

Exploring Emerging Technologies for Highway Construction Inspection

By
Fuad Al-Bataineh
B.S., Texas Southern University, 2011
M.S., Prairie View A&M University, 2013

Submitted to the graduate degree program in the Department of Civil, Environmental, and Architectural Engineering and the Graduate Faculty of the University of Kansas in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Chair: Daniel Tran, PhD

Brian Lines, PhD

Chien-Ho Ko, PhD

Michael Murray, PhD

Long Nguyen, PhD

Date Defended: August 15th, 2022

The dissertation committee for Fuad Al-Bataineh certifies that this is the approved version of the following dissertation:

**Exploring Emerging Technologies for Highway Construction
Inspection**

Chair: Dr. Daniel Tran

Date Approved: August 29, 2022

Abstract

Inspection for highway construction is essential for State Departments of Transportation (DOT) and the Federal Highway Administration (FHWA) to provide high-quality products and facilities that meet or exceed specified quality standards. State DOTs have historically specified quality standards based on detailed instructions describing the required materials and construction methods. However, because of the growing infrastructure demand and reductions in the number and experience levels of inspectors, state DOTs are seeking methods to achieve greater efficiencies in quality management.

In the digital age, various technologies exist that convey efficient approaches for completing specific tasks and assignments. In addition, emerging new and innovative technologies are changing how state DOTs deliver, inspect, and maintain highway construction projects. New and emerging technologies support the acquisition of digital data for estimating quantities, verifying and accepting, creating as-built records, and enhancing visualization. Despite these rapid advancements, these technologies are still in their infancy, and much work remains. When implemented thoughtfully and appropriately, technology can produce a significant return on investment, safety, and efficiency benefits.

To address this knowledge gap, this research aims at exploring the technologies used by DOTs to inspect highway infrastructure during the construction and maintenance of assets. Three main types of technologies, including geospatial technologies, remote sensing & monitoring technologies, and mobile devices & software applications, were investigated in detail.

This dissertation is divided into four main segments. The first segment is a literature review to understand the use of various technologies in highway construction and maintenance sites. The second part is a survey distributed to members of state DOTs to gather information about the using

of various technologies in different highway construction and maintenance activities. The survey also aimed to collect the issues preventing some DOTs from fully adapting technologies in highway construction. The data collected from the survey is then analyzed and visually represented.

The third segment is conducting a statistical analysis to examine prior experience's effect on using the technologies in various activities. Finally, a descriptive conclusion regarding the need for expertise to use the technology is presented from the analysis.

The fourth segment of this dissertation is a case study regarding the Return on Investment (ROI) of using mobile mapping technologies on highway construction sites. A case study in Jordan was conducted in detail. The ROI result of this case study is compared to a case study conducted in the United States (Oregon DOT) to see how different environments can affect the ROI on the use of similar technology. The results varied substantially due to labor and implementation environment variables.

This research found that state DOTs have used various technologies for highway inspection during construction and maintenance with different degrees of success. Furthermore, it was found that the lack of training is one of the main factors that are holding back the adaptation of technology in the inspection process. According to the Chi-square statistical analysis, it was found that some technologies can be used for certain activities without having a significant experience to achieve the desired results.

This study is one of the first attempts to examine the use of technologies for inspection for both construction and maintenance. This study's results may help practitioners better understand which technologies are suitable for their specific construction inspection activities. The findings

also help transportation asset managers evaluate and select the technologies to better understand the asset conditions.

Acknowledgments

I thank the Department of Civil, Environmental, and Architectural Engineering at the University of Kansas for continuous encouragement with research and teaching opportunities, giving me a great platform to mound myself with great passion and intellectuality. I will always cherish this incredible doctoral journey and be proud to be a Jayhawk throughout my lifetime. But, first, I want to convey my sincere gratitude and utmost respect to my advisor Dr. Dan Tran, a wonderful mentor with an incredible vision. Without his inspiration and constant support, I cannot even imagine my research career.

Table of Contents

<i>Abstract</i>	<i>iv</i>
<i>Acknowledgments</i>	<i>vii</i>
CHAPTER 1 : INTRODUCTION	1
1.1 Dissertation Purpose	3
1.2 Key Concepts and Definitions	5
1.3 Research Questions	9
1.4 Research Deliverables	9
1.5 Dissertation Organization	10
CHAPTER 2 : LITERATURE REVIEW	12
2.1 Introduction	12
2.2 Geospatial Technologies	12
2.2.1 <i>e-Ticketing</i>	12
2.2.2 <i>Unmanned Aircraft Systems (UAS)</i>	16
2.2.3 <i>Global Positioning Systems (GPS) and Global Navigation Satellite Systems (GNSS)</i>	20
2.2.4 <i>Geographic Information Systems (GIS)</i>	22
2.3 Remote Sensing and Monitoring Technologies	24
2.3.1 <i>Barcodes</i>	24
2.3.2 <i>Radio-Frequency Identification (RFID)</i>	25
2.3.3 <i>Light Detection and Ranging (LiDAR)</i>	29
2.4 Mobile Devices & Software	33
2.4.1 <i>Automated Machine Guidance (AMG)</i>	33
2.4.2 <i>3D Engineered Models/BIM</i>	35
2.4.3 <i>Handheld Data Collectors (HDC)</i>	37
2.4.4 <i>Mobile Mapping Systems</i>	38
2.5 Summary	39
CHAPTER 3 : RESEARCH QUESTIONS AND METHODOLOGY	40
3.1 Introduction	40
3.2.1 <i>Identifying the Research Problem and Establishing Research Questions</i>	41
3.2.2 <i>Points of Departure</i>	43
3.2.3 <i>Data Collection Survey</i>	43
3.2.4 <i>Evaluation Metrics</i>	46
CHAPTER 4 : GEOSPATIAL TECHNOLOGIES FOR HIGHWAY INSPECTION	48
4.1 Introduction	48
4.2 Results of Using Geospatial for Highway Infrastructure Inspection	48
4.2.1 <i>Application of Geospatial Technologies for Highway Inspection during Construction</i>	49
4.2.3 <i>Application of Geospatial Technologies for Highway Inspection during Maintenance</i>	59

4.3 Key Findings from Interviews.....	64
4.3 Summary	70
CHAPTER 5 : REMOTE SENSING & MONITORING TECHNOLOGIES.....	71
5.1 Introduction.....	71
5.2 Results of Using Remote Sensing and Monitoring Technologies for Highway Infrastructure Inspection	71
5.2.1 Application of Remote Sensing & Monitoring Technologies for Highway Inspection during Construction.....	72
5.2.2 Impact of Experience on Use of Remote Sensing and Monitoring Technologies During Construction	78
5.2.3 Application of Remote Sensing & Monitoring Technologies for Highway Inspection During Maintenance	81
5.2.4 Impact of Experience on Use of Remote Sensing and Monitoring Technologies During Maintenance	84
5.3 Key Findings from Interviews.....	86
5.3.1 Florida DOT (FDOT).....	87
5.3.2 Pennsylvania DOT (PennDOT).....	88
5.4 Summary	89
CHAPTER 6 : MOBILE DEVICES AND SOFTWARE APPLICATIONS	91
6.1 Introduction.....	91
6.2 Results of Using Mobile Devices and Software Applications for Highway Infrastructure Inspection	91
6.2.1 Application of Mobile Devices & Software Applications for Highway Inspection during Construction	92
6.2.2 Impact of Experience on Use of Mobile Devices & Software Technologies During Construction ..	96
6.2.4 Impact of Experience on Use of Mobile Devices & Software Application During Maintenance ..	101
6.3 Key Findings from Interviews.....	103
6.3.1 Minnesota DOT (MnDOT).....	104
6.3.2 New York State DOT (NYSDOT).....	105
6.4 Summary	106
CHAPTER 7 : INSPECTION TECHNOLOGIES EVALUATION METRICS.....	108
7.1 Introduction.....	108
7.2 Evaluation Metrics for Inspection Technologies Metrics	108
7.3 Case Study	113
7.3.1 Selection of Case Study	113
7.3.2 Case Study Interview	114
7.3.3 Challenges and Barriers	115
7.3.4 Benefits Gained	115
7.3.5 Finances and Technical Point of View.....	116
7.4 Case Study Analysis.....	117
7.5 Oregon State Mobile Mapping ROI.....	120

7.5.1 Mobile Mapping Expenses and Cost in Oregon DOT	120
7.5.2 Oregon State Mobile Mapping Benefits	123
7.6 Discussion of Case Study Findings	124
7.7 Conclusion	124
CHAPTER 8 : SUMMARY AND CONCLUSION	126
8.1 Summary	126
8.2 Conclusion	129
8.3 Contribution	130
8.4 Limitations.....	131
8.5 Future Work.....	131
REFERENCES	133
APPENDIX A : SURVEY QUESTIONNAIRE	145
APPENDIX B: WORKING PAPER	161

