered the following NDT methods only: chain drag/hammer sounding, IR thermography, CIP, half-cell potential (HCP), GPR, and IE. This section explains the basic theory behind each method, the type of deteriorations they are capable of locating, how the methods are performed, and the limitations.

Acoustic methods such as chain drag and hammer sounding are commonly used by inspection agencies to locate delaminated areas. The chain drag method involves exactly what its name implies: the operator drags a chain or set-up of multiple chains, as shown in Figure A.2, along the deck and listens to the sound made by the chain as it moves. Sound concrete has a distinct, high-pitched ring as the chain is dragged. When a delamination is present, the sound changes to a dull, hollow sound. Hammer sounding is a more refined version of chain drag and involves tapping a hammer on portions of the deck to more clearly delineate the border of the delamination. The operator marks the delaminations on the deck edges while another worker notes the area and location.

One limitation of chain drag is that it can find only advanced and severe delaminations. Incipient delaminations generally cannot produce a distinguishable sound (Clemeña & McKeel, 1977). In addition, chain drag is inherently subjective because of its reliance on the operator's experience and hearing ability, which may be compounded by sounds such as high traffic volume on the bridge (Oh et al., 2013). Despite these drawbacks, the chain drag method is still used because the equipment is inexpensive and data processing is performed in the field. The collection speed varies greatly, depending on the deck condition and the operator's experience. Chaining a deck that has a higher percentage of delaminations will take significantly longer than one with little to no delaminations (Gucunski et al., 2013).

IR thermography is another method used to locate voids and delaminations beneath the surface. An IR camera captures the thermal radiation emitted from objects in sight (Gucunski et al., 2013); and differences in temperature can be seen as changes in color. IR is used on bridge decks because delaminations and voids are visually distinguishable. Air and concrete conduct heat at drastically different rates. When a deck is exposed to the sun for hours, it absorbs thermal energy, which is absorbed more quickly by the air trapped in the void or delamination and may lead to a temperature difference between the sound concrete and the damaged area. The IR camera measures this difference, which can be seen on a map of the deck. Rebar and corrosion are not visible with this method. One study found that IR was capable of locating 88% of delaminations at depths of 2.5″ or less (Yehia et al., 2007).

Figure A.2 Chain drag system used by INDOT.

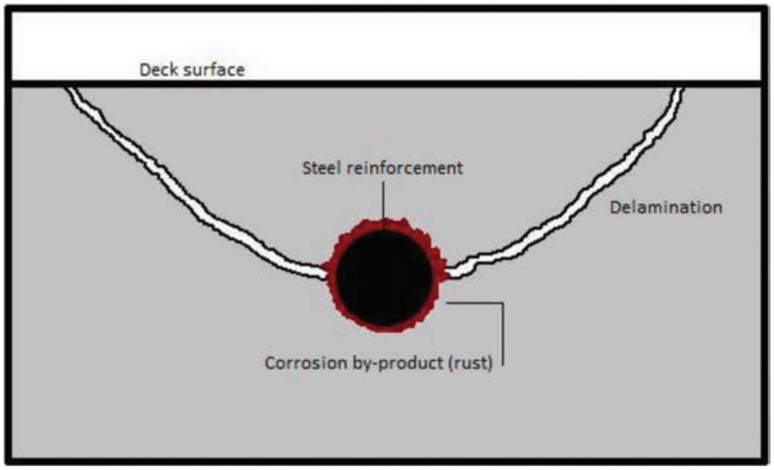

Figure A.1 Cross-section of delaminated reinforced beam.

IR can be performed in multiple ways for bridge deck applications. One of the most common is to mount the camera on a vehicle as shown in Figure A.3. Depending on the type of camera, the data collection and storage capacity, and the desired image quality, the vehicle can be driven at different speeds. This method can be performed using video cameras, which then can be used to create one continuous mapped photo of the deck, or with cameras that take rapid photographs that can be stitched together using software. Another recently developed option involves setting up a camera on a pole attached to the bridge rail. This camera is stationary and takes pictures throughout the day so that the locations of delamination can be seen from the same viewpoint. Finally, IR can be conducted with handheld cameras to take discrete photographs, which then are meshed together to form a map.

IR is a useful tool, but it has its limitations. Although ASTM D4788 states that it can be used on both new decks and decks with up to 4″ of overlay, most of the past studies found that the cameras can only collect distinguishable data at depths of 2 to 3 inches; anything deeper will yield faint images or nothing at all (Yehia et al., 2007). Additionally, IR is highly dependent on the conditions at the site. It must be a clear, sunny day, it must be dry for the previous 24 hours, and it cannot be too windy (ASTM, 2013). Only a two-dimensional image is produced, which means that IR cannot determine the depth of the delamination. The deck surface should be clear of debris as it can affect the data (Gucunski et al., 2013). Also, if crawling speed or handheld cameras are used, lane closures are required.

CIP, also known as the chloride ion concentration profile, is a method that can be used to either determine if the environment is suitable for corrosion or to predict when corrosion will begin. As mentioned earlier, corrosion of reinforcing bars begins once the passive layer is dissolved; and the chlorides cause the depassivation of the rebar. The theory behind the method is that when the amount of chlorides inside the concrete is below a certain threshold, the rebar will not spontaneously start corroding. Therefore, the concrete is tested to determine the concentration of chlorides at varying depths; and when the concentration at the rebar level reaches or exceeds a set threshold, corrosion is believed to have begun or will begin shortly.

Figure A.3 Infrared thermography camera mounted on vehicle. (Photograph courtesy of Infrasense, Inc. (Maser et al., 2012).)

Data collection can be performed in one of the following ways. One method involves taking cores of the deck from multiple locations and grinding them down to powder in depth increments. Another method, shown in Figure A.4 (left), involves drilling a hole and then using a hammer drill with a coring bit adjacent to the hole; and as the coring bit is drilled in depth increments, the powder it produces is collected in the hole next to it. After the powder samples are collected (see Figure A.4, right), they are chemically analyzed in a laboratory to determine the percent by mass of water-soluble chlorides in the concrete. There is also a rapid chloride test method that can analyze the chloride content of powdered samples in situ. The collection and analysis are detailed in AASHTO T 260-97 (2011) andASTM C1218 (2008).

Various thresholds are used for chloride concentration at the rebar level. INDOT Research and Development Division uses thresholds ranging from 1.4 kg/m^3 to 2.8 kg/m^3. A NCHRP report recommended thresholds ranging from 0.025 to 0.033% by the weight of the concrete (Sohanghpurwala, 2006). Once the chloride content exceeds the selected threshold, it is presumed that corrosion is occurring or likely will occur in the near future. A plot similar to Figure A.5 is subsequently produced to show the chloride readings at varying depths compared to the threshold.

The chloride concentration method can predict when corrosion will begin and how long it will take to propagate using Fick's Law of Diffusion. Knowing

Figure A.4 Chloride ion concentration data collection performed by INDOT (left). Concrete powder sample collected by INDOT (right).

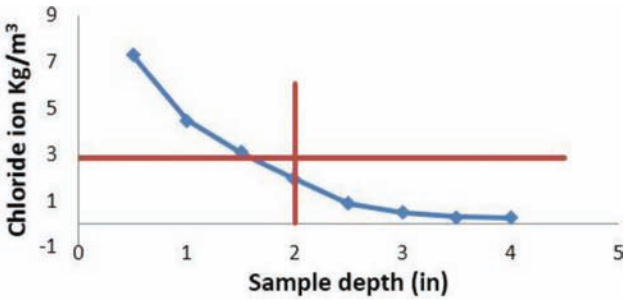

Figure A.5 Chloride ion penetration plot. (Courtesy of INDOT.)

certain properties of the concrete such as the rate of diffusion and using the measured levels of chlorides, the time remaining before corrosion begins can be predicted (Sohanghpurwala, 2006).

One major limitation for the chloride ion concentration method is that it requires lane closure and is a relatively time consuming method to complete. INDOT's collection time is about 20 minutes per hole. The number of holes needed is not defined so INDOT Research and Development Division arbitrarily elected to collect about two holes per hundred feet of deck length. The average length of an Indiana bridge deck is determined approximately 200 feet, which would equate to nearly 90 minutes of collection time. Limited research has been conducted on the effects of chlorides on epoxy-coated rebar since corrosion can only occur if the epoxy layer is damaged. Therefore, it is recommended that this method be used on decks with bare rebar only unless the agency assumes a threshold for epoxy-coated rebar.

Half-cell potential (HCP) is a method used to determine the probability of active corrosion at discrete locations. HCP utilizes a galvanic system that includes a voltmeter, a reference electrode, and the reinforcing steel bars of interest. Figure A.6 (left) shows a typical setup. If corrosion is occurring at the rebar, then a potential difference begins to build up, which is the half-cell in the concrete. The reference electrode acts as the other half-cell in the system. When the reference electrode, usually composed of copper in a copper sulfate solution, is connected to the rebar, then the two have a difference in electrical potential (Gucunski et al., 2013). A greater amount of corrosion corresponds to a larger potential difference.

To perform the HCP method, the rebar first must be checked for continuity; if part of the rebar in the area to be inspected does not touch other reinforcement, the current cannot flow throughout the mat, and the method becomes useless. Usually, a grid is marked on the deck (e.g., 2′ x 2′), and each point is wetted. Once the half-cell is connected to the rebar, data collection can begin. The portable half-cell touches each grid point on the deck, where the potential difference is measured and recorded. A rolling collection system is displayed in Figure A.6 (right).

ASTM C876 specifies set thresholds for potential difference readings: -0.35 V or less correlates to a 90% probability of corrosion, and -0.20 V or greater correlates to a 90% probability of no corrosion (ASTM, 2009). Readings in between these two thresholds do not have designated probabilities of corrosion. The readings can be depicted two-dimensionally using mapping software that show where and how severe corrosion likely is occurring.

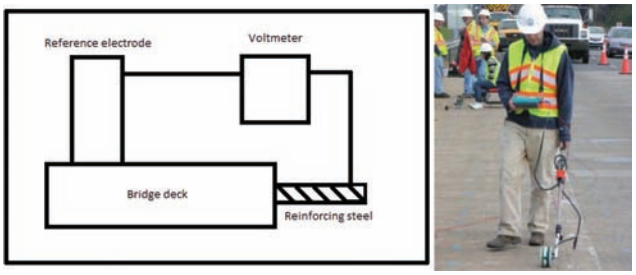

Figure A.6 Half-cell potential test setup (left). Half-cell potential equipment in use (right). (Photograph courtesy of Nenad Gucunski.)

Much like the other NDT methods, the HCP method has limitations. One of its major disadvantages is that it requires lane closures. The HCP method also is one of the most time-consuming methods as far as data collection because it requires a long set-up time and point-by-point application. ASTM C876 (2009) indicates that only black, uncoated reinforcing bars can be tested using HCP since epoxy can disturb the electrical connection. Although past studies investigated using HCP on epoxy-coated rebar, it is still recommended that its use should be limited to uncoated rebar. Cover, moisture, temperature, and chloride ion concentrations can all affect the results (Gucunski et al., 2010).

Ground-penetrating radar (GPR) is a reliable method that can be used in many applications. For bridge decks, GPR can locate rebar, determine concrete cover, and find probable locations of corrosion and delaminations. GPR sends electromagnetic radar signals into the concrete deck, and the signals pass through the concrete until they strike a surface with a change in dielectric properties, which can be a steel reinforcing bar, a corrosion by-product, a void, or the bottom of the deck. The signal reflects back to the antenna, and the time and amplitude are recorded. The theory underlying GPR is that a rebar without corrosion and the sound concrete around it have a certain reflection amplitude. When delaminations or corrosion are present, the signal experiences attenuation due to this change in dielectric properties (Gucunski et al., 2013). It should be noted that GPR does not directly detect delaminations, but rather delamination locations can be inferred by finding corrosion by-products (Donnelly et al., 2012).

After the frequency record is collected, the data can be analyzed. The readings are normalized to sound concrete, which can be determined through calibrations against a known standard (ground truths) or the analyst's experience (Gucunski et al., 2010). The analyst observes that deterioration is present at the locations of signal attenuation. After assumptions are made about the depth correction, the deteriorations can be seen throughout the depth. GPR can be used on both bare decks and decks overlaid with concrete or asphalt (ASTM, 2008).

Two types of GPR systems are commonly used for bridge deck applications: ground-coupled and air-launched horn. The difference in their means of collection and results is shown in Figure A.7. Ground-coupled GPR requires contact or very near proximity with the deck and slow speeds at walking pace. The system consists of a data collection and control unit, antennae, and a computer as shown in Figure A.8 (left) and is either pushed by an operator on a cart or positioned on a vehicle and driven. Air-launched GPR can be two

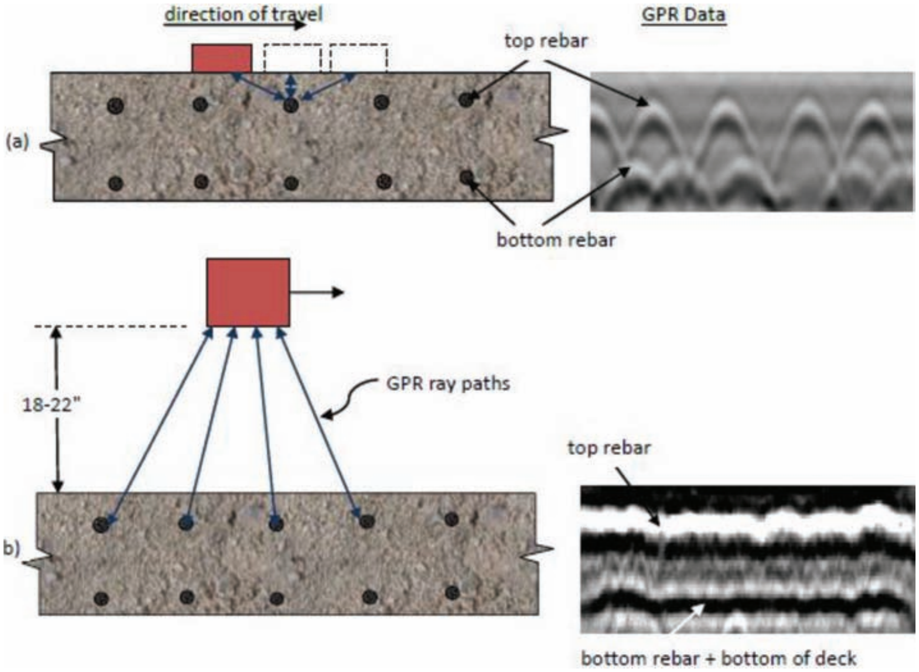

Figure A.7 Ground-coupled GPR collection diagram with results (top). Air-launched horn GPR collection diagram with results (bottom). (Figure courtesy of Infrasense, Inc. (Maser et al., 2014).)

Figure A.8 Ground-coupled GPR system used by INDOT (left). Air-launched horn GPR system on vehicle (right). (Right photograph courtesy of Infrasense, Inc. (Maser et al., 2012).)

feet off of the deck and can be performed at speeds of up to 50 mph and is set up on a vehicle as shown in Figure A.8 (right).

Ground-coupled GPR determines the deterioration occurring at each individual rebar, while air-launched horn GPR yields a "condition smear" that shows the general condition near several rebar. In other words, ground-coupled systems provide more detailed results than air-launched systems. The difference in quality and accuracy of the data is noticeable but small since the deterioration quantities were found to only have a 4% difference (Maser et al., 2012).

A few issues related to GPR should be mentioned. The deck should be clear of debris (ASTM, 2008). Moisture and chlorides, such as those from deicing salts, can affect the readings significantly (Gucunski et al., 2010); thus, data collection is not recommended during winter months (Gucunski et al., 2013). One study found that shallow defects that were less than one inch from the surface were not detected reliably by GPR (Yehia et al., 2007). Also, ground-coupled GPR requires lane closures when in use.

IE is another method used to locate delaminations and rebar. The theory behind IE relates to wave reflections. As the impactor strikes the deck, a wave propagates through the thickness of the deck until it hits an acoustical impedance, which can be any surface that has different acoustical properties from the concrete, such as air in a delamination, air at the bottom of the deck, or tendons and rebar (Gucunski et al., 2013). The wave will change direction with a return frequency. Sensors near the impact measure the time response. Through Fourier transformations, the frequency response is obtained, from which the thickness of the deck can be determined. When anomalies are present, this thickness will vary and shows up as peaks as shown in Figure A.9, facilitating the search for delaminations.

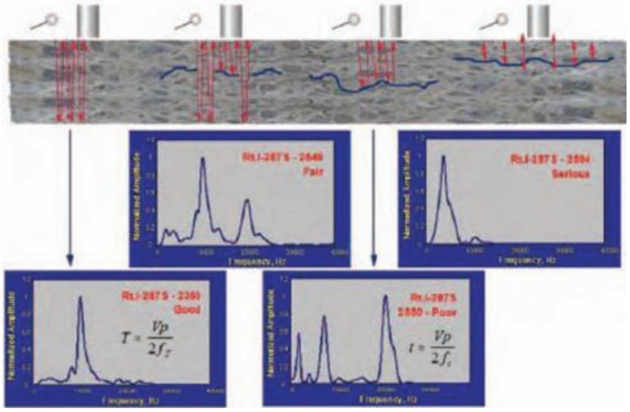

Figure A.9 Diagram of impact echo locating delaminations and respective frequency records. (Courtesy of Gucunski et al., 2013.)

Figure A.10 Handheld impact echo in use (left). Rolling impact echo system (right). (Photographs Courtesy of Gucunski et al., 2013).

If the dominant frequency correlates to the thickness of the deck, then that location is sound concrete without deterioration. ASTM C1383 describes this method thoroughly (ASTM 2010). Because the frequencies of vibrations caused by vehicles are much lower than the frequencies caused by the system, traffic has no effect on the results. It is also said to be usable at any temperature above freezing and has been shown to work well even in light rain or snow. IE works on pristine decks, concrete overlays, and asphaltic overlays if the temperature is low enough to make the surface hard (Gucunski et al., 2013).

SHRP2 R06A concluded that IE provided the best results at locating delaminations when considering accuracy and repeatability (Gucunski et al., 2013). The IE system consists of an impactor, sensors, and control unit. A typical handheld system is shown in Figure A.10 (left) and a faster, rolling system in Figure A.10 (right). Similar to some of the other NDT methods, IE is a point-by-point collection system; and the grids are normally produced beforehand so that the discrete data collection points are visible. Also like the other methods, the rolling system shortens the data collection time substantially. New technologies are being developed to create an air-coupled IE system which would not require contact with the surface. One study found that a prototypical air-coupled system correctly identified delaminations in 87% of the test locations (Oh et al., 2013).

Significant limitations are associated with IE which relate to the time of data collection. Because it involves point-by-point collection, data collection requires more time, which thus requires maintenance of traffic. Data collection must be done using a tight grid to assure that the delaminations are being correctly defined (Gucunski et al., 2013). Of the NDT methods considered, IE also requires more time for data evaluation. Each deck has hundreds if not thousands of data points to analyze, and the analyst must interpret the responses for these data to determine the severity of the delamination.

Several past studies compared the results gathered by different NDT methods in addition to testing the individual capabilities of each method. In a study by Rutgers, two decks were inspected using GPR, HCP, IE, and two other NDT methods which were not being investigated for this study (Gucunski et al., 2010). For deck one, the results between the NDT methods were quite similar, while there were large variances on deck two, which the author attributed to the different NDT methods finding different sources of deterioration.

Wiss, Janney, Elstner Associates, Inc. (WJE) conducted a case study on a bridge deck using GPR, IR, IE, HCP, chain drag, and visual inspection to quantify the extent of corrosion and delamination in a deck and found that the results varied significantly from one method to another (Donnelly et al., 2012). One study compared chain drag, GPR, and IE and concluded that GPR was faster than both of the other methods, but the results from chain drag and IE were more accurate (Scott et al., 2002).

Collectively, the findings from past studies suggested that using multiple NDTs is a better approach to correctly characterizing deck deterioration than using one method. One method alone often is insufficient, especially when conditions are not ideal. Using complementary NDTs can more accurately determine the condition in the deck. In addition to locating deterioration, using multiple types of NDT methods also can help to determine the causes since each NDT method is more specialized in finding certain deterioration types.

Table A.1 shows the data collection speed and data analysis speed for each method. Each value was estimated either by INDOT personnel, vendors, or manufacturers of the equipment. The chain drag collection speed is highly variable, therefore, it is estimated based on experience. The analysis speed for air-launched horn GPR is assumed to be the same as that for ground-coupled GPR. Finally, the chain drag and rapid CIP methods both can produce results rapidly on site. For analysis purposes, a value of 10,000 square feet per hour was used.

TABLE A.1
Data Analysis and Collection Speeds for NDT Methods

Type of NDT	Collection Speed (ft^2/hr)	Analysis Speed (ft^2/hr)
Chain drag	2,000	–
Infrared thermography	48,000	3,000
Chloride ion penetration	3,000	–
Half-cell potential	3,000	3,500
Ground-penetrating radar (ground-coupled)	4,800	3,200
Ground-penetrating radar (air-launched horn)	12,000	3,200
Impact echo	1,500	900

APPENDIX B: ANALYTICAL METHODOLOGY

The project and the network are two distinct levels of bridge management. The project level involves one specific bridge or a small set of bridges that are inspected at regular intervals to determine the need for work actions, while the network level requires the inspection of every bridge in a system. In this study, the network level refers to of the approximately 5,000 state-owned bridges in Indiana.

Project-level inspections can be conducted more slowly and methodically than inspections at the network level, which must be performed quickly and efficiently to ensure that every deck in the network is evaluated with reasonable frequency. Due to this difference in the volume of work, the optimal type of NDT method may not be the same at both levels; therefore, they must be considered separately.

A cost-benefit analysis (CBA) was conducted in this study for the project level and network level. A CBA involves comparing alternatives to a base case and measuring the financial advantages and disadvantages of each (MnDOT, n.d.). For the purposes of this study, the base case was the current INDOT programmatic method of planning work actions, while the alternative was a condition-based planning approach where NDT methods are used to determine the condition of the decks.

The first step in CBA is to determine the related costs that the structure or structures of interest will incur. Any costs resulting from the implementation of NDT methods were categorized separately from the work action costs as the NDT methods are an added cost that would not have been spent in the base case. Every time a work action was performed to repair or rehabilitate the structure, the NDT costs were included in the work action costs. The determination of these types of costs are described below, as well as any associated assumptions that were made.

One of the main deterrents to using NDT methods is their cost. The testing equipment and software often is a significant capital investment; and the personnel and training required to learn to operate the equipment can be substantial as well. This section discusses these costs.

This study assumed that INDOT did not own any of the needed NDT equipment or software so those costs were a reasonable place to start the analysis. Table B.1 provides the purchase and maintenance costs for the necessary equipment and software of various NDT methods.

The estimates for the equipment and software costs were gathered through vendors, all of whom will remain anonymous in this study. The annual maintenance costs were assumed to be 5% of the original purchase cost. In addition to the NDT equipment, a vehicle must be purchased in order to perform certain methods, which was assumed to be a large van at an estimated cost of $30,000. Since the life of the NDT equipment was assumed to be five years, the purchase of new equipment and software also was assumed to be necessary every five years.

Personnel costs included the salaries of the INDOT personnel to perform the data collection, analysis, and management of the NDT operations. It was assumed that the operation would be supervised by an engineer with a PhD degree and testing and analysis experience, who hereafter is to as the “NDT expert.” The annual salary for the NDT expert was assumed as $70,000, which is comparable to the salaries of personnel within the INDOT Research and Development Division.

The NDT expert must attend training to become highly proficient in each NDT method selected by INDOT, for which a total of $15,000 was assumed for the initial training based on cost data from the South Dakota Department of Transportation (SDDOT; Infrasense, 2006). This cost covers by equipment manufacturers, attending conferences, and any other events that will familiarize the NDT expert with the methods.

Once the NDT expert has sufficiently learned every aspect of the NDT methods, the next task would be to train the equipment operators and data analysts. In this study, the necessary personnel were categorized into two groups: collection crews and analysts; in reality, however, these positions are likely interchangeable, which means that each of these individuals has the capability of both collecting and analyzing NDT data. Therefore, the salary for both data analysts and data collectors is $55,000, which also is based on comparable INDOT salaries. The initial training for these personnel was assumed to be conducted in-house by the NDT expert. The collectors and analysts would be expected to be knowledgeable of computers, and an undergraduate degree in an engineering, technology, or science field is preferred.

In addition to the initial training for the NDT expert and the subsequent training for the collectors and analysts, an annual expense for on-going training, which includes attending conferences and workshops, purchasing NDT-related subscriptions, and other costs

TABLE B.1
Purchase and Annual Maintenance Cost of NDT Equipment (2015 Dollars)

Type of Nondestructive Method	Combined Cost of Equipment and Software	Annual Maintenance Cost
Infrared thermography	$10,000	$500
Chloride ion penetration	$12,150	$610
Half-cell potential	$14,650	$735
Ground-penetrating radar (ground-coupled)	$25,350	$1,270
Ground-penetrating radar (air-launched horn)	$78,960	$3,950
Impact echo	$82,500	$4,125

TABLE B.2
NDT Personnel Salaries and Training Expenses

Personnel Type	Annual Salary	Salary Including Benefits	Annual Training Allowance
NDT Expert	\$70,000	\$91,000	\$3,500
Data Analyst and Data Collector	\$55,000	\$71,500	\$2,750

that keep the worker up to date with current NDT technology. This expense was assumed in this study to be an amount equal to 5% of each person's salary. Finally, 30% was assumed as the cost of the benefits for each employee. All of the salary and training costs are summarized in Table B.2.