List of Tables

Table 2.1: Summary of e-Ticketing experience and effective practices	15
Table 2.2: Typical application of UASs for highway infrastructure inspection	19
Table 2.3: Typical use of GNSS/GPS for highway construction.....	21
Table 2.4: Project characteristics for using different LiDAR methods.....	30
Table 2.5: Summary of different LiDAR systems	30
Table 2.6: Typical use of LiDAR for highway construction	31
Table 4.1: Geospatial technologies years of experience	56
Table 4.2: Chi-Square analysis for geospatial technologies during construction	58
Table 4.3: Geospatial technologies Chi-Square analysis for the maintenance phase	64
Table 5.1: Remote sensing & monitoring technologies years of experience.....	78
Table 5.2: Chi-Square analysis results for remote sensing & monitoring technologies during construction.....	80
Table 5.3: Remote sensing technologies Chi-Square analysis results for maintenance phase	86
Table 6.1: Mobile devices & software application years of experience	97
Table 6.2: Chi-Square analysis results for mobile devices & software application during construction.....	98
Table 6.3: Mobile devices & software application Chi-Square analysis for maintenance phase	102
Table 7.1: Overall return on investment (ROI) from using the technologies for highway infrastructure inspection.....	110
Table 7.2: Summary of mobile mapping adoption cost	118
Table 7.3: Summary of surveying and transportation expenses	119
Table 7.4: Summary of mobile mapping benefits.....	119
Table 7.5: Summary of mobile mapping costs for Oregon state case study	121
Table 7.6: Summary of mobile mapping benefits for Oregon state case study.....	123

List of Figures

Figure 2.1: GIS and BIM data flow	23
Figure 2.2: RFID-Based concrete tracking system	26
Figure 2.3: Use of 3D engineered models for construction inspection.....	36
Figure 3.1: Overview of research methodology	42
Figure 4.1: Use of geospatial technologies for highway infrastructure inspection	49
Figure 4.2: Types of geospatial technologies used for highway infrastructure inspection during construction.....	50
Figure 4.3: Application of GNSS/GPS for highway infrastructure inspection during construction	51
Figure 4.4: Application of GIS for highway infrastructure inspection during construction.....	52
Figure 4.5: Application of UAS for highway infrastructure inspection during construction	53
Figure 4.6: Application of robotic total stations (RTS) for highway infrastructure inspection during construction	54
Figure 4.7: Application of terrestrial photogrammetry (TP) for highway infrastructure inspection during construction	55
Figure 4.8: Application of e-Ticketing for highway infrastructure inspection during construction	56
Figure 4.9: Usage of geospatial technologies for the construction phase in different states DOTs based on experience	57
Figure 4.10: Types of geospatial technologies used for highway infrastructure inspection during maintenance or asset management.....	59
Figure 4.11: Application of GNSS/GPS for highway infrastructure inspection during maintenance or asset management.....	60
Figure 4.12: Application of GIS for highway infrastructure inspection during maintenance or asset management	61
Figure 4.13: Application of UAS for highway infrastructure inspection during maintenance or asset management	62
Figure 4.14: Usage of geospatial technologies for maintenance activities in different states DOTs based on years of experience.....	63
Figure 5.1: Use of remote sensing and monitoring technologies for highway infrastructure inspection	72
Figure 5.2: Types of remote sensing & monitoring technologies used for highway infrastructure inspection during construction.....	73
Figure 5.3: Application of LiDAR/3D laser scanning technologies for highway infrastructure inspection during construction.....	74
Figure 5.4: Application of intelligent compaction for highway infrastructure inspection during construction.....	75
Figure 5.5: Application of remote sensors for highway infrastructure inspection during construction.....	76
Figure 5.6: Application of infrared sensors for highway infrastructure inspection during construction	77
Figure 5.7: Application of remote cameras for highway infrastructure inspection during construction.....	77
Figure 5.8: Usage of remote sensing & monitoring technologies for highway inspection during construction based on DOT's experience	79

Figure 5.9: Types of remote sensing & monitoring technologies used for highway infrastructure inspection during maintenance or asset management	82
Figure 5.10: Application of remote sensors for highway infrastructure inspection during maintenance or asset management	83
Figure 5.11: Application of LiDAR/3D for highway infrastructure inspection during maintenance	84
Figure 5.12: Usage of remote sensing technologies for maintenance in different states DOTs based on years of experience	85
Figure 6.1: Use of mobile devices & software application for highway infrastructure inspection	92
Figure 6.2: Types of mobile devices & software application used for highway infrastructure inspection during construction.....	93
Figure 6.3: Application of 3D engineered models/BIM for highway infrastructure inspection during construction	93
Figure 6.4: Application of automated machine guidance for highway infrastructure during construction.....	94
Figure 6.5: Application of tablets computers/smart phones for highway infrastructure inspection during construction	95
Figure 6.6: Application of handheld data collectors for highway infrastructure inspection during construction.....	96
Figure 6.7: Usage of mobile devices & software application for highway inspection during construction based on DOT's experience	97
Figure 6.8: Types of mobile devices & software applications used for highway infrastructure inspection during maintenance or asset management.....	99
Figure 6.9: Application of TS for highway infrastructure inspection during maintenance or asset management	100
Figure 6.10: Application of HDC for highway infrastructure inspection during maintenance or asset management	101
Figure 6.11: Usage of mobile devices & software applications for maintenance activities in different states DOTs based on experience.....	102
Figure 7.1: Performance metrics to evaluate the use of technologies for inspection	109
Figure 7.2: Agency track the cost-effectiveness of implementing technologies	110
Figure 7.3: Primary drivers for selecting technologies for highway inspection.....	112
Figure 7.4: Systematic procedure of calculating ROI.....	117

CHAPTER 1 : INTRODUCTION

Highway infrastructure such as roadways, bridges, and drainage systems are essential for society and communities' livability, sustainability, and resilience. Inspection of highway infrastructure during construction and maintenance of assets is critical in any transportation system because it ensures conformance with plans, specifications, and material requirements that can impact the asset's lifecycle. In fact, one of the main missions of state departments of transportation (DOTs) and the Federal Highway Administration (FHWA) is to provide high-quality products and facilities that meet or exceed specified quality standards. Historically, state DOTs have specified quality standards, including detailed instructions describing the required materials and construction methods often referred to as "method specs." The acceptance requirements are often based on national standards or engineering experience and judgment. State DOTs traditionally have employed on-site workforces to perform infrastructure inspections.

Because of the growing infrastructure demand and reductions in both the number and experience levels of inspectors, state DOTs are seeking methods to achieve greater efficiencies in quality management. One of these methods is to use emerging and innovative technologies for highway infrastructure inspection. For example, the FHWA Every Day Counts (EDC) initiatives promote the use of various advanced and emerging technologies for construction and inspection. Under the e-Construction innovation area of EDC-3 (2015-2016), the FHWA focused on readily available and already-proven technologies, including digital electronic signatures, electronic communications, secure file sharing, version control, mobile devices, web-hosted data archival and retrieval systems, and radio-frequency identification (RFID) tags for tracking the location of resources (FHWA, EDC-3 Final Report). During EDC-4 (2017-2018), the FHWA emphasized speeding up the adoption of e-Construction and envisioned growing the use of sophisticated

technology applications across state agencies. These technology applications include having inspectors adopt survey-grade positioning data on tablets as well as real-time data processing. The FHWA viewed EDC-4 as an opportunity to promote e-ticketing, remote video monitoring, and seamless data integration across project life cycles. For EDC-5 (2019-2020), the FHWA placed a focus on unmanned aircraft systems (UAS) to expedite data collection needed for making better-informed decisions while increasing safety and accuracy and providing access to hard-to-reach locations (FHWA, EDC-4 Final Report). The FHWA highlighted that “construction inspection with UAS allows for a bird’s-eye view of a project’s progress and for the development of 3D terrain models that document construction processes and assist in the assessment of earthwork quantity measurement.” (FHWA, EDC-5 Progress Report). Recently, EDC-6 (2021-2022) was initiated. Under EDC-6, FHWA has focused on the use of e-ticketing and digital as-built related technologies. The FHWA highlighted that “e-Ticketing improves the tracking, exchange, and archiving of materials tickets. Digital information, such as 3D design models and other metadata, enhances the future usability of as-built plans for operations, maintenance, and asset management” (FHWA, EDC-6).

In the digital age, various technologies exist that convey efficient approaches for completing specific tasks and assignments. Emerging new and innovative technologies are changing how state DOTs deliver, inspect and maintain their highway construction projects. In particular, with the latest technological advancements, the inspection landscape has been rapidly changing through the incorporation of technologies. The adoption of mobile devices and advanced surveying equipment for construction inspection has proven timely and beneficial for inspectors, who play a vital role in overseeing and managing construction processes and asset conditions. A wide variety of digital tools are available to support construction inspection

activities and collect digital data for estimation of quantities, verification and acceptance, and creation of as-built records. These tools offer numerous benefits, including improved data quality and consistency, enhanced communication, improved transparency, and improved safety of the site personnel.

Various technologies such as geospatial technologies, remote sensing and monitoring technologies, mobile devices, 3D and 4D models, automated machine guidance (AMG), UASs, and other technologies are available and being used in the highway construction industry. The use and implementation of these technologies for construction inspection and maintenance vary between state DOTs depending on their level of maturity. The variety of applications and experience with technologies is attributed to challenges and barriers that DOTs face in investigating, testing, and implementing specific technology tools for construction inspection and maintenance of assets. As technologies continue to be introduced and enhanced, state DOTs continue to consider and explore various technologies for highway infrastructure inspection. Therefore, the purpose of this dissertation is to document the various technologies used by DOTs to inspect highway infrastructure during the construction and maintenance of assets.

1.1 Dissertation Purpose

The goal of this dissertation is to investigate the various technologies used by DOTs to inspect highway infrastructure during the construction and maintenance of assets. To achieve this goal, the main objectives of this dissertation are to:

- Identify technologies currently in use by DOTs for inspection of new and existing highway infrastructure assets (e.g., geospatial technologies, mobile software applications, remote sensing, and monitoring);

- Evaluate different methods used to assess the viability, efficiencies, and return on investment (ROI) of inspection technologies; and
- Identify how information from these assessments is being used for construction project management, allocating resources, and determining the condition of assets.

Additionally, the dissertation examined strategies for the implementation of technologies for highway infrastructure inspection. Finally, the dissertation identifies knowledge gaps and provides suggestions for future research to address these gaps. To achieve the aforementioned objective, the following approach was used for dissertation development:

- Conducting a literature review.
- Review information from vendors that manufacture and supply the technologies used for inspection.
- Survey state DOTs using a web-based questionnaire
- Conducting case studies using technologies for highway infrastructure inspection.

This study focuses on the three main categories of technologies (Geospatial Technologies, Remote Sensing & Monitoring Technologies, and Mobile Devices & Software Applications).

For Geospatial Technologies, this study includes the following specific technologies:

- Global Navigation Satellite Systems (GNSS)/ Global Positioning System (GPS)
- Geographic Information Systems (GIS)
- Unmanned Air System (UAS)
- e-Ticketing

For Remote Sensing & Monitoring Technologies, this study includes the following specific technologies:

- Barcodes
- Radio-frequency identification (RFID)
- Detection and Ranging (LIDAR)/ 3D laser scanning
- Unmanned Aircraft Systems (UAS)

For Mobile Devices & Software Applications, this study includes the following specific technologies:

- Automated Machine Guidance (AMG)
- 3D Engineered Models/BIM (3D)
- Handheld data collectors (HDC)

1.2 Key Concepts and Definitions

Technological improvements in the inspection process will be proposed and studied to assess the ability of the states to adopt these technologies. This includes states' regulations, benefits, feasibility analyses, obstacles facing the implementation, the infrastructure needed, and the inspectors' previous knowledge with such technologies. The study will be conducted by investigating several states' current technological adaptation status by analyzing surveys distributed among public and private sectors.

In the digital age, state DOTs have used various technologies to inspect highway infrastructure during the construction and maintenance of assets. To help the reader gain a full understanding of the meaning of this study, this dissertation will use a number of key terms

related to inspection technologies. It is recognized that each state may have its own unique definitions of technical terms describing its use of inspection technologies. Additionally, it is important to note that some technologies can be classified into different categories. For example, UAS can be classified as geospatial technology or remote sensing technology. However, to maintain consistent definitions throughout this dissertation.

The following terms are used in this dissertation:

- **Construction Inspection:** The functions, duties, tests, and measurements provided by DOT inspection staff or their consultants during project construction in adherence with state or other standard methods to achieve quality assurance, basis for payment, and general conformance to DOT specifications and contract requirements (FHWA, 2004).
- **Asset Maintenance:** The work that is performed to maintain the condition of the transportation system or to respond to specific conditions or events that restore the highway system to a functional state of operation. Maintenance is a critical component of an agencies asset management plan that is comprised of both routine and preventive maintenance (FHWA, 2016).
- **Inspection Technologies:** Any host of digital or electronic tools capable of being applied to provide efficiency or replacement of traditional inspection approaches for application during construction or in the evaluation of assets to determine condition, location, characteristics, dimensions, features, or other data collection needs (FHWA, 2017).
- **Geospatial Technologies:** The use of the global positioning system (GPS) or global navigation satellite system (GNSS) to provide the ability to indicate a location that can

then be recorded as a feature of an asset or to input inspection or asset data into geographic information system (GIS) database (FHWA, 2006).

- **Remote Sensing & Monitoring Technologies:** The use of technologies and sensors to provide inspection or monitoring at a physical distance from the point of assessment. Remote sensing can include a range of technologies and sensors (e.g., accelerometers, remote cameras, or traffic loops) that are configured to operate remotely and provide data access via radio, cellular, internet, or other communication means (FHWA, 2018).
- **Mobile Devices & Software Applications:** A software package designed to function on a mobile device such as a Smart Phone or tablet and typically with a specific or customized purpose. Some state DOTs have mobile applications specifically customized to serve their inspection staff (e.g., applications for sign inventories). Mobile applications typically transfer data to larger enterprise or GIS systems (NCHRP Synthesis 491, 2016).
- **Building Information Modeling (BIM):** A process that begins with creating an intelligent 3D model and then using the model to facilitate efficient design and documentation, better coordination, simulation, and visualization that gives architecture, engineering, and construction professionals the insight and tools to digitally plan, design, and construct buildings and infrastructure projects (Autodesk, 2018).
- **Automated Machine Guidance (AMG):** A technology that uses positioning devices, singly or in combination, such as global positioning systems, total stations, or rotating laser levels, to determine and control the real-time position of construction earthwork and paving equipment (California Department of Transportation, 2013).

- **Augmented Reality (AR):** Technology that superimposes spatially contextual information over the user's view of the real world, providing additional data while permitting interactions with the surrounding physical environment (Campbell, 2017).
- **Light Detection and Radar (LiDAR):** An active optical remote sensing system used for measuring the distance between a surface and its sensing units using laser light pulses to create accurate three-dimensional (3D) models of any surface within visual sight of the sensing unit (Jeganathan et al., 2017).
- **Real-time Kinematic (RTK) System:** A global positioning system that uses a base station receiver to transmit raw measurements or corrections to a rover receiver via a wireless data communication link to improve the accuracy of a location in real-time rather than during post-processing (Rizos, 2002).
- **Unmanned Aircraft Systems (UASs):** An aircraft and its associated elements which operate with no human pilot on board. The elements of a UAS include the unmanned aircraft vehicle, a ground-based controller, and a communication system between the aircraft and the controller. UASs can be equipped with various components such as cameras and sensors to collect specific data (Austin, 2010).
- **Virtual Reality (VR):** A computer-simulated environment that allows you to interact in a realistic or physical way within that environment using an interactive 3D model that allows a user to manipulate the model to test the impact of changes before making them in the real world (Campbell, 2017).

1.3 Research Questions

To obtain the research objectives, the following specific research questions were addressed:

- How do inspectors use specific technologies for conducting highway inspections during construction and asset management? And what technologies are mostly used to achieve the goal of inspection?
- What are the driving factors and benefits of using technology for the inspection process? And what are the barriers that prevent the use of some technologies in the inspection process?
- What are the main metrics state DOTs considered to evaluate the use of technologies for highway inspection?
- How can the ROI be determined, and does the implementation environment affect ROI?

1.4 Research Deliverables

This research will offer the following deliverables:

- Technologies used in construction site inspections and transportation assets.
- The effect of inspection technology on the projects' duration, potential outcome, and accuracy of the collected data.
- Obstacles preventing inspectors from using specific technologies if proven feasible and efficient.
- Suggestions aimed to help overcome the issues that prevent the use of technologies in the inspection process.

The resources have three main categories:

- *Literature reviews*: the data and analysis approaches that were used previously in the literature. A comprehensive review of the literature has been conducted. The purpose of this review is to gain background knowledge about similar topics, research, and methodologies.
- *Data Collection*: The proposed study involved both a national survey and case studies. The surveys contained specific technical questions about the technologies currently used by inspectors during the inspection process. These questions relate to the efficiency and effect of these technologies, why these specific technologies are used, and the obstacles that prevent the inspector from using other technologies if they are more beneficial. The survey contained some general questions, such as position, years of experience, projects' budget, and state of occupancy. The case studies were conducted after completing the survey.
- *Data Analysis*: the results and findings will be obtained from the analysis of the survey and case studies.