To obtain the cost of travel, the distance traveled must be calculated first. Once the distance is calculated, then an assumption can be made regarding the cost per mile. The Internal Revenue Service (IRS) rate of 57.5 cents per mile traveled for business driving (IRS 2014), was used in this study.

Some of the NDT methods considered in this study require lane closures. For network-level NDT inspections, lane closures typically are not required; therefore, the maintenance of traffic (MOT) cost was only a consideration for project-level inspection. INDOT's cost for closing lanes include the personnel, vehicles, and equipment needed to safely divert traffic. The MOT cost can vary depending on the number of lanes. The estimates shown below in Table B.3 were provided by INDOT. The total cost of MOT was determined by multiplying INDOT's hourly rate by the amount of time spent for NDT deck inspection.

The cost of deck work actions is a separate expense from the inspection cost. Over a bridge's life cycle, its deck is assumed to be patched, overlaid, and eventually replaced. These activities happen regardless of the type of inspection method used. For the purposes of this study, the assumption was that deck action decisions were dictated only by the condition of the deck and no other elements. In other words, a deck work action occurred because it was needed, not because of work undertaken on the substructure or superstructure of the bridge.

Four work actions were considered in this study. The least invasive action is patching, which involves removal of the deteriorated sections of concrete below the top mat of rebar and replacing them with new concrete. The next action, epoxy overlay, is a fairly new action type used experimentally in Indiana to provide an impervious skin to protect the deck from water and chlorides. Epoxy overlay consists of first patching any deteriorated areas; then milling the top 1/8″ of the deck to remove any chlorides on the surface; and finally, laying a thin 3/8″ layer of an epoxy and gravel mix on the deck.

The next work action, an overlay, is categorized as rehabilitation and is considered a major action. Latex-modified concrete (LMC) overlay is used when there is significant deterioration in the deck. LMC overlays involve patching, milling the top ½″ of the deck, and then pouring a layer of LMC ranging from 2-4″ deep on top.

TABLE B.3
Cost of Traffic Maintenance

Number of Lanes	Hourly Cost
Two lane	\$112
Multilane	\$150

TABLE B.4
Unit Cost of Deck Work Actions

Type of Work Action	Cost per Square Foot
Patching	\$45
Epoxy overlay	\$15
LMC overlay	\$60
Replacement	\$95

Replacement is the last work action considered, which is undertaken only when the deck has damage so extensive that it would be more economically prudent to install a new deck rather than repair the current one. The estimated unit costs, provided by INDOT, in year 2015 dollars for each of the various deck work actions, are presented in Table B.4.

Each cost shown is the per unit area. Patching is measured per square foot of patched area, while the other work actions are applied to the full deck area. The cost of a second consecutive overlay is approximately 10% more than the cost of the first layer because the former must be removed via hydrodemolition before applying the second overlay.

An integral aspect of this study's simulation was a deterioration curve used to model the spread of deterioration throughout the deck. Decisions regarding deck work actions were made based on the amount of deck deterioration; and the deteriorated areas were considered as a percentage of the entire deck area. The severity of delamination was not considered so the quantity is a binary value. Since the main goal of this study was to determine if the NDT methods are viable on the INDOT network level, the deterioration mechanism of interest was delamination. The NDT methods recommended by this study for the network level are air-launched GPR and IR, both of which are effective in locating delaminations and can be operated at highway speeds.

In 2013, the INDOT Division of Research commissioned this exploratory research study to investigate NDT inspection techniques on Indiana bridge decks. All of the NDT methods in this study were implemented on different bridge decks at on-site testing locations.

A total of 27 bridge decks were surveyed, and chain drag was implemented on 21 of them. Of the 21 decks that used chain drag, five were found to have no delaminations, and the 16 remaining decks produced meaningful delamination data. The deck age was determined from the NBI database. Table B.5 shows the NBI number, the deck age, and the percentage of delamination found through chain drag.

As mentioned earlier, the chain drag method of NDT inspection is unable to identify all of the delaminations, especially incipient delaminations that have not progressed. To account for this shortcoming, the percentages of delamination were multiplied by a factor. A number of past studies compared chain drag to other delamination locating methods.

One such study in Iowa used chain drag, IR, GPR, and IE to identify the delaminations in a specific bridge deck (Donnelly et al., 2012). Delaminated concrete quantities were collected using each NDT method. Since IE was found to be the most accurate NDT in finding delaminations in a previous study (Gucunski et al., 2013), their comparison of IE and CD was considered to be of greatest relevance for this study. The authors found that dividing the delamination quantities found using IE by the quantities found using chain drag yielded a factor of 1.79, which was assumed by this study to be a representative value for the true amount of delaminations versus the amount found using chain drag. Table B.5 presents the percentages of delamination after adjustment using this factor.

Using regression analysis, it was found that an exponential function provides the best fit for the data and also is explained intuitively by the knowledge of how deterioration propagates in bridge decks (i.e., slowly at first, then at an accelerated rate as it spreads). The data set used was the amplified percentage of delamination, which accounts for the delaminations not found using chain drag and the age of the corresponding deck. Nonlinear regression found the best fit curve for the data was Equation B.1.

$$D = 0.98\, e^{0.079\, A} \tag{B.1}$$

A is the age of the deck, and D is the percentage of delamination of the deck. Figure B.1 presents the discrete factored chain drag data points and the curve (Equation 3.1) on the same plot.

In reality, there is no deterioration at age zero. Equation B.1 has an exponential functional form. Therefore, the deterioration can never equal zero without a correction. Equation B.2 is the final equation with the correction factor in order that the percentage of deterioration will be zero at the start, which further was incorporated in the simulations.

$$D = 0.98\, e^{0.079\, A} - 0.98 \tag{B.2}$$

In this section, the specific methodology used in the CBA is discussed. Background on the economics of the

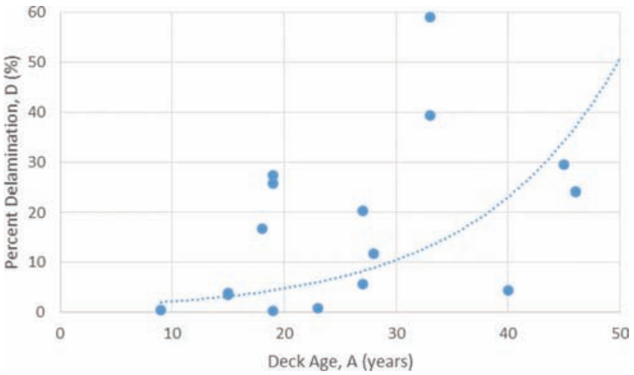

Figure B.1 Nonlinear regression function with amplified chain drag data.

TABLE B.5
Chain Drag Data Collected on INDOT Bridge Decks

NBI Number	Age of Deck (years)	Percent Delamination, No Factor	Amplified Percent Delamination, Factor = 1.79
05006	40	2.5	4.5
08290	23	0.5	0.9
11300	9	0.2	0.4
14210	19	14.4	25.8
14220	18	9.4	16.8
14230	27	3.2	5.7
14240	27	11.4	20.4
14260	28	6.6	11.8
32970	33	33	59.1
32980	33	22	39.4
37730	45	16.5	29.5
39290	19	15.3	27.4
41310	46	13.5	24.2
44270	15	2.2	3.9
44830	15	2.0	3.6
49410	19	0.1	0.2

process, important factors to consider, assumptions, and unique aspects of the project- and network-level analyses are explained. INDOT's current planning of work actions is then described, and finally, the option of hiring a consultant is considered.

This study involves performing a particular type of CBA. Although it is possible that implementing NDT methods for bridge decks may lead to direct benefits, such as decreasing lane closure time, those benefits are not considered in this study. Only the costs associated with the NDT inspections and deck work actions are included in the analysis. Therefore, the method with the least cost over the analysis period was considered the best option.

The discount rate is an important variable when performing a CBA. "Discounting converts future costs and benefits that occur in different years into a value for a common year" (MnDOT, n.d.). The discount rate is the percentage of decrease a monetary value may experience at a future point in time. Money spent in the future is less than money spent today so money can be saved by deferring spending. The commonly used conservative discount rate of 4% was used in this simulation because that is a commonly used value.

The NPC is the present worth of all future costs and benefits that have been discounted according to their respective year. In a conventional CBA, the benefits are positive and the costs are negative. If their summation leads to a positive NPC, then a project is deemed financially beneficial. Since no direct benefits were considered in this study, only the costs are considered. Equation B.3 shows the calculation of the NPC. The variable C represents the capital costs, annual costs, and any other future costs that arise. The variable i represents the discount rate, and n is the year corresponding with C.

$$NPC = \sum_{t=o}^{n} \frac{C}{(1+i)^n} \tag{B.3}$$

The NPC then is converted to an equivalent uniform annual cost (EUAC) using Equation 3.4. Using the interest rate i, the future worth of the NPC is spread out in equal annual payments. The interest rate is the same value as the discount rate. The changed nomenclature relates to its usage and effect; the discount rate decreases the value of future costs when they are converted to present values, while the interest rate compounds costs by converting the present costs to the future costs.

The EUAC is a critical criterion because it enables the comparison of the life-cycle costs of projects with differing lifetimes or analysis periods. The EUAC is more a conceptual result used in comparing alternatives than a meaningful output because it is not the actual amount that will be spent per year; rather, it is a representation only of all the costs incurred over the project life. Once the EUAC is calculated for each alternative, then the alternative with the lowest EUAC is the best choice from a cost-effectiveness standpoint. As implied in Equation B.4, the EUAC is sensitive to the analysis period and the interest rate.

$$EUAC = NPC \frac{i(1+i)}{(1+i)^n - 1} \tag{B.4}$$

This subsection discusses the importance of some of the variables in this study and why they were selected or assumed. Additionally, the differences in the project-level and network-level analyses are explained in greater detail.

One of the crucial aspects of this study was the decision matrix. Once the percentage of delamination of a deck was determined and where it fell in the bin range of deterioration limits, the percent likelihood of each work action was found as shown below in Table B.6.

This study's analysis (and its corresponding simulation) was stochastic due to the probabilistic nature of the decision matrix. The percentage of delamination for each deck was tracked each year. Given the deck inspection results, one of five decisions was necessary based on the percentage of delamination and the likelihood of an action occurring. For example, if the inspection of a deck found that 13% of its area was delaminated, then the likelihood of doing nothing was 10%, patching was 15%, LMC overlay was 40%, and replacement of the deck was 25%. In the simulation code, these decision probabilities were achieved through random variable generation.

INDOT currently does not utilize a decision matrix for deck work action on the basis of the percentage of delamination, therefore, it was necessary to develop the decision matrices introduced in this study. The probabilities for each decision were determined using engineering judgment. Reality was reflected at various levels of delamination, also known as the deterioration limits. At low delamination levels, there was a high likelihood of nothing being done, and replacement was not even an option. As the percentage of delamination increased, the chance of work actions being performed increased. Finally, as the percentage of delamination reached high levels, the likelihood of replacement became the most dominant decision.

The deterioration limits, or the collection of bin ranges for deck delamination, significantly impacted the effects of the decision matrix. The percentage of delamination ranges determined when certain work action decisions were made. The ranges shown in Table B.6 were made using engineering judgment. Above 25% delamination, it was believed that a deck would be showing serious signs of degradation on the surface and therefore replacing the deck would be the likely decision.

The decision matrix shown in Table B.6 is one of three that were used for the simulations in this study. The other two were used only when certain criteria were met. When two LMC overlays were applied consecutively without a replacement between them chronologically, then a different decision matrix with zero

TABLE B.6
Decision Matrix

Deterioration Limits (Percent Delamination)	Probability of Work Action (%)				
	Do Nothing	Patching	Epoxy Overlay	LMC Overlay	Replacement
0–2.5	90	10	0	0	0
2.5–5	70	20	10	0	0
5–10	35	25	5	25	10
10–15	10	15	0	40	25
15–20	5	10	0	35	50
20–25	0	5	0	10	85
>25	0	0	0	0	100

TABLE B.7
Decision Matrix after Two Consecutive LMC Overlays

Deterioration Limits (Percent Delamination)	Probability of Work Action (%)				
	Do Nothing	Patching	Epoxy Overlay	LMC Overlay	Replacement
0–2.5	90	10	0	0	0
2.5–5	70	20	0	0	0
5–10	60	20	0	0	0
10–15	0	50	0	0	50
15–20	0	0	0	0	100
20–25	0	0	0	0	100
>25	0	0	0	0	100

TABLE B.8
Decision Matrix after Deck Replacement

Deterioration Limits (Percent Delamination)	Probability of Work Action (%)				
	Do Nothing	Patching	Epoxy Overlay	LMC Overlay	Replacement
0–2.5	90	10	0	0	0
2.5–5	70	20	10	0	0
5–10	35	25	5	20	0
10–15	10	0	0	40	0
15–20	5	0	0	60	0
20–25	0	0	0	80	0
>25	0	0	0	100	0

probability of overlays was used for the analysis (see Table B.7). Once the deck was replaced, it could not be replaced again until another overlay was applied. Another decision matrix was used in this situation that gave no probability of replacement occurring (see Table B.8). These decision matrices were used in the analysis to ensure that realistic sequences of deck actions were performed on the decks.

A large portion of this study was based on the findings from other researchers and the input of INDOT personnel. Where data were not available, assumptions were made. Some of these assumptions were discussed previously, but all others are explained here.

The starting year of this analysis was 2015, and inspections and decisions were made on an annual basis. The life of the complete bridge system – deck, superstructure, and substructure – was assumed to be 100 years based on INDOT's programming process and engineering judgment. Thus, the analysis period for the bridge deck system in this study was 100 years. This is a maximum value for decks built prior to 2015; therefore, the bridge service life ended once it reached its 100-year limit. Additionally, the bridge service life ended if three major actions occurred in the analysis period.

Major actions (i.e., either a LMC overlay or a deck replacement) account for a large portion of the cost of a bridge deck over its lifetime. INDOT utilizes programmatic planning of work actions which specifies the following three major actions: (1) an overlay, (2) a replacement, and (3) another overlay that would last until the bridge service life ended. This study therefore selected these three major actions as potential limiting factors that influence the age of the bridge deck system.

Once a bridge deck has its third major action, the remaining life that the last action provides was assumed in this study. When a LMC overlay was applied on a deck at the end of the bridge service life, it was assumed to add 10 years, and for a replacement 20 years was assumed. For example, a 70-year-old bridge that had a deck replacement will be taken out of service at age 90. These extensions of bridge life were based on judgment and are slightly conservative values considering that replacements and overlays often survive many more years than these assumed values.

The age of the bridge deck was crucial to this study because it is a major criterion for determining deterioration. While the NBI data used in this study did not provide a detailed history on the work actions undertaken on a bridge deck in the past, the data did indicate when the last reconstruction occurred. Since a deck replacement was assumed to be a major action, the deck age started at zero in that year.

If no information was provided on the last reconstruction, then the deck age was assumed to start at the year the bridge was built. Unfortunately, this meant that some decks were unrealistically old at the beginning of the analysis, but this is an unfortunate consequence of the lack of data. The old decks typically also had abnormally high delamination levels so a deck replacement was performed after the first inspection.

The annual daily truck traffic (ADTT) describes the truck loading the bridge experiences. High ADTT values indicate that many trucks cross the bridge per day; and these high loads directly affect the bridge deck and accelerate the deterioration process. The ADTT was known for each bridge and was used to place the bridge load environment into one of three categories: (1) ADTT of less than 100, (2) ADTT between 100 and 500, and (3) ADTT greater than or equal to 500. ADTT ratings of 2 and 3 called for more frequent inspections. The ADTT category values used in this study were used in a University of Nebraska study (Hatami & Morcous, 2012).

The frequency of inspections was an assumed value assigned to the deck based on its age and ADTT classification (Table B.9). For example, a 15-year-old bridge deck with 75 ADTT (category 1) would be inspected every seven years while a 53-year-old deck with an ADTT of 600 (category 3) would be inspected every three years. The use of age together with the load environment reflected the importance of these bridge decks and how likely they were to have significant damages that needed to be addressed.

There is another method for assigning inspection frequencies based on functional classes that is simpler and easier to implement, which recommends the following schedule: Interstate bridges are inspected every two years, non-Interstate NHS bridges every four years, and all other bridges every six years. Interstate highways have the highest traffic volume of all road classes in the state so their ADTT is also high. Since higher likelihood of accidents is directly related to the volume of traffic on a road, the importance of Interstate highways to the state is therefore higher from a safety perspective. In the winter, more deicing chemicals are applied to Interstates and NHS roads because of their higher priority, but their use accelerates the deterioration process and is another reason to inspect these roads more frequently.

When a work action is performed, it has a corresponding effect on the deterioration level of the deck. Patching and epoxy overlay are considered minor work actions, and their effect is to simply reduce the degree of deck delamination by a certain percentage. Table B.10 presents the effectiveness of these work actions in terms of delamination reduction.

The effect of these work actions decreases as the level of deterioration increases. For example, a deck that requires 3% patching before a work action will leave 1.2% delamination after work action, while a deck requiring 22% patching before a work action will leave 19.8% delamination after a work action. Hence, the work action is more effective on lower deterioration levels. If this were not the case, then the minor actions would always be better options, at least from a cost-effectiveness standpoint, compared to the major work actions.

The effect of major work actions is similar but is achieved in a different manner. In the simulation of this study, the, actual age was defined as the deck age starting from a bridge's year of construction or last reconstruction. Once a major work action was triggered, the actual age was reduced to yield the modified age due to the rejuvenating effects of the work action, hence, the term "modified." Because age and deterioration were related via the deterioration curve, a reduction in the modified age led to a reduction in the deterioration. Additionally, by reducing the modified age of the deck, the deterioration rate was decelerated because the slope at younger ages was smaller. Figure B.2 illustrates how the modified age changed in response to different work actions. The aging of a bridge continued unimpeded, while the age of its deck was reset to zero when the deck was replaced. The deck's modified age changed whenever there was a major work action.

The conceptual variable (modified age) was used in this analysis to show that major work actions have a greater impact on deterioration compared to minor work actions. Minor work actions are generally temporary solutions so their effects are limited to merely a reduction, or jump, in deterioration (see Figure B.3a). Major work actions are meant to be more lasting solutions; therefore, in the simulations of this study, it was assumed that they reduced not only the deterioration, but also the slope of the deterioration curve (see Figure B.3b). By slowing the deterioration rate, major work actions lengthened the life of the deck.

TABLE B.9
Frequency of Inspections Determination (Years)

ADTT Loading Category	Deck Age, A (years)			
	A < 25	25 < A < 50	50 < A < 55	A > 55
1	7	6	5	2
2	6	5	4	2
3	5	4	3	2

TABLE B.10
Percent of Delaminated Area Repaired by Minor Work Actions

Deterioration Limits (Percent Delamination)	Percent Repaired by Type of Action	
	Patching	Epoxy Overlay
0–2.5	80	99
2.5–5	60	80
5–10	40	60
10–15	20	40
15–20	10	30
20–25	10	30
>25	10	30

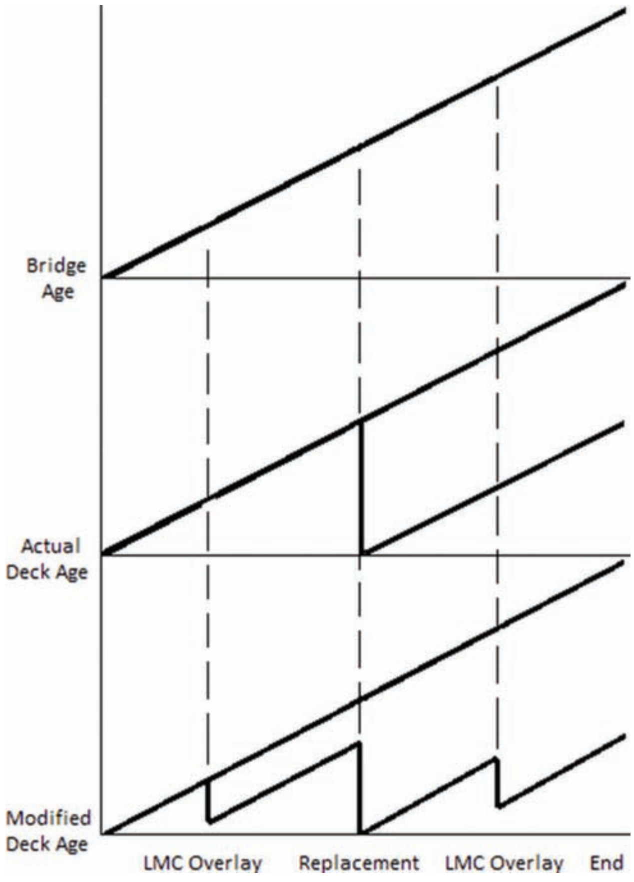

Figure B.2 Effect of work actions on age variables.

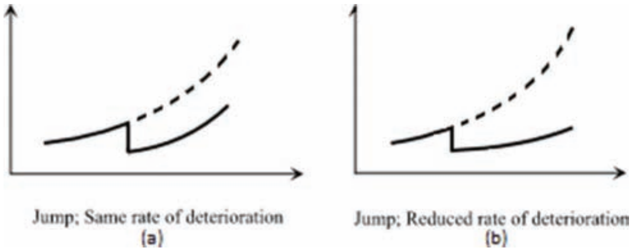
Jump; Same rate of deterioration
(a)
Jump; Reduced rate of deterioration
(b)

Figure B.3 Effect of work actions on deterioration. (Modified from Sinha & Labi, 2017.)

For analysis purposes, since a new deck was assumed to be in perfect condition initially, a deck replacement reset the modified age, and thus the deterioration, to zero. A LMC overlay, on the other hand, decreased the modified age by a certain percentage, which in turn decreased the deterioration. For decks with modified ages of less than 50 years, a LMC overlay decreased the modified age by 80%; and if the deck was 50 years or older, then it decreased the modified age by 60%. This assumption changed if the last major work action was also an overlay because a second consecutive overlay is typically not as effective as the first. The modified age reduction for decks younger than 50 years was 40%, while that for decks 50 years or older was assumed to be 30%.

The hours per day spent analyzing NDT data and collecting NDT data were assumed separately. As mentioned earlier, the analysts and data collectors would have distinct responsibilities, but they likely will have interchangeable duties. The analysts were assumed to spend the full eight-hour workday analyzing data, and the collectors were assumed to spend four hours of the workday collecting data and the remaining four hours traveling, either from the office to a specific deck location or from one deck to another.

The base for the NDT in-house operations was assumed to be INDOT Research and Development Division in West Lafayette, which is located in north central Indiana, making it a good location to be near the majority of areas within the state. The distance traveled and the required number of collection crews were calculated based on the assumption that a specific area of decks must be inspected each year. The area of decks that must be inspected therefore was calculated first; and, based on the calculated area, the distance traveled and required number of crews needed to inspect that area were determined.

Assuming that the collection crews would take one trip per day, the area per trip was calculated by multiplying the NDT collection speed by four hours. The number of required trips was calculated by dividing the area required by the area per trip. Then, the number of crews needed to inspect that required area of decks was calculated based on the required trips and the amount of days the crew was collecting.

The average latitude and longitude for the decks being inspected were calculated. The distance between these averages and the latitude and longitude of the NDT operations base in West Lafayette yielded the distance for each trip. Knowing the number of trips, the distance traveled then was calculated.

The project-level NDT program would involve monitoring individual bridge decks or small groups of decks. In this study, project-level simulations were run to achieve two goals: (1) compare the NDT methods to each other and (2) compare INDOT's current practices to the alternative of using NDT methods. The methodology for each goal is explained below. Note that the same deterioration curve was used for the project-level simulation. Although some of the methods being used can locate corrosion-based deterioration, it was deemed sufficient to use only the curve based on delaminations in order to keep the analysis relatively simple.

To determine the inspection costs, several factors were considered. Knowing the area of the bridge or bridges being inspected, the collection speed, and the analysis speed of the NDT method being used allowed for simple calculation of the time spent collecting and analyzing the data. Multiplying these times by the estimated hourly wage for the collectors and analysts produced the cost of the inspectors' time. If the NDT requires lane closures, then the collection times were multiplied by the MOT hourly cost to obtain the cost of maintaining traffic.

The MOT cost and the cost of inspectors comprised the total inspection cost. The other cost considered was the purchase and maintenance costs of the NDT equipment. Since project-level inspection was being considered in this part of this analysis, the total equipment costs could not be considered in the cost evaluation for the following two reasons: (1) the equipment would be used for many other bridge deck inspections, and the purchase cost would become the deciding factor since it is much larger than the cost of inspection.

One way to remedy this issue was to divide the purchase cost by the expected life of the NDT equipment, and then distribute the cost over each year of the equipment's usable life. The other option was to divide the sum of the inspection, maintenance, and equipment costs by the number of bridges being inspected. Both options were used in this analysis.