1.5 Dissertation Organization

This dissertation contains eight chapters covering the following topics:

- 1) Chapter 1: Introduction
- 2) Chapter 2: Literature Review
- 3) Chapter 3: Research Questions and Methodology
- 4) Chapter 4: Geospatial Technologies for Highway Inspection
- 5) Chapter 5: Remote Sensing & Monitoring Technologies for Highway Inspection
- 6) Chapter 6: Mobile Devices & Software Applications for Highway Inspection

- 7) Chapter 7: Inspection Technologies Evaluation metrics
- 8) Chapter 8: Summary and Conclusion

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

The information gathered from a literature evaluation of technologies for highway infrastructure inspection during construction and asset management is presented in this chapter. This chapter aims to provide background and context for the survey findings and case studies. This chapter presents a variety of technologies that are used for the inspection of roadway infrastructure. The following technologies are the topic of this chapter: (1) geospatial technologies, (2) remote sensing & monitoring technologies, and (3) mobile devices & software applications. This chapter discusses typical technologies in each of these three categories. It is noted that there is a blurred boundary among these three categories of technologies. As a result, most technologies can be classified in more than one category. For example, some technologies in the geospatial categories are used based on remote sensing technologies or mobile devices.

2.2 Geospatial Technologies

2.2.1 e-Ticketing

State DOTs are embracing e-Construction technology at an ever-increasing rate in an effort to eliminate paper-based recordkeeping and increase efficiency. As part of its Every Day Counts (EDC) initiative, the FHWA has actively supported electronic construction. E-ticketing is one technology that deserves special attention owing to its dependency on wireless technologies, even if e-Construction is a comprehensive concept and many of its characteristics and functions lay beyond the purview of this project.

Traditionally, DOT inspectors have authorized material delivery using paper tickets (e.g., aggregate, concrete, asphalt). These tickets include batch characteristics, load and delivery

timings, tonnage, asphalt temperature, and signatures in the case of asphalt. The data from the ticket is then utilized to compute payments in a spreadsheet or database. The condition of e-ticketing methods across the United States was the focus of a recent synthesis by Dadi et al. (2020). Paper tickets present a number of difficulties, including (1) they are inconvenient and vulnerable to environmental damage; (2) their collection puts workers and inspectors in danger; (3) inspectors are unable to monitor activity across a jobsite; and (4) manual data collection can cause delays in billing and payment. Previous studies showed that e-ticketing improves fleet management, cuts down on environmental waste, and strengthens project management (Dadi et al., 2020). In recent years, e-ticketing system architecture has advanced significantly.

E-ticketing has grown in popularity over the past five years, but the COVID-19 outbreak caused a sharp increase in demand. Because e-tickets allow for the contactless transmission of information, several state DOTs have swiftly implemented this technology, including Florida, Ohio, Alabama, and Minnesota (NAPA, 2020). For instance, when materials are delivered to project sites, the Alabama DOT no longer accepts paper tickets and is pressing its contractors to immediately embrace e-ticketing (Dadi et al., 2020). In response to COVID-19, the National Asphalt Pavement Association collected e-ticketing procedures utilized by agencies (NAPA, 2020). In response to the epidemic, a number of manufacturers gave free access to their e-ticketing systems. Even though acceptance rates are still inconsistent, DOTs are moving faster than before the outbreak to implement e-ticketing.

Case studies from more recent times add to the information provided by Dadi et al. (2020). A Minnesota DOT e-ticketing pilot was detailed by Korzilius et al. (2019). Staff can trace vehicles from the place of production to the project using haul trucks carrying hot mix asphalt that are equipped with GPS transponders. The paver, project area, and plant were all

enclosed by geofences. Time and location stamps were generated as a truck entered the geofenced areas. Inspectors utilized a smartphone app to track vehicles in real-time, while proprietary software was used to record and view data. The e-ticketing procedure met Minnesota DOT regulations, despite the system's occasionally erratic operation. Korzilius et al. (2019) came to the conclusion that e-ticketing greatly improves productivity, makes it simpler to handle paperwork, enhances inspection procedures, and produces higher-quality pavement. The latter result is optimizing the mix delivery process, doing away with paver pauses, aiding with pavement uniformity, and ensuring the laydown temperature range is ideal. Along with paver-mounted thermal profiling, intelligent compaction, and density measurement using dielectric profile technology, they also recommended using e-ticketing. Resh (2020) also noted that e-ticketing is helpful for monitoring labor compliance data (such as prevailing wage monitoring) and helps resolve arguments over the origin of plant material and the usage of acceptable transport routes. Poor server connectivity, incorrectly configured geofences, GNSS transmitters emitting signals at intervals too far apart to account for quick paving operations, delivery trucks connecting to multiple pavers for the same load, and other problems encountered during the field test all contributed to inconsistent performance. The Minnesota DOT is quickly expanding the use of electronic tickets. The organization finished ten e-ticketing-related initiatives in 2018 and 2019.

Sicaras (2020) discussed an Illinois DOT e-ticketing pilot program that began in June 2020 and was motivated by COVID-19's social distancing criteria. This pilot seems to be less dependent on geofencing and GNSS systems. E-tickets were created and sent to the contractor when trucks departed the factory. Contractors or agency staff could electronically sign for the cargo on an app when the material arrived at the project, or they could text back to confirm

delivery. The platform and mobile app made possible real-time access to data, including plant quantities, quotations, project histories, and truck status. Users can enter field test results and explanations for accepting or rejecting a load in the notes portion of the smartphone app (Sicaras 2020).

The current e-ticketing practices typically involve a third-party provider connecting to the loadout system of a material producer (most often asphalt or concrete) to collect material and load information. Additionally, in some cases GPS units are installed on mobile equipment such as haulers and pavers and a web-based interface to allow for real-time tracking of deliveries and reporting of electronic load information (NCHRP Synthesis 545, 2020). The three main types of e-ticketing include (1) hot mix asphalt (HMA), (2) Portland cement concrete (PCC), and (3) aggregate. Other types of projects that are less common e-tickets include structural steel, rebar, guardrail, signs, and millings. Table 2.1 summarizes the experience of early adopters of e-ticketing with important aspects and effective practices of their pilot efforts.

Table 2.1 Summary of e-Ticketing experience and effective practices (Adapted from Dadi et. al, 2020)

Material Type	Procurement	DOTs Implemented	Vendors Used	Effective Practices
Asphalt	<ul style="list-style-type: none"> • Bid Item • Change Order • Developed own system • Purchased by DOTs 	AL, FL, IA, KY, MN, MO, ND, PA, UT, VA	<ul style="list-style-type: none"> • Fleetwatcher by Earthwave • In-House • Trimble • Libra Systems 	<ul style="list-style-type: none"> • Early stakeholder communication • Hands-on training • Data storage and transfer plan
Concrete	Change order	FL, IA	<ul style="list-style-type: none"> • iStrada • Command Alkon 	<ul style="list-style-type: none"> • Contractor-producer early buy-in • Contractor-producer communication • Thorough stakeholder training
Aggregate	Change order	VA	Fleetwatcher by Earthwave	

Material Type	Procurement	DOTs Implemented	Vendors Used	Effective Practices
Millings	Bid Item	PA	<ul style="list-style-type: none"> • Fleetwatcher by Earthwave • Libra Systems 	<ul style="list-style-type: none"> • Early stakeholder communication • Hands-on training • Data storage and transfer plan

2.2.2 Unmanned Aircraft Systems (UAS)

Over the past five years, there has been an increase in research projects aimed at figuring out how UASs integrate into DOT operations (Wells et al., 2017). Some of these studies examined the effectiveness of UAS data collecting, despite many of them concentrating on creating high-level standards and implementation frameworks. Academic journals have also published several review papers that address UAS in the construction sector. Ham et al. (2016) highlighted drones' use to monitor construction performance and assess the quality of civil infrastructure. Duque et al. (2018) assessed continuing initiatives at state DOTs to utilize UAS for inspecting, monitoring and analyzing infrastructure. Zhou and Gheisari (2018) compiled a list of drone applications in the construction sector. Dorafshan and Maguire (2018) provided arguably the most thorough scholarly analysis of the use of UAS in bridge inspection. The following applications for UAS in the highway industry are presented in research reports and academic articles: bridge inspection, radio tower inspection, surveying, aerial photography, high-mast light tower inspection, stockpile measurement, congestion mapping, work zone monitoring, development of 3D models, production of as-built data, post-hazard damage assessment, detecting the deterioration of bridges (e.g., wetland, stream).

Bridge and culvert inspection and surveying/mapping construction sites are the use cases for UASs that are most frequently mentioned in the literature. UASs cannot completely replace conventional inspection and surveying procedures, as some of the studies described below

demonstrate. For instance, whereas conventional methods are more effective, they are not fit for all bridge inspection jobs, and many smaller bridges are not suitable for drone-based inspections. Although estimates differ, studies have discovered that between 10% and 20% of DOT inventories are most likely to gain from UAS-based inspection (Hubbard et al., 2020).