The total cost for using a particular NDT was determined by combining the equipment and maintenance costs with the inspection costs. The NDT method having the least cost was considered the best option. Combinations of varying NDT methods were shown to produce better results than a single NDT method. A few combinations of NDTs were analyzed to determine the best choice from a cost-effectiveness standpoint.

To compare the current INDOT programmatic work scheduling procedure to the alternative of using NDT methods, most of the assumptions described previously for bridge age, frequency of inspection, remaining life of last work action, effects of work actions on deterioration level, etc. were used. This section describes the part of the methodology that is different.

One difference between the network-level analysis and project-level analysis was that the inspection cost in the latter did not account for the full salary of the data collectors and analysts. Similar to the project-level comparison of NDT methods, the cost was determined by the time spent collecting and analyzing. Another difference was that only a small portion of the bridge inventory was investigated in the project-level analysis, specifically, 30 bridge decks were used in this study because INDOT generally is capable of inspecting that number of bridges in one year.

There was no NDT expert assumed in the project-level analysis of this study because the expert as well as the team of collectors and analysts would not be needed if INDOT were to implement the NDT methods only at the project level. Network-level use, however, is a large-scale operation and requires both precise coordination of the team members as well as in-depth knowledge of the NDT methods and deterioration types. Because the network level involves the inspection of thousands of bridges, speed and efficiency are critical criteria when considering the qualities of NDT methods. If INDOT were to decide to use NDT methods that require lane closures for network-level inspection, the decks would not be inspected at a reasonable frequency. Two methods, air-launched horn GPR and IR, can be used to collect data without lane closures; and a combination of both methods is commonly used by many NDT consultants. For the above reasons, air-launched GPR and IR were assumed as the optimal combination of NDT methods for use in this study for network-level inspections.

The estimation of costs associated with implementing NDTs into the deck inspection program was presented earlier. A number of assumptions were made regarding certain variables. The number of days that inspections can be performed determined how much time the data collectors can spend, thus determining how many decks can be inspected in a given amount of time. Since air-launched GPR and IR are the NDT methods being used in tandem, the method with more restrictions is the limiting factor; in this case, this is identified as IR because it must be performed on sunny days. The average number of sunny days per year in Indiana is about 200 (*Comparative* 2012). Adjusting for work days only, the days that data can be collected is 140.

The maintenance of a large bridge network is a challenging undertaking. Two general approaches to bridge deck management were considered in this study: (1) the current method, which is programmatic planning of work actions, and (2) the alternative method, which is condition-based planning. The condition-based option involves using NDT methods to estimate the level of deterioration in the deck and then planning and executing the appropriate work action based on that condition.

The programmatic option is simply the scheduling of major work actions based on the deck age, which is the method INDOT currently utilizes to manage their bridge decks. The problem with scheduling deck work actions in this manner, without a thorough condition-based assessment, is that work actions may be carried out much earlier or much later than when they should be done. One study found that using NDT methods versus programmatic work actions led to a different work action in 53% of the cases (Carmichael et al., 2014).

In addition to the programmatic schedule currently utilized by INDOT, three more schedules were considered in this study. The first schedule, referred to as Work Schedule 1, involved performing an overlay at 20 years, then a replacement 20 years thereafter, another overlay 20 years after that, and finally, the bridge was taken out of service after another 20 years. Work Schedule 2 involves the same schedule, but instead of taking the bridge out of service at 80 years, the deck was replaced; and the bridge was replaced at 100 years (see Table B.11). Work Schedules 3 and 4 involved performing more overlays than Work Schedules 1 or 2 (see Table B.12).

In addition to these major work actions, an assumption was made regarding the patching frequency, namely, patching was performed midway between each major work action. The work action frequencies in Work Schedules 1 and 2 were adjustable, which allowed selecting whatever frequency of major work actions best suits the agency's procedures.

The options considered thus far assumed that INDOT would perform the data collection and analysis in-house, which involved purchasing equipment and software, hiring and training capable individuals, and sending them to conduct on-site inspections. However, a great number of NDT consultants are available to collect, analyze, and present the data. This alternative must be considered in this analysis of the economic viability of the in-house option.

One consultant provided a cost estimate of $0.08 per square foot, and another consultant's estimate was similar. Of course, the cost varied based on the scale and proximity of the decks as well as the extent of the investigation. The price ranges were described in the main report. These costs provided a general figure that was used to calculate the cost of inspection and analysis based on the deck area requiring inspection. The inspection cost for in-house NDT operations was compared to the consultant cost estimates.

TABLE B.11
Programmatic Schedules for Major Work Actions, Schedule 1 and Schedule 2

Work Schedule 1		**Work Schedule 2**	
Action	**Years After Origin**	**Action**	**Years After Origin**
Overlay	20	Overlay	20
Replacement	40	Replacement	40
Overlay	60	Overlay	60
End of Bridge Life	80	Replacement	80
		End of Bridge Life	100

TABLE B.12
Programmatic Schedules for Major Work Actions, Schedule 3 and Schedule 4

Work Schedule 3		**Work Schedule 4**	
Action	**Years After Origin**	**Action**	**Years After Origin**
Overlay	22	Overlay	22
Overlay	40	Overlay	40
Replacement	53	Replacement	53
Overlay	75	Overlay	75
Overlay	93	Overlay	93
End of Bridge Life	106	Replacement	106
		End of Bridge Life	128

APPENDIX C: ANALYSES RESULTS AND DISCUSSION

This appendix presents the results of the project-level and network-level analyses. The base case variables first are discussed and how they were used to determine the variability of the simulations. At the project level, the results of comparing the NDT methods to each other and further comparing a combination of NDT methods to INDOT's current practices. Then, the results of the network-level analysis are presented, which compared the NDT methods to INDOT's current practices for the entire bridge inventory in Indiana. A discussion of the results of the comparison of using a consultant at the network level versus INDOT doing this work in-house concludes this appendix.

The base case was the set of variables that were most representative of the true conditions in the field, making the simulations as realistic as possible. Table C.1 summarizes the value of each input used in the base case; and the deterioration limits, decision matrix, and frequency of inspection are shown later in the sensitivity analysis because they are collections of values.

Since the simulations in this study were probabilistic, the results varied for each run. For a given bridge deck, different decisions could be made at different times, which of course affected the cost in some cases. If the simulations produced vastly different results for each run, then a large number of simulation runs would be required to ensure the outcomes were not anomalies. To determine the variance of the analysis routine in order to reduce the number of runs, the base case was run 100 times for each bridge in the system using the network-level simulation code. The mean, standard deviation, and coefficient of variation are shown in Table C.2.

The coefficient of variation, a measure of the variance of the outcome, was found by dividing the standard deviation by the mean. The outcomes were found to have very low coefficients of variation, and repeated runs changed the results only slightly. Thus, it was decided for this study that five runs would be sufficient when investigating the effect of each variable.

This section first discusses how the best cost-effective NDT method and collection of NDT methods were determined. The optimal collection of NDT methods was then used in the project-level simulation and compared to current INDOT practices.

A goal of this research was to conduct a comparison between the various NDT methods. Although past studies attempted to determine the accuracy of NDT methods, currently there is no definitive measure of accuracy available. It was not within the scope of this study to directly use NDTs in order to quantitatively estimate accuracy; therefore, in the simulations, it was assumed that all of the NDT methods were equally accurate in locating deterioration. Therefore, the only difference between the NDT methods was the cost that each incurs, which included equipment purchase and maintenance, inspectors, and MOT cost.

Thirty decks were randomly selected from the state inventory in Indiana. Table C.3 presents the analysis results for each NDT method when the purchase costs were distributed during the life of the equipment. The results indicated that when the total inspection, equipment, and maintenance costs were divided by the number of bridges scheduled for inspection. The costs also were determined per deck area.

The results indicated that the least expensive option was IR, both when distributing the cost throughout the equipment life and by the number of bridges being inspected. IR's low purchase cost and relatively quick collection and analysis speeds made it is the best cost-effective option. It should be noted that the vehicle speed during IR inspection at the project level was

TABLE C.1
Base Case Variables

Variable	Value
Days of Inspection	140
Days of Analysis	200
Discount Rate	4%
Life of NDT Equipment (years)	5
Remaining Life of Final Treatment – Deck Replacement (years)	20
Remaining Life of Final Treatment – LMC Overlay (years)	10

TABLE C.2
Results from Base Case, Network Level

	EUAC ($)	NPC ($)	Inspection NPC ($)	Repair NPC ($)	Age (years)	Average Percent Delamination
Mean	136 M	3.33 B	19.6 M	3.31 B	99.0	7.6
Standard Deviation	761 K	18.7 M	1.16 K	18.7 M	0.03	0.02
Coefficient of Variation	0.56%	0.56%	0.01%	0.56%	0.03%	0.22%

TABLE C.3
Cost Comparison between Different NDT Types at the Project Level

NDT Type	Cost for One Year ($)	Cost per Bridge ($)	Annual Cost ($/sq. ft.)	Cost per Bridge ($/sq. ft.)
GPR (Ground)	16,600	1,230	0.08	0.01
IR	8,900	560	0.04	<0.01
CIP	16,570	880	0.08	<0.01
HCP	18,530	1,010	0.09	0.01
IE	54,250	4,010	0.27	0.02
Chain drag	19,970	670	0.10	<0.01

TABLE C.4
Combinations of NDTs and Their Respective Costs of Inspection

NDT Combinations	Cost for One Year ($)	Cost per Bridge ($)	Cost for One Year ($/sq. ft.)	Cost per Bridge ($/sq. ft.)
GPR, HCP, and IR	45,330	2,840	0.23	0.01
IE and CIP	71,100	4,900	0.35	0.02
CIP, IR, and GPR	43,040	2,700	0.21	0.01

TABLE C.5
Sample Results from NDT Usage on Bridge Set 1, Project Level

EUAC ($)	NPC ($)	Inspection NPC ($)	Repair NPC ($)	Average Service Life (years)	Average Percent Delamination
627 K	15.4 M	816 K	14.5 M	99.5	5.3

assumed to be 10 mph, which is only about 20% of the speed for network-level collection. Thus, the collection rate was reduced by a factor of five to determine an inspection rate of 9,600 square feet per hour at the project level. The most expensive option, by far, was IE for both the project and network levels. The initial cost was much higher in comparison to the other methods, and the collection and analysis speeds were slower.

When only their annual costs were compared, the top three NDT methods when used individually were IR, ground-coupled GPR, and CIP, which also comprised one of the three combinations considered. As mentioned previously, the intent of this study was to utilize a combination of NDTs that were capable of locating different types of deterioration to obtain a more complete picture of the deck condition. Table C.4 shows the costs of the three NDT combinations.

The combination of CIP, IR, and ground-coupled GPR was the least expensive option. This combination was used in the subsequent analysis comparison of project-level NDT to INDOT's current practices. In the field, the combinations of NDT methods would be expected to locate both corrosion and delaminations, making it more robust than any one method. However, for the purposes of simplifying the analysis by utilizing one deterioration equation, only delaminations were considered, assuming that each NDT was capable of locating the same type of deterioration.

The best combination of NDT methods for project-level application, identified earlier as CIP, IR, and ground-coupled GPR, was used on five sets of 30 bridge decks for an analysis period of 100 years or until the service life of the bridge ended. The inputs for the base case also were used in the project-level analysis. The bridges were selected at random. Sample results from one of these sets of bridge decks are shown in Table C.5.

The four programmatic schedules currently used by INDOT, which were explained in Tables B.11 through B.14, were implemented for the same bridge decks. Table C.6 shows sample results from the same set of bridges.

The net present cost (NPC) is the sum of every cost incurred for the duration of the analysis for each bridge in the inventory; and to account for the time value of money, these costs were normalized to 2015 dollars using the discount rate. This is the total cost to INDOT. However, to compare alternatives with different analysis periods, the equivalent uniform annual cost (EUAC) needed to be calculated in order to make the comparisons more direct. The inspection NPC refers to the NPC of all of the costs associated with implementation of NDT inspection; likewise, repair NPC is the NPC of all the costs associated with deck work actions. Since the programmatic scheduling option does not utilize NDT methods, its overall NPC was equal to the repair NPC.

The average service life is an averaged value representing the time at which the service life for each bridge ends. For the NDT methods, this value could not

TABLE C.6
Sample Results from Four INDOT Programmatic Planning Schedules for Bridge Set 1, Project Level

	EUAC ($)	NPC ($)	Average Service Life (years)	Average Percent Delamination
Schedule 1	771 K	18.4 M	80	2.5
Schedule 2	950 K	23.3 M	100	1.9
Schedule 3	883 K	21.7 M	106	2.1
Schedule 4	960 K	23.9 M	128	1.8

exceed 100 years because of the imposed limit. The average percentage of delamination is the percentage of delaminated areas as a fraction of the entire deck area. Each bridge deck has a delamination value every year, which were totaled for the deck's entire service life. Then, the complete inventory was totaled and divided by the total number of years. This value describes the average condition of the bridge inventory. A higher average indicates a poorer condition, while a low value indicates a better condition.

In the example bridge set, the disparity in costs between the inspection NPC and the repair NPC was remarkable. The inspection NPC was a small "piece of the pie," accounting for only 5% of the overall NPC, while the repair NPC accounted for the remaining 95%. When the NDT methods were used for inspection, the EUAC was $626,000 and the overall NPC was $15.4 million. Every programmatic (age-based) schedule implemented by INDOT resulted in a higher EUAC and NPC, which indicated that INDOT spent more money throughout the analysis period than the condition-based NDT methods. The least expensive INDOT option for this set of bridges was Schedule 1 but was still about 23% more expensive than the condition-based timing of repairs using the NDT methods. The most costly INDOT option, Schedule 4, was roughly 53% more expensive than the NDT methods. These options were more expensive because the work actions were performed earlier than necessary using INDOT's age-based programming method while the NDT-recommended work actions were performed at a later, more appropriate time.

Most of the INDOT programmatic schedules yielded a bridge service life equal to or longer than the average bridge service life when using the NDT methods. For example, 99.5 years was longer than Schedule 1, about the same as Schedule 2, and less than Schedules 3 and 4. Additionally, a better average condition was maintained using the INDOT programmatic scheduling because the average percentage of delamination was about three times lower than that of the NDT methods. However, the better condition and longer life associated with programmatic scheduling are achieved at a great expense because more actions are performed throughout the life of the structure to achieve these apparent benefits. Figure C.1 compares the results from the five sets of bridges when using the NDT methods to the results using the INDOT programmatic scheduling, which, on average, required about 52% higher costs. Based on these results, it was determined that at the project level, NDT condition-based scheduling was not only feasible, but was financially beneficial when compared to INDOT's current programmatic scheduling.

The analysis for the network level was explained in detail earlier, and Table C.2 shows the average results using the base case inputs at the network level. This section first delves into how these results changed when one input or a set of inputs was altered. Then, the results from the base case are compared to the results of INDOT's current programmatic scheduling to determine if implementation of the NDT methods would be a cost-effective endeavor. Lastly, the costs for the base case results are compared to the costs using a NDT consultant's services for the same bridge inventory to ascertain whether it would be more cost-effective for INDOT than to perform NDT collection and analysis using in-house resources.

This portion of the analysis investigated the changes in the collective cost, age, and condition of the bridge inventory in response to changes in the input variables. The input variables of interest were as follows: decision matrix, number of inspection and analysis days, NDT equipment life, remaining life of final treatment (replacement or LMC overlay), deterioration limit, and discount rate. Each variable was changed and evaluated one at a time; and any noticeable trend was noted and a possible explanation found. Where no effect on the outcomes was observed, the input variable was described as inconsequential.

The decision matrix produced the probability that a certain action was the best action when the percentage of delamination fell within a given range and therefore represented the inclination of the agency to perform certain actions under specific conditions. The base decision matrix, which is presented in Table B.6, was the only decision matrix that changed in the sensitivity analysis.

The base decision matrix was altered to create two different matrices: one that was more likely to perform less invasive actions like patching and epoxy overlay; and the other was more likely to perform more invasive actions like LMC overlay and deck replacement. The less invasive matrix and the more invasive matrix are shown in Tables C.7 and C.8, respectively.

When the less invasive matrix was used, the EUAC decreased slightly; and when the more invasive decision matrix was used, the EUAC increased. Figure C.2 depicts the changing EUAC in response to the changing decision matrix. When the less invasive matrix was used, minor actions were more likely to occur sooner,

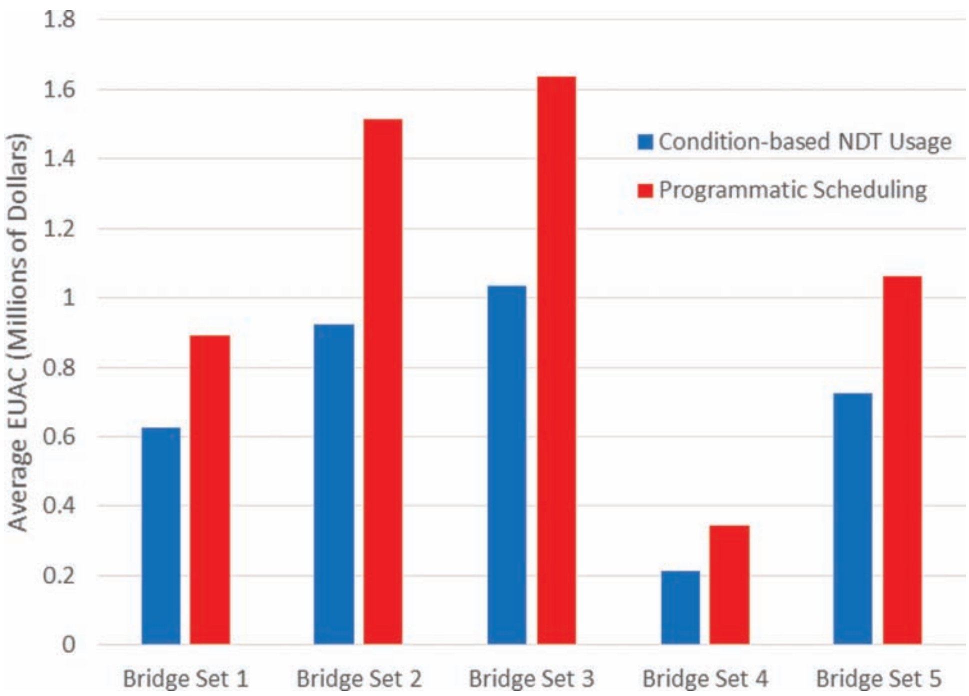

Figure C.1 Results of comparative analysis for project-level inspections.

TABLE C.7
Decision Matrix for Less Invasive Actions

Deterioration Limits (Percent Delamination)	Work Action				
	Do Nothing	Patching	Epoxy Overlay	LMC Overlay	Replacement
0–2.5	80	20	0	0	0
2.5–5	50	40	10	0	0
5–10	35	30	20	15	0
10–15	10	15	10	35	30
15–20	5	10	0	35	50
20–25	0	5	0	10	85
>25	0	0	0	0	100

TABLE C.8
Decision Matrix for More Invasive Actions

Deterioration Limits (Percent Delamination)	Work Action				
	Do Nothing	Patching	Epoxy Overlay	LMC Overlay	Replacement
0–2.5	90	5	5	0	0
2.5–5	70	15	5	10	0
5–10	50	10	0	25	15
10–15	30	5	0	40	25
15–20	10	0	0	40	50
20–25	5	0	0	15	80
>25	0	0	0	0	100

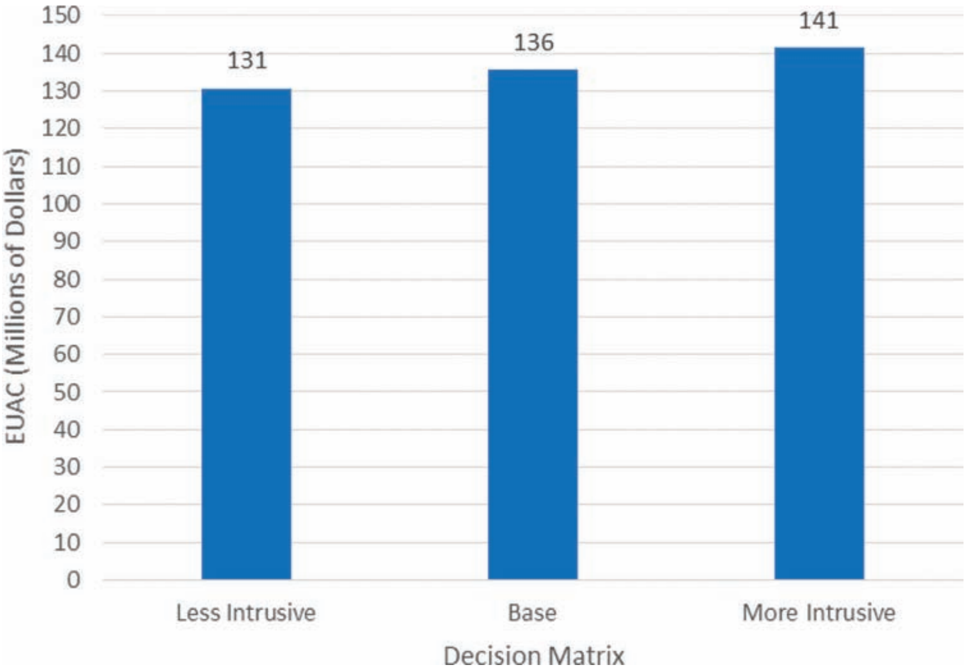

Figure C.2 Impact on EUAC by changing the decision matrix.

thereby delaying major work actions, but only enough to decrease the EUAC from the base case by less than 3%. Using the more invasive matrix, undertaking major actions was more likely to occur but increased the EUAC from the base case by more than 4%. Both of the alternative decision matrices led to a small but noticeable difference in the costs. Even though it would need to be unrealistic, a more drastically different matrix would result in a larger change in costs.

In this study, the number of days on which inspections could be performed is called the "inspection days." The base case therefore assumed 140 days were available for inspection. To study this variable, inspection days of 80 and 200 also were used. No changes were observed in either the EUAC or the overall NPC, however, the inspection cost NPC was impacted significantly.

Figure C.3 shows that when more inspection days were possible, the inspection cost decreased because the bridge deck area to be inspected was predetermined, the number of data collectors needed was calculated because the number of inspection days available changed the required number of collection crews.

"Analysis days" refers to the number of days required to analyze and evaluate the collected NDT data. A total of 200 days was the base case number, and 140 and 260 days were used for the sensitivity analysis. The results, shown in Figure C.4, were similar to those from changing the inspection days. The EUAC and NPC did not change, but the inspection cost decreased as the number of analysis days increased.

The life of the NDT equipment represented how often the equipment and software needed to be purchased. The base case variable of five years was changed to a conservative value of two years and a liberal value of ten years. The resulting EUAC and overall NPC did not show any signs of change as expected. However, the inspection cost NPC changed, albeit by 4% and 2% for two and ten years, respectively, indicating that the NDT equipment life had only a minor impact on the analysis outcomes.

The remaining life of the deck after its last major action was characterized in the analysis by variables referred to as the replacement life and LMC overlay life, which were assumed as 20 years and 10 years, respectively. These variables were varied to ascertain how they impacted the results. For replacement and overlay, the shorter lives were 15 and 7 years and the longer lives were 30 and 15 years, respectively. Figure C.5 shows how the average age of the decks changed.

The only result affected by changing the remaining life of the last action was the average service life of the bridge. As the remaining life decreased, the average service life decreased, which was not a surprising outcome since age is directly related to the remaining life.

The deterioration limits define the boundaries of the percentage of delamination utilized within the decision matrix. The base case deterioration limits are shown in Table C.9. These deterioration limits were made stricter and more lenient. A stricter limit generally meant that the deck likely would be replaced much sooner than for the base case, while a more lenient limit meant that the deck would last much longer prior to replacement.

When the deterioration limits were changed, all the key outcomes were affected. The effects on the EUAC, age, and average percentage of delamination are shown in Figures C.6, C.7, and C.8, respectively.

The stricter deterioration limits increased the costs because more work actions were undertaken, and major work actions were undertaken sooner while the lenient

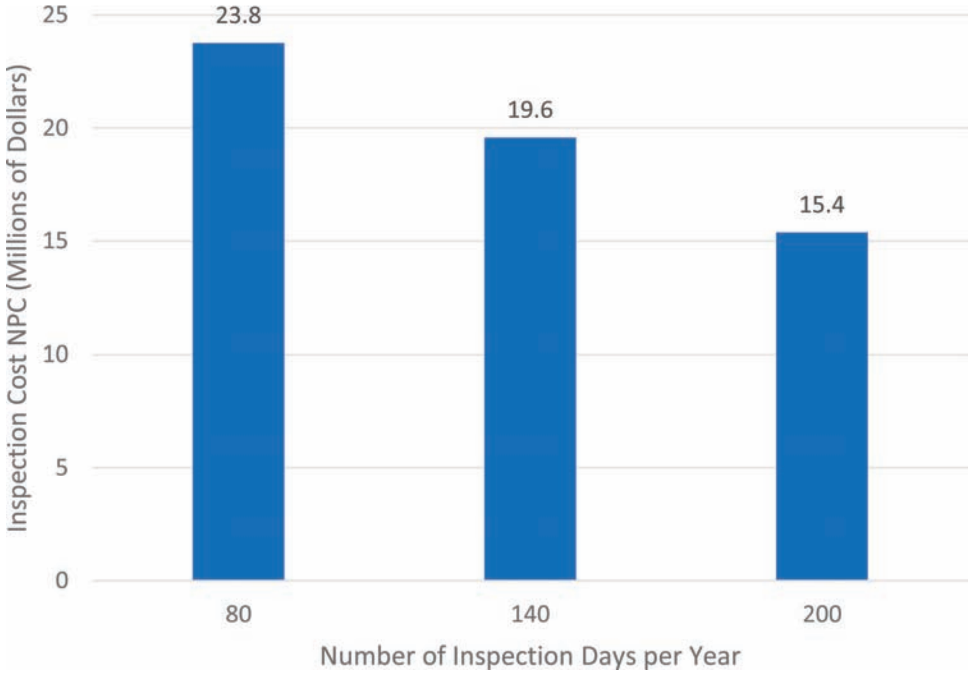

Figure C.3 Impact on inspection NPC by changing inspection days.