DOTs may employ drone-based technology for various reasons, including to increase safety, cut costs, provide high-resolution aerial photography quicker, finish projects more quickly, and increase data collecting accuracy (McGuire et al., 2016). UASs often cause less traffic disturbance during inspections, have fewer inspection-related accidents, don't require as much heavy logistics, and require fewer support workers to be there (Otero et al., 2015). In fact, one of the key factors influencing the adoption of UASs has been the promise of increased safety. Using platform trucks, snooper cranes, and other under-bridge inspection vehicles (UBIVs) is less necessary when remote image capture is used (Gillins et al., 2019). Multicopters (usually quadcopters or hexacopters), which have six degrees of freedom, outstanding agility, and can be flown by rookie pilots, are the most often utilized UASs, at least for inspection tasks (Scherer, 2019). The ultimate goal is for drone-based inspections to result in more productive workflows (Irizarry and Johnson, 2019).

UASs provide various advantages, but implementing them will present a number of difficulties for DOTs and practitioners. These might include issues that need to be resolved through planning and policy and practical challenges. The difficulty of maneuvering UAS in environments where GNSS signals are unavailable is because of weather conditions, lack of tactile interactivity, and decisions about balancing vehicle payload and maneuverability, flight times, and battery life. Dorafshan and Maguire (2018) discussed the viability of creating 3D bridge models and concluded that the pre-processing, model-creation and post-processing steps

were too laborious for frequent usage. Inspection employees have also noted the processing of 2D and 3D data obtained by UAS as being time-consuming and less effective than traditional inspection methods (Irizarry and Johnson, 2019).

Lercel et al. (2018) indicated that it's crucial to understand that launching a UAS program does not always require a big expenditure. Purchasing drones and starting research on new uses only costs a few thousand dollars frequently. Early on, agencies will also gain by collaborating with other state and local organizations, academic institutions, and business partners since these alliances may provide the basis for successful and affordable UAS programs. Additionally, organizations must develop thorough liability management plans that specify what personnel is expected to do when performing UAS-related duties (Irizarry & Johnson, 2019).

In demonstration inspection efforts, Tomiczek et al. (2019) examined areas of bridges that were suitable for using a modular UAS. An upward-facing optical flow sensor, a compass, a laser range finder, and a barometer were mounted to the UAS to help with navigation and keep the vehicle in a fixed position because bridge undersides might be devoid of GNSS signals. Although the UAS could record normally inaccessible views, it could not distinguish between bearings on steel girders in a way comparable to existing inspection techniques because it could not see the top surfaces of bottom flanges.

Burgett et al. (2019) examined several UAS uses and their advantages, including surveying, calculating stockpile quantities and inspecting bridges. Drone-based surveys had an accuracy range of 0.68 cm to 0.91 cm for the horizontal dimension and 0.09 cm to 0.81 cm for the vertical dimension. UAS-based surveys are useful when a high number of points are required or when surveying terrain is difficult, even if conventional surveys are more accurate than photometric surveys. While the remote inspection was practical, certain drawbacks were

observed, including erratic cellular connectivity (which interfered with video transmission) and latency problems with both speech and video instructions. Burgett et al. (2019) claimed that rather than equipping a top-of-the-line drone with the most cutting-edge technology, it may be wise to use less expensive UAS and reasonably priced cameras and sensors. It is important to maintain replacement prices as low as possible.

Wells and Lovelace (2017) created guidelines for UAS-based bridge inspections for the Minnesota DOT based on several field experiments. It is essential to create thorough site-specific plans that cover safety measures, possible risks that may be encountered during flights, and mitigation techniques before starting UAS work in the field for each structure that will be inspected. Although flights can be automated, having this capacity is essential for navigating locations without GPS. Pilots also need enough expertise and skill to simultaneously handle a drone-mounted camera (or other movable sensors) and fly the vehicle manually.

Researchers studying UAS have increasingly focused on safety applications. Drones were employed, for instance, by de Melo et al. (2017) to identify workplace dangers, which information may subsequently be utilized to direct the correction of harmful circumstances. A safety management model that incorporates 4D BIM and UAS data on the location of possible risks was created by Alizadehsalehi et al. (2018). Table 2.2 summarizes typical applications of UASs associated with benefits and limitations related to highway infrastructure inspections.

Table 2.2 Typical application of UASs for highway infrastructure inspection (Adapted from FHWA 2018a)

Areas of Applications	Studies/Authors	Benefits	Limitations
Construction Safety Inspection	Gheisari et al. 2014	Increased efficiency; permanent digital records	Potential distraction and collisions hazards

Areas of Applications	Studies/Authors	Benefits	Limitations
Roadside Condition Inventorying, Assessment, and Inspection	Barfuss et al. 2012; Hart and Gharaibeh 2011; Zhang 2008	Permanent digital records; bird's view not possible by vehicle-mounted imaging systems	Data collection of visible assets via "bird's view" only
Topographic Mapping and Estimating Earthwork Volumes	Judson 2013; Siebert and Teizer 2014; Hugenholtz et al. 2015; Brooks et al. 2014	Quick data collection to produce preliminary 3D mapping products	Less accurate than other technologies
Monitoring Construction Progress and Status	Zollman et al. 2014; Wang et al. 2014; Lin et al. 2015	Quick data collection to produce 3D as-built models; permanent digital record	Lack of automation tools to create building information model components
Monitoring Unstable Slopes	Lucieer et al. 2014; Niethammer et al. 2010	Inexpensive and quick data collection over uneven terrain	Requires ground control points or aerial targets

2.2.3 Global Positioning Systems (GPS) and Global Navigation Satellite Systems (GNSS)

GNSS is the standard generic term for satellite navigation systems (i.e., constellation) that provide autonomous geospatial positioning anywhere on earth. The main GNSS constellations include GPS, GLONASS, Galileo, and BeiDou. These satellites provide signals from space and transmit positioning and timing data to GNSS receivers. The use of multiple satellites results in reduced delays in finding adequate ranges (FHWA 2018a) and are able to maintain the accuracy, redundancy, and availability at all times for collecting location data. If one satellite does not provide a quality position or fails to operate, GNSS receivers can pick up signals from other systems.

GPS has been fully operational for more than two decades and has become a vital tool in the construction industry (FHWA 2018a, Ogaja 2011). GPS consists of up to 32 medium Earth orbit satellites in six different orbital planes. The exact number of satellites in GPS varies because older satellites are retired and replaced. A number of GPS-based systems have been proposed or implemented to facilitate highway infrastructure inspection through the

identification and tracking of materials on construction sites. Typically, GPS and GNSS technologies include three main segments as follows:

- **Space segment**—This segment consists of satellites that continuously broadcast position and time data to GNSS receivers.
- **Control segment**—This segment consists of ground stations that monitor, track, and collect the satellite broadcast signals.
- **User segment**—This segment consists of receivers, processors, and antennas allowing operators to determine the position, velocity, and time of the operator’s location.

Table 2.3 summarizes the typical use of GNSS/GPS technologies reported by state DOTs, construction contractors, and instrument developers/service providers through a series of interviews (FHWA 2018a). Table 2.3 shows that both state DOTs and construction contractors use GNSS/GPS technologies for highway inspection during construction and for asset management.

Table 2.3 Typical use of GNSS/GPS for highway construction (Adapted from FHWA 2018a)

Applications	Use of GNSS/GPS for highway infrastructure		
	by State DOTs	by construction companies	by instrument developers/service providers
Topographic surveying	✓	✓	✓
Earthwork	✓	✓	✓
Paving	✓		✓
Roadway design	✓	✓	
AMG and control	✓	✓	✓
Verification	✓	✓	
As-built surveys	✓	✓	✓

Applications	Use of GNSS/GPS for highway infrastructure		
	by State DOTs	by construction companies	by instrument developers/ service providers
Site/progress monitoring	✓	✓	
Inspection	✓	✓	
Quality assurance/quality control	✓	✓	
Asset management	✓	✓	✓

Given that GPSs/GNSSs are an essential component in positioning, it is difficult to address them separately from the other technologies. Cho (2019) evaluated practices for establishing grade control and referencing using various technologies (mobile mapping, UASs, terrestrial laser scanning, and robotic total stations), as a number of the technologies they looked at rely to some extent on GPS or GNSS. While contractors can choose from a variety of technologies for grade control and location reference, inspectors verify elevations using conventional survey methods (including GPS and laser scanning). But interoperability issues in systems have led to increased costs, material overruns, and protracted project schedules due to rework. Cho (2019) provided a number of justifications for differences between contractor measures and inspector measurements, such as long stretches between the design and construction phases, subpar surveying techniques, and far-flung survey stations.

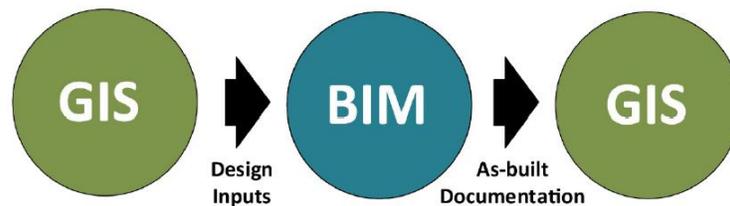
2.2.4 Geographic Information Systems (GIS)

Creating, maintaining, analyzing, and displaying geographic data may be accomplished using a computer-based system called a geographic information system (GIS), which offers a variety of tools. The deployment of a computer-based GIS for transportation (GIS-T) was initiated in the 1980s. At that time, 2D cartographic displays of roadway data were used to apply computer-based GIS-T. Since then, GIS has changed to accommodate the increasing number of

federal, state, and municipal applications, such as infrastructure planning and management, routing, and scheduling.

GIS was first used to display the data in text-based inventory database systems. With the substantial deployment in many areas of the transportation industry, GIS is increasingly becoming the common roadway inventory database (FHWA 2019). As a result, GIS serves as a data management tool integrated into civil infrastructure management (CIM), which is an “asset management system that starts with planning the construction or modification of a transportation asset, moves through design and construction, and, once built, transitions to deployment, operations, maintenance, and performance evaluation system” (FHWA 2019). Figure 2.2 shows the data flow between GIS and building information modeling (BIM) platforms to provide roadway inventory updates when a construction project ends.

Figure 2.1: GIS and BIM data flow (FHWA 2019b)



Integrating GIS and BIM may assist agencies in streamlining their business processes by visualizing, sharing, analyzing, and monitoring asset data. GIS is useful in the field of transportation asset management. Maps may help decision-makers gauge the size of the problem, comprehend how their choices will affect the surrounding area, and eventually reach better conclusions. Maps may help the general public see and understand the global relevance of the transportation resources they use on a daily basis. GIS enables transportation authorities to

present data about their assets on maps that are clear to audiences of various technical backgrounds FHWA, (2012).

2.3 Remote Sensing and Monitoring Technologies

2.3.1 Barcodes

There are fewer examples of 1D, 2D (QR codes), and 3D barcodes being utilized on construction projects or for asset management. A barcode-assisted document management system can boost productivity and cut expenses (Shehab et al.2009). Lee et al. (2015) analyzed whether using QR codes might enhance document control procedures on highway projects. They discovered barcodes have historically been used for applications like quantity takeoff, controlling materials in the field, warehouse inventory, and maintenance, issuance of tools and consumable materials, cost engineering, and document control (Lee et al. 2015). Both 1D barcodes and QR codes have a number of advantages, including increased agency and contractor database management, reduced project costs, and more effective team communication. However, a number of obstacles prevent broad adoption. Barcodes are less useful in the field if there is no (or weak) internet connection since the information gathered by scanning them cannot be promptly synchronized with project databases. If physical copies become damaged, QR codes on paper documents may become illegible. Agencies and contractors may also be resistive to new technology at the organizational level. In order to evaluate the efficacy of QR codes, Lee et al. (2015) used papers taken from a bridge repair project in Oregon. The study discovered that QR codes could greatly decrease the time required to obtain and evaluate project papers and that their adoption produced a benefit-cost ratio of 1.70 (Lee et al. 2015).

Barcodes and RFID have been combined for supply chain management, inventory, and material tracking Moselhi & El-Omari, (2006). Barcodes have been tested in these situations by state DOTs. A recent Iowa DOT pilot project used QR tags attached to haul truck dashboards to track concrete deliveries (Shepard, 2017). A barcode-based automated material tracking system was created and implemented in Louisiana (Icenogle et al., 2013). Barcodes were attached to asphalt delivery tickets and read as trucks arrived at project locations to remove the need for human data entry. Tsai and Yang (2016) evaluated the use of barcodes in Georgia DOT to inventory freshly installed roadway signage. The North Carolina DOT plans to fully adopt barcodes and RFID tags for material product clearances as part of a larger shift toward e-Construction (FHWA, 2019). However, it is important to note that barcodes and the material they are printed on have a tendency to be more brittle when subjected to abrasive environmental factors. Barcodes are not the best option for storing geographical data without the use of other technologies.

2.3.2 Radio-Frequency Identification (RFID)

Research on RFID technologies has grown exponentially over the past two decades. Jaselskis et al. (1994), one of the seminal studies on RFID, indicated three main applications of RFID in the construction industry, including: (1) monitoring concrete deliveries, (2) tracking workers and equipment, and (3) managing critical materials. Monitoring concrete delivery is a common highway infrastructure inspection activity among these three applications. Figure 2.2 shows an overview of RFID-based concrete tracking system. RFID tags are pinned to trucks and/or materials, encoded with information, and readers extract and transmit data to a central database.

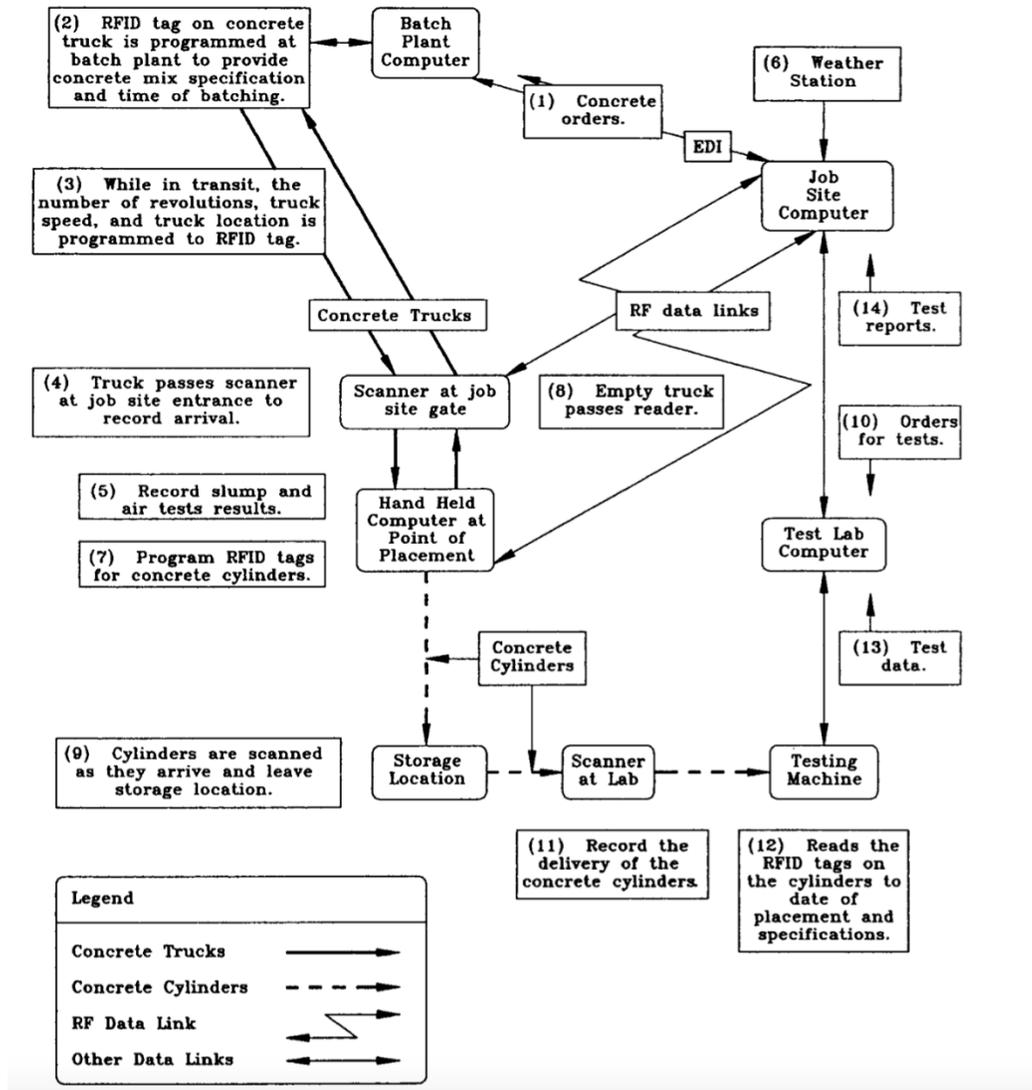


Figure 2.2 RFID-Based Concrete Tracking System (Jaselskis et al. 1994)

Figure 2.2 indicates that truck assignments are determined once a concrete order is received, and truck ID numbers are communicated to a computer at the batch facility along with concrete mix needs. RFID tags attached to vehicles are programmed with specifications for the concrete mix, admixtures, loading time, and delivery. A vehicle passes an RFID reader as it departs the facility, logging the departure and transmitting data to a central computer that can be viewed at the final jobsite. Data on the truck's position, speed, and the number of mixing

rotations may be logged as it makes its way to the project (if the vehicle is outfitted with GPS). Arriving at a jobsite, an additional RFID reader reads the tag and sends data to the main computer, which confirms that the mix time and number of rotations adhere to the criteria. The results of air tests and slump tests are then recorded by employees using portable computers, and the truck's RFID device associates test data with the vehicle ID. Following that, data, such as truck ID and delivery time, is written to the RFID tags that have been attached to the concrete test cylinders. Tagging concrete cylinders make billing and paying the contractor, testing lab, and concrete supplier more efficient. After the delivery is finished, the vehicle departs the jobsite and drives through the RFID reader once more, which logs the time of departure. The batch facility will then get this information to schedule the next truck assignments. The RFID reader records the return time and may also get information on the vehicle's speed and route when the truck returns to the batch facility. This procedure may be stated more succinctly as follows: RFID tags are pinned to vehicles and/or materials, encoded with data, and readers retrieve and transmit the information to a central database.