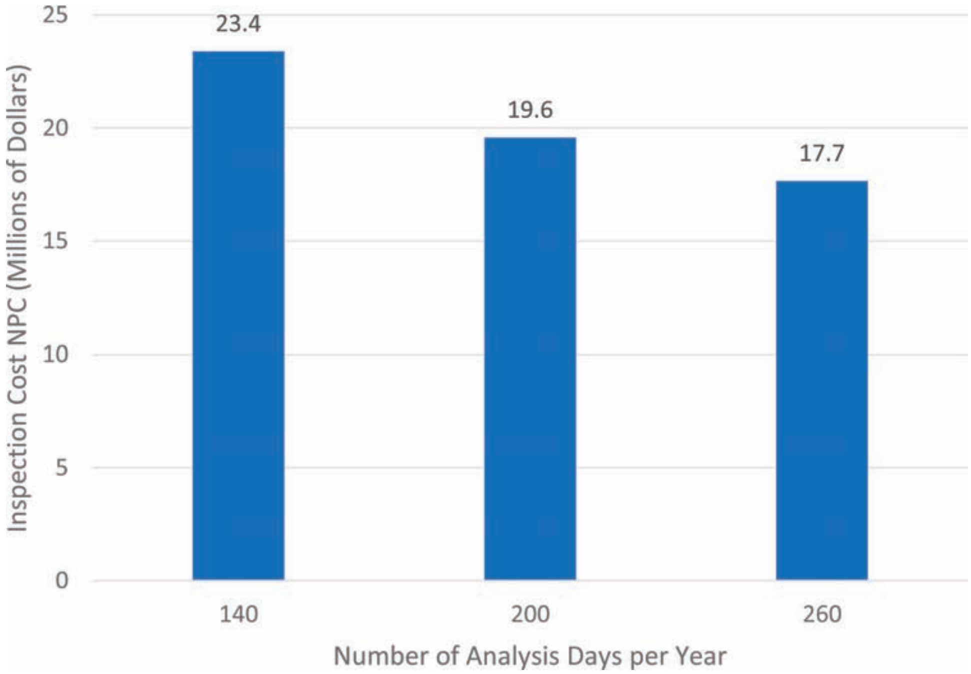

Figure C.4 Impact on inspection NPC by changing analysis days.

limits decreased the costs. Additionally, the lenient limits led to a greater average bridge service life because by stretching their resources, a deck underwent fewer actions (see Figure C.8). As expected, the use of stricter limits led to a lower average percentage of delamination throughout the bridge deck inventory. In summary, stricter deterioration limits led to increased costs, a lower age for the end of service life, and a better overall condition; and more lenient limits had the opposite effect.

The interest rate and discount rate are the same value but are known by different names because of their usage. The interest rate is used when converting present day money to future values, while the discount rate is

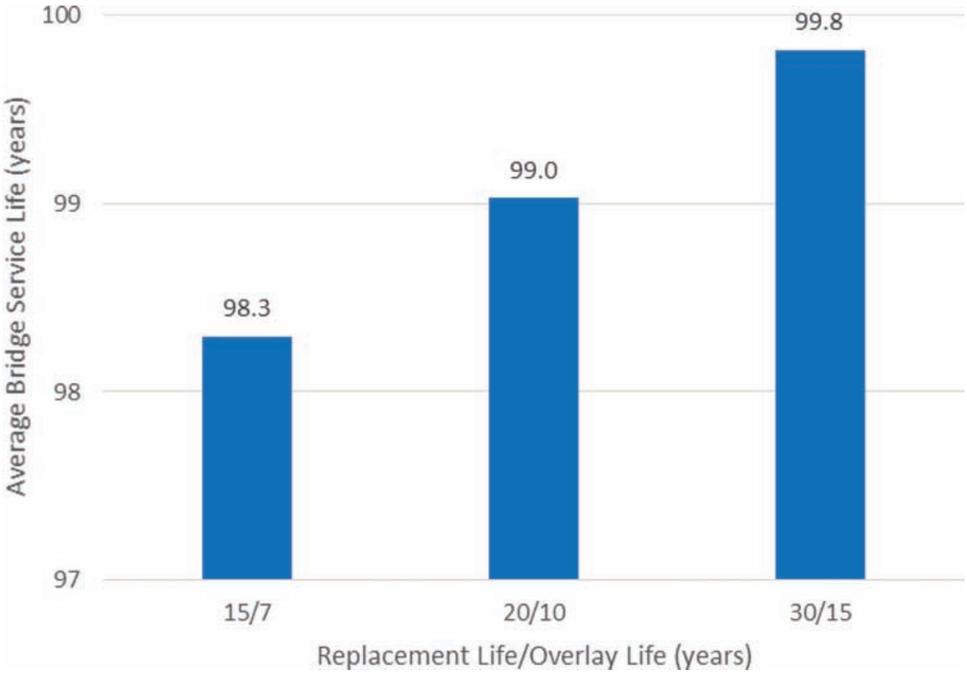

Figure C.5 Impact on bridge service life by changing remaining life of replacement and LMC overlay.

TABLE C.9
Deterioration Limits of Percent Delamination Used in the Decision Matrix

Stricter	Base Case	More Lenient
0–1	0–2.5	0–5
1–2.5	2.5–5	5–10
2.5–5	5–10	10–20
5–7.5	10–15	20–30
7.5–10	15–20	30–40
10–15	20–25	40–50
15 +	25 +	50 +

used when converting future costs to present costs. Figures C.9 and C.10 present the analysis outcomes for different values of the interest or discount rate. Predictably, the EUAC increased as the interest rate increased, and the overall NPC decreased as the discount rate increased. The EUAC ranged from $113 million dollars for an interest rate of 2% up to 164 million dollars for an interest rate of 8%. At 2%, the NPC was almost $5 billion, while a discount rate of 8% produced a NPC that barely exceeded $2 billion.

Clearly, a variation in the discount/interest rate can result in significant differences in the results of a financial model. While there is no “correct” value, INDOT indicated that a 4% rate was most appropriate for the associated deck costs.

The frequency of inspections can be determined on the basis of the bridge ADTT and age (see Table C.9). Another option, which was suggested by INDOT, is to set the frequency to two years for Interstate highway bridges, four years for NHS bridges, and six years for all others. The greatest effect of using the alternate frequency was on the inspection cost NPC, as shown in Table C.10.

The inspection NPC increased by more than 40% while the repair NPC increased by 6%. Moreover, the overall NPC changed by almost 7%. These results suggest that the analysis outcome was influenced the most by the repair costs and not the inspection costs. The other results were not significantly impacted by the frequency variations. One intangible benefit of using the alternate system is its simplification for determining the inspection frequency.

Inspecting only the travel lanes as a portion of the population, which effectively reduces the inspection area, was also investigated as an option to decrease the costs. The analysis found that while such restrictions on the investigation area reduced the inspection time, it did not affect the number of data collectors needed; thus, the inspection cost did not change significantly.

Another option investigated was to inspect only the Interstate or NHS bridges, which reduced the eligible bridge population by almost half, and as a result, the EUAC decreased by 32%.

Finally, if the travel lanes only and bridge classification exclusions were implemented together, the EUAC was roughly the same as when only Interstate and NHS highways were inspected (Figure C.11).

Table C.2 displays the results from the base case for the network-level analysis. When these values were compared to the results from INDOT’s current programmatic scheduling (Table C.11), the outcome was similar to the results from the project-level analysis. Both the EUAC and NPC for each schedule were at least 40% greater than their respective values found

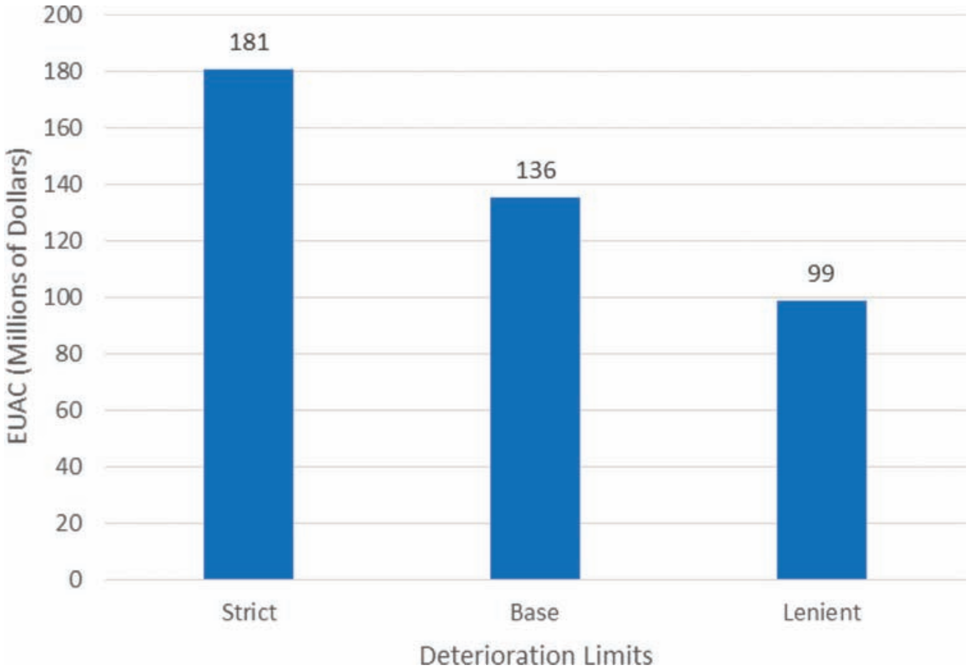

Figure C.6 Impact on EUAC by changing the deterioration limits.

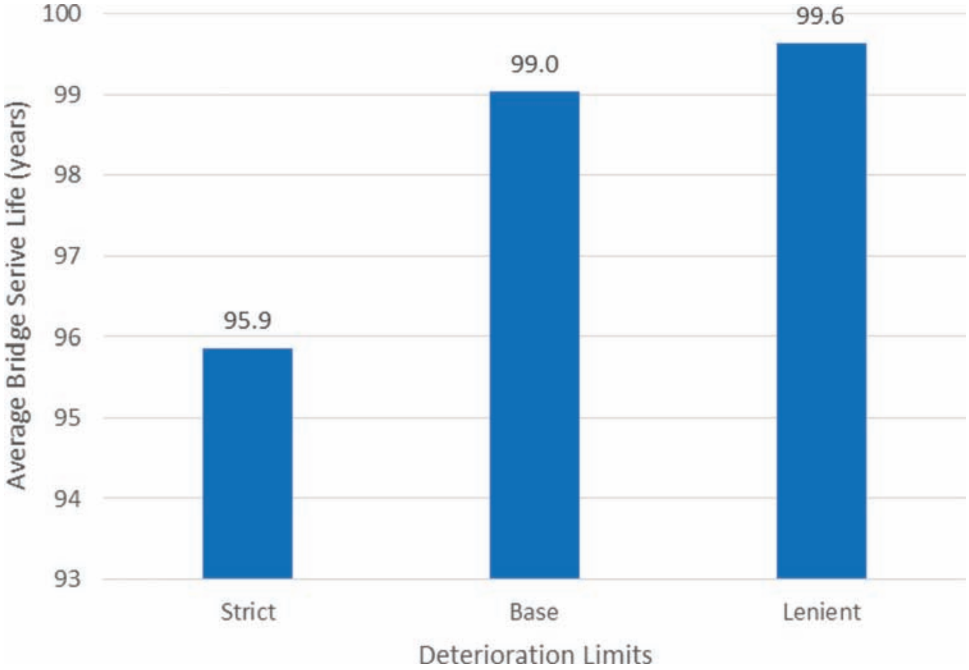

Figure C.7 Impact on average bridge service life by changing the deterioration limits.

using the NDT condition-based scheduling methods. Once again, the average service life of the bridges was generally higher when using INDOT's programmatic scheduling, and the average percentage of delamination was about five times less as well. That same reasoning applies here: the increase in longevity and decrease in average percentage of delamination were due to the higher frequency of major work actions and the consequent higher expenditures.