Several studies have documented how RFID technology is used in transportation and other fields (Jirik et al, 2007). The tracking and monitoring of hazardous materials, managing component inventories in storage yards, accelerating and automating the delivery and receipt of materials, monitoring labor, tracking the movement of materials throughout the construction supply chain and on project sites, and enhancing onsite inspection activities are just a few of the key applications. For example, using RFID-based systems to manage assets found in state-owned rights of way, such as utilities, outdoor advertising, right-of-way markers, traffic signs and signals, bridges, culverts, buried structures (such as foundations, piers) (Lodgher et al., 2010).

Qiao et al. (2009) also examined existing and potential applications of RFID in the transportation industry.

Some of the advantages and disadvantages of RFID technology were succinctly outlined by Li and Becerik-Gerber (2011). Its capacity to facilitate wireless communications is one of their features. RFID tags have larger read ranges than barcodes and can operate without a clear line of sight and in cluttered situations without being hindered by noise, impurities, light, or dirt. Like barcodes, RFID technologies may be used in challenging environments and do not require highly specialized skill sets to operate (Qiao et al., 2009). Concerning disadvantages, read ranges and data transmission speeds may suffer when tags are placed on or near metals or liquids owing to radio wave interference. However, because of advancements in RFID, these concerns are now controllable. For instance, keeping some distance between tags and metal surfaces can help with tag reading issues, as can altering tags to make them readable underwater or inside of concrete.

Although passive RFID tags have an infinite lifespan, active tags normally only last many years. While systems are increasingly being designed to endure challenging, unpredictable, and complicated environmental conditions, readers and tags still need to be able to function under challenging situations. Although this problem can be remedied by integrating RFID systems with other technologies like GNSS, their ability to determine precise locations on their own is typically restricted. Numerous authors have noted that RFID's widespread acceptance has also been hampered by a lack of standards and the inconsistent frequency ranges utilized by various nations, which can complicate supply chains (Iacovidou et al, 2017).

Although RFID devices have grown throughout numerous industries over the past 20 years, their application in the construction sector is still rather limited. The more developed nations and areas, where labor is more expensive. Additionally, there is a larger need for labor-

saving technology. RFID applications are likely to become increasingly prevalent in the transportation and construction sectors as they become more fully integrated with other technologies.

2.3.3 Light Detection and Ranging (LiDAR)

LiDAR, which is also considered as a geospatial technology, is an optical remote sensing technology typically used for measuring the distance between a surface and the sensing units.

LiDAR is effectively used to acquire X, Y, Z (three-dimensional or 3D) positions of any surface within visual sight of the sensing unit.

There are three main LiDAR applications: (1) static LiDAR (e.g., a system mounted at a single location), (2) mobile LiDAR (e.g., a system can be attached to a vehicle such as a truck or unmanned aircraft), and (3) airborne LiDAR (e.g., a system is attached a manned aircraft) (FHWA 2018b). Static LiDAR collects highly accurate data but is comparatively much slower in data collection than mobile and airborne LiDAR and exposes DOT workers to more traffic and hazard risks. Both mobile and airborne LiDAR provide mapping-grade accuracy at high rates of travel. Mobile LiDAR applications involve digital highway measurement vehicles, LiDAR, inertial navigation systems, and GPS to provide measurements of elements such as pavement markings, pavement cross sections, shoulders and curbs (Ogle, 2007; NCHRP Report 748, 2013). Airborne LiDAR systems can collect data when traveling at 115 miles per hour at an elevation of about 1,640 feet (Dye Management, 2014). Table 2.4 shows typical project characteristics for using the different LiDAR methods.

Table 2.4 Project characteristics for using different LiDAR methods (adapted from FHWA 2018b)

Aerial LiDAR	Mobile LiDAR	Static LiDAR
<ul style="list-style-type: none"> • Mainline lengths > 1,300 ft • Large areas and wide corridors • Large bridge replacements • Variable terrain • Rural reconstructions • Areas with limited foliage 	<ul style="list-style-type: none"> • Long, rural corridors • High-speed corridors • Corridors with high volumes • Multilevel interchanges • Resurfacing projects with cross-slope or super-elevation corrections • Data collection time constraints 	<ul style="list-style-type: none"> • Mainline lengths < 1,300 ft • Small areas • At-grade intersections • Low-volume and low-speed roadways • Flat terrain • Small bridge replacements • Urban resurfacing projects with drainage or cross-slope repairs • Interstate widening

Table 2.5 summarizes a description, the capabilities and limitations of each of these types of LiDAR systems. Aerial LiDAR systems include airborne and helicopter platforms. Mobile LiDAR systems include UAS, handheld, and vehicle platforms.

Table 2.5 Summary of different LiDAR systems (Adapted from FHWA, 2018a)

LiDAR Type	Description	Capabilities	Limitations
Aerial-Airborne	Sensor attached to fixed-wing aircraft at 1000 m or more above ground; co-acquired photographic images are becoming more common	<ul style="list-style-type: none"> • Rapid coverage over large areas • Fairly uniform sampling • Can collect other remote sensing data simultaneously 	<ul style="list-style-type: none"> • Large footprint • Poor coverage on vertical faces • Flight logistics
Aerial-Helicopter	Sensor mounted to a helicopter flying closer to the ground	<ul style="list-style-type: none"> • Similar to airborne, but closer to ground 	<ul style="list-style-type: none"> • Flight logistics may be complicated
Mobile-UAS	Lightweight sensor mounted to an unmanned aerial system; flight	<ul style="list-style-type: none"> • Detailed information for a site • Pre-programmed flight paths 	<ul style="list-style-type: none"> • Short flying time limits to relatively small areas

LiDAR Type	Description	Capabilities	Limitations
	heights are typically less than 150 m	<ul style="list-style-type: none"> • Nadir and oblique scanning possible 	<ul style="list-style-type: none"> • Few systems available, experimental
Mobile-Handheld	Sensor carried in hand or on a backpack frame	<ul style="list-style-type: none"> • Flexible system • Indoor/outdoor • Only one person required 	<ul style="list-style-type: none"> • Slower than most other methods for large areas
Mobile-Vehicle	Sensor mounted to a vehicle and data are collected kinematically while a vehicle is in motion	<ul style="list-style-type: none"> • Fast coverage along highways 	<ul style="list-style-type: none"> • Limited to navigable paths • Obstructions from traffic
Static	Instrument is mounted to a tripod. Photographic images are often co-acquired; typically implemented only for smaller sites	<ul style="list-style-type: none"> • Highest resolution • Highest accuracy • Some flexibility • Indoor/outdoor 	<ul style="list-style-type: none"> • Slower than other techniques • Non-uniform sampling

Many state DOTs have used LiDAR technology for highway infrastructure inspection-related applications. Table 2.6 summarizes the typical use of LiDAR systems for highway infrastructure construction and inspection reported by state DOTs, construction contractors, and instrument developers/service providers (FHWA 2018a).

Table 2.6 Typical use of LiDAR for highway construction (Adapted from FHWA 2018a)

Applications	Use of LiDAR systems for highway infrastructure		
	by State DOTs	by construction companies	by instrument developers/service providers
Topographic surveying	✓(1), ✓(2), ✓(3)	✓(1), ✓(2), ✓(3)	✓(1), ✓(2), ✓(3)
Earthwork	✓(1), ✓(3)	✓(1), ✓(2), ✓(3)	✓(1), ✓(2), ✓(3)
Paving	✓(1), ✓(2)	✓(1)	✓(1), ✓(2), ✓(3)
Roadway design	✓(1), ✓(2), ✓(3)	✓(3)	✓(2), ✓(3)
AMG and control	✓(1), ✓(2)	✓(3)	
Verification	✓(1), ✓(2)	✓(1)	✓(1), ✓(3)
As-built surveys	✓(1), ✓(2)	✓(1), ✓(2), ✓(3)	✓(1), ✓(2)
Site/progress monitoring	✓(1), ✓(2)		

Applications	Use of LiDAR systems for highway infrastructure		
	by State DOTs	by construction companies	by instrument developers/ service providers
Inspection	✓ ⁽¹⁾ , ✓ ⁽²⁾ , ✓ ⁽³⁾	✓ ⁽²⁾	✓ ⁽¹⁾
Quality assurance/quality control	✓ ⁽¹⁾ , ✓ ⁽²⁾	✓ ⁽¹⁾ , ✓ ⁽²⁾ , ✓ ⁽³⁾	✓ ⁽¹⁾ , ✓ ⁽³⁾
Asset management	✓ ⁽¹⁾ , ✓ ⁽²⁾ , ✓ ⁽³⁾	✓ ⁽¹⁾ , ✓ ⁽²⁾ , ✓ ⁽³⁾	✓ ⁽²⁾