The least costly INDOT programmatic scheduling had a 49% higher EUAC and a NPC that was 46% higher when compared to the NDT methods. The fact that both the EUAC and NPC were significantly lower when using the NDT methods compared to INDOT's programmatic scheduling was a convincing reason to recommend that INDOT begin utilizing the NDT methods. Another reason was apparent when the inspection cost NPC was compared to the repair cost NPC.

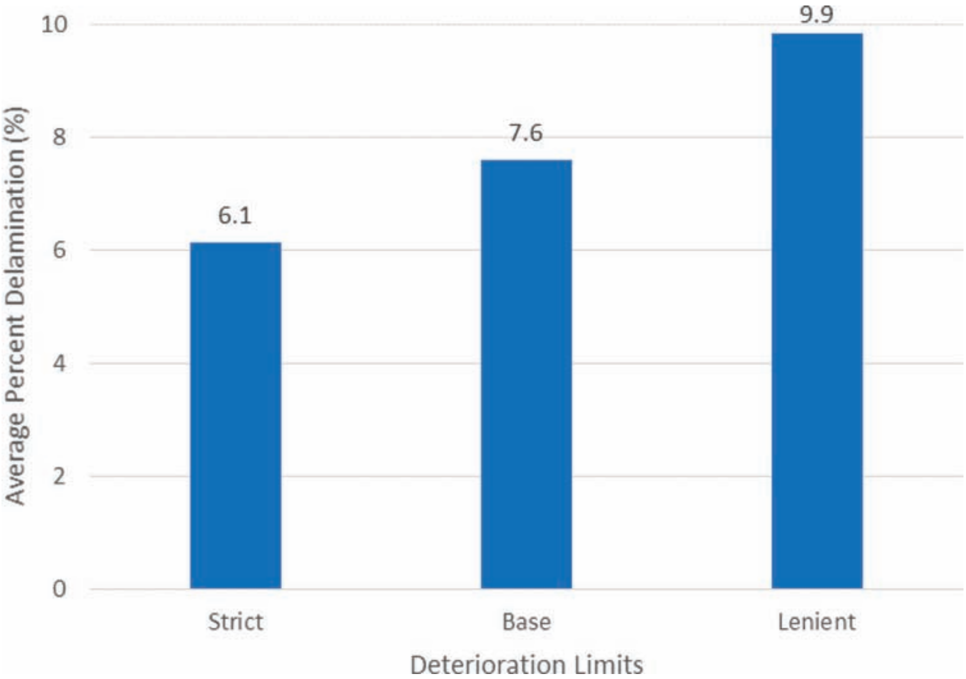

Figure C.8 Impact on average percent delamination by changing the deterioration limits.

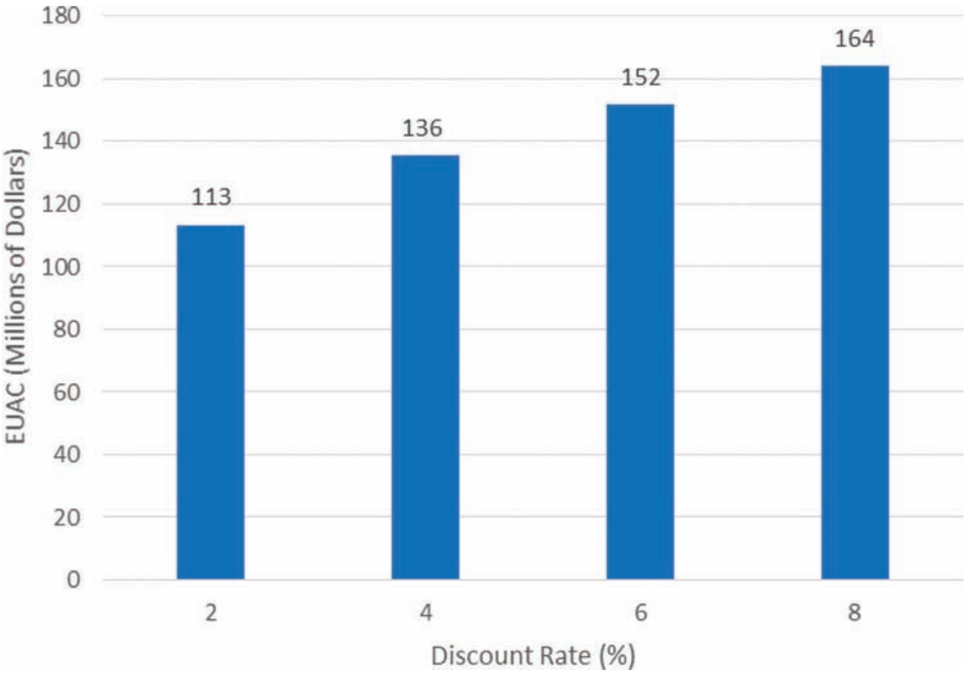

Figure C.9 Impact on EUAC by changing the interest rate.

Referring to Table C.2, the inspection cost, which was less than 1% of the repair cost, was dwarfed by the repair cost over the analysis period.

The funding needed by INDOT to initiate and maintain an active, functioning NDT inspection and analysis team was not negligible. However, the savings earned by reducing the work action costs made it a worthwhile investment. The above results make a strong economic case for implementing NDT applications at the network level.

The option of using a consultant also was considered because it provides a simpler solution for collecting and analyzing bridge deck data. In this case, INDOT would not need to purchase or maintain NDT equipment, hire any additional staff, perform training, or pay for any additional expenses related to using the NDT methods.

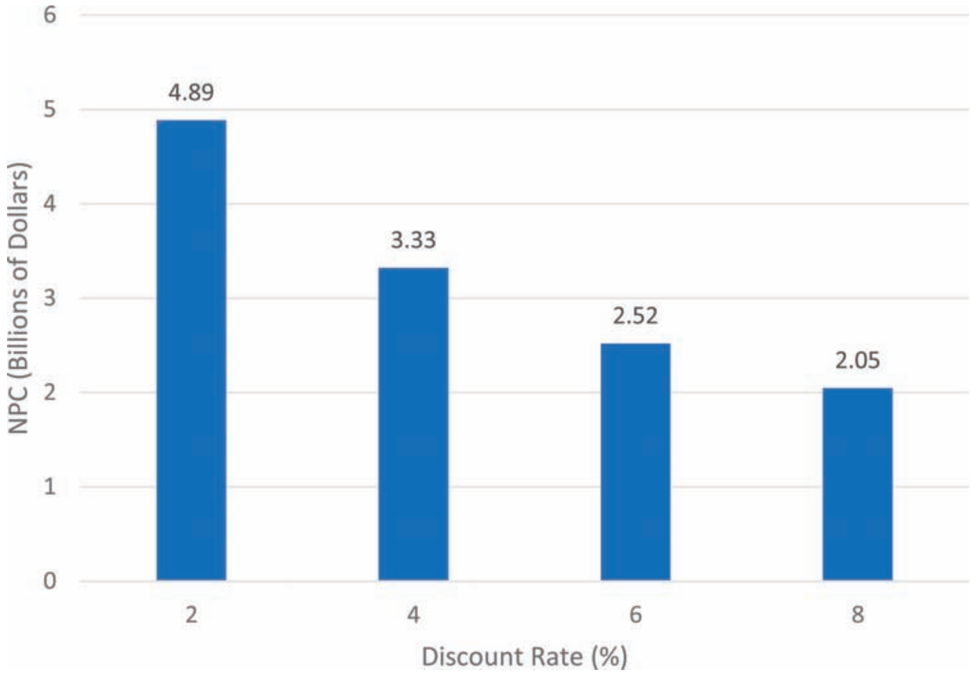

Figure C.10 Impact on NPC by changing the discount rate.

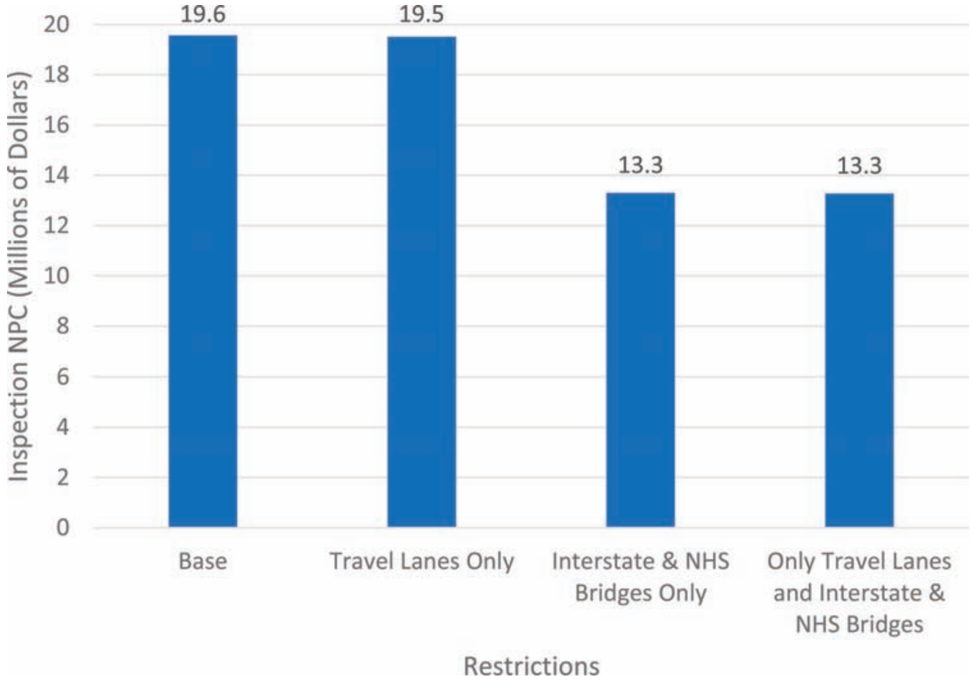

Figure C.11 Impact on NPC by adding restrictions to area and bridge highway classification.

TABLE C.10
Comparison of Results between Different Frequency of Inspection Options

	EUAC ($)	NPC ($)	Inspection NPC ($)	Repair NPC ($)	Age (years)	Average Percent Delamination
Base Frequency	136 M	3.33 B	19.6 M	3.31 B	99.0	7.6
Alternate Frequency	145 M	3.54 B	27.8 M	3.51 B	99.1	7.4

TABLE C.11
Results from Four INDOT Programmatic Planning Schedules, Network Level, and Results from NDT Base Case, Network Level

	EUAC ($)	NPC ($)	Age (years)	Average Percent Delamination
Schedule 1	203 M	4.86 B	80	1.8
Schedule 2	245 M	5.99 B	100	1.5
Schedule 3	212 M	5.21 B	106	2.1
Schedule 4	227 M	5.64 B	128	1.8
NDT Option	136 M	3.33 B	99.0	7.6

TABLE C.12
Consultant Price Ranges

Consultant ID	Low End of Price Range ($/sq. ft.)	High End of Price Range ($/sq. ft.)
1	$0.08	$0.20
2	$0.07	$0.30

Instead, the consultant would perform all the inspections for a fee based on the area of bridge decks, the proximity of the decks to each other, and the extent of work desired on each deck.

Two consultants were contacted as part of this study. Both consultants utilized IR and air-launched GPR for inspections and each provided a range of estimated costs per square foot of bridge deck. The cost range was generally related to the amount of work contracted, among other factors, which are shown in Table C.12.

Prices of $0.10, $0.20, and $0.30 per square foot were selected to examine how the cost of NDT inspection by consultants would vary. Due to the huge number of decks in Indiana's inventory and the accompanying scale economies, the actual contract prices would likely be on the low end of the ranges shown in Table C.12. To find the total cost of utilizing a consultant, the area of decks needing inspection was multiplied by the cost per square foot.

At $0.10 per square foot, the NPC was $8.81 million, which doubled and tripled to $17.62 million for $0.20 per square foot and $26.43 million for $0.30 per square foot. At $0.20 per square foot, the cost was less than the base case inspection NPC of $19.57 million. Using a simple linear interpolation, the break-even consultant cost was determined to be $0.22 per square foot. Consultant costs performed at less than $0.22 per square foot would be more cost-effective for INDOT than to staff a NDT group to conduct network-level inspections. It should be noted, however, that this cost recommendation is based strictly on the costs submitted by the consultants. The technical merit of the consultants, although both are known to have extensive NDT experience, was not extensively considered in this study.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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