Notes: (1) denotes for static LiDAR, (2) denotes for mobile LiDAR, and (3) denotes for Aerial LiDAR

One of the key benefits of LiDAR technology is that its acquired data is useful for a number of applications. The collected data using LiDAR can also be mined for additional information to serve as suitable input for different applications. NCHRP Report 748 (2013), “*Guidelines for the Use of Mobile LIDAR in Transportation Applications*” shows various applications of using mobile LiDAR related to construction delivery, including:

- *As-built and maintenance documentation*—the data is integrated into a centralized database that is continuously updated for future planning, maintenance, and construction.
- *Pavement smoothness and quality determination*—data collected at higher resolutions can be used to evaluate pavement smoothness and quality.
- *Construction automation and quality control*—Change detection and deviation analysis software uses design models to identify deviations from LiDAR point clouds for construction quality control.
- *Performing quantity take-off*—LiDAR data is used to determine lengths, areas, or volumes of construction quantity.
- *Virtual and 3D Design*— LiDAR data can be used for clash detection by checking for intersections of proposed objects with existing objects modeled in the point cloud
- *Inspections*—LiDAR can provide overall geometric information and an overall condition

assessment.

2.4 Mobile Devices & Software

2.4.1 Automated Machine Guidance (AMG)

In several publications, researchers have presented overviews of the possible applications of automated machine guidance (AMG) for building and maintaining highways (Vonderohe and Hintz, 2010). Due to its capacity to enable users to obtain exact grade control, which in turn permits greater control of earthwork and paving volumes, AMG has traditionally been reserved for projects involving significant earthwork or paving activities. Additionally, Azar and Kamat (2017) discovered that AMG works best when given monotonous, linear tasks to do repeatedly. Although AMG frequently uses GNSS receivers for machine navigation, activities that need the use of costly materials (such as stone base, asphalt, or concrete) would benefit from controls obtained from total stations. AMG has the power to streamline operations, but to fully utilize this ability, there must be strong collaboration between the survey, design, and construction processes.

Adopting AMG has numerous advantages. Some advantages of AMG are more directly due to modeling because of its emphasis on 3D modeling, but they also have an impact on construction. These comprise the capacity to identify and correct design flaws before to construction, clearer project site visuals, and improved communication of design intent von (Ellenrieder and Wampler, 2016). Locally, AMG can shorten turnaround times, enhance quality, tighten schedules, and foster a safer workplace (White et al. 2018). AMG also encourages real-time results verification, more precise inspections, and more seamless integration of design and construction processes (Mallela et al., 2018). The main AMG advantages are classified into five

areas: (1) Lower Construction Costs; (2) Reduced Schedules; (3) Environmentally Friendly; (4) Higher Quality; and (5) Safer Working Conditions

- *Lower Construction Costs*—This advantage includes less money spent on fuel, maintenance, operating costs, agency support, greater equipment productivity, and greater potential to prepare electronic as-builts.
- *Reduced Schedules* – This includes less time dedicated to staking and surveying, increased equipment productivity, and improved equipment logistics from less rework.
- *Environmentally Friendly*—This includes greener construction with less time where equipment is idling.
- *High Quality*—This may include the following:
 - Greater accuracy and precision compared to traditional construction methods
 - On asphalt paving projects, better control of elevation and cross slope
 - More accurate calculations when performing quality assurance and quantity calculations
 - Better calibration and control of paving equipment with fewer errors
- *Safer Working Conditions*—This advantage typically includes fewer field staff exposed to heavy equipment, less chance for back-over/run-over incidents, and less need to eliminate string lines.

It is noted that implementation difficulties and equipment complexity are two possible downsides of AMG. Expanding their use at transportation agencies is the first challenge to be overcome because AMG depends on 3D models. The adoption of 3D design methodologies has historically been difficult for agencies for several reasons, including a lack of resources, internal

expertise, organizational inertia, ingrained business processes, and training choices (Vonderohe and Hintz, 2010). The generation of 3D models from preconstruction survey data that is erroneous or partial, software issues, and the inability of machine hydraulic controls to react quickly to AMG inputs (White et al., 2018). Additionally, machine speed is important because it affects measurement accuracy because faster machines struggle to detect errors. Several strategies can be used to overcome agency-level obstacles, including obtaining support from upper-level management, thorough implementation planning that identifies short- and long-term goals, and developing AMG usage specifications.

2.4.2 3D Engineered Models/BIM

A well-known method that makes it possible for more accurate, timely, and economical planning and construction is 3D engineering modeling. FHWA has promoted the use of 3D created models for highway construction inspection through its "Every Day Counts" (EDC) campaign (FHWA EDC 3, 2017). According to FHWA (2017), 3D models are being used increasingly often in building projects for real-time verification and collecting post-construction survey data for figuring out payment amounts. In the three phases of construction—pre-construction, construction, and post-construction—3D engineering models are employed for inspection procedures.

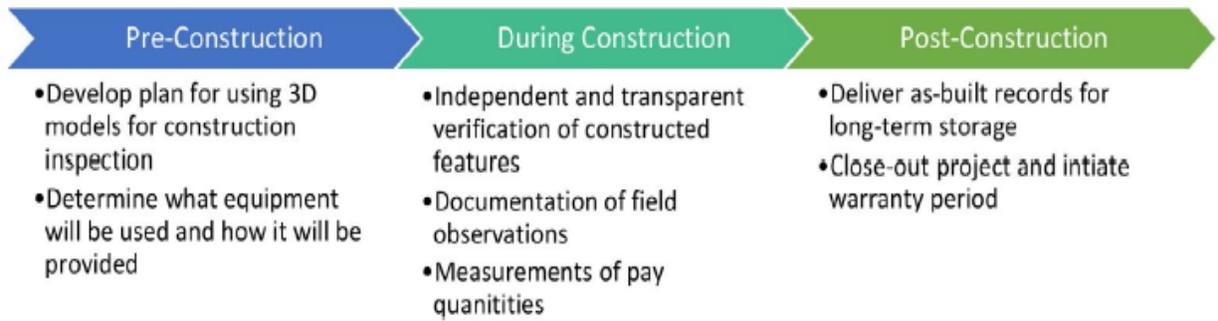


Figure 2.3: Use of 3D Engineered Models for Construction Inspection (FHWA-EDC3, 2017)

The inspectors can utilize 3D models to create an inspection plan for the pre-construction stage. The plan helps inspectors manage digital data, define inspection tools and methods, find a source of inspection support during construction, establish a process for measuring and calculating quantities for payment, and decide on the requirements and formats for 3D as-built records. It also helps inspectors assess the effects of differences between survey data and field conditions (FHWA-EDC3, 2017).

Inspectors can evaluate the actual conditions in the field in respect to the plans and specifications using 3D models during the construction process in a fair and transparent manner. Inspectors can record and compute pay amounts more accurately and efficiently by using 3D models. With 3D models, the data may be examined in many different ways, such as through spreadsheets and visual field representations.

In the post-construction phase, 3D models let the inspector comprehend the project's precise as-built conditions. Accurate data from 3D-built models is also provided for long-term asset management and recordkeeping. The Iowa Department of Transportation said that while construction is taking place, a mobile computer system may be used to update a 3D engineering model (Reeder and Nelson, 2015). The record sketch, which is necessary for highway infrastructure inspection and asset maintenance, is created from the 3D model. The 3D model

serves as a guide for ongoing asset management system upkeep and improvements (Reeder and Nelson, 2015).

2.4.3 Handheld Data Collectors (HDC)

Handheld devices are described as "self-contained electronic devices that fit in a user's hand and have, at a minimum, enough computer processing power to exceed the functions of an electronic personal organizer and to execute software programs that can enhance their built-in capability" Hannon, (2007). Some portable devices, such as smartphones and tablets, use satellite network positions to determine the user's location and then employ inertial movement to change the view as the device travels about the environment (Mallela et al., 2020).

Many state DOTs have used handheld equipment to examine road infrastructure. For instance, Wisconsin DOT provides its inspectors with portable tools that enable them to quickly and precisely measure the site of work and record amounts. When using portable technologies, inspectors no longer need to carry tape measures and other tools to do the same tests. WisDOT tablet devices come with a tool called OnStation that enables inspectors to quickly and accurately trace the station offset from a specific project item (Harper et al., 2019). Similarly, the New York State DOT provides inspectors with portable equipment to quantify amounts for inspection reasons. According to the New York State DOT, training inspectors to use mobile devices and other technologies has helped field operations become more effective and inspections become more accurate (Harper et al., 2019).

The ability of smartphone and tablet cameras and displays to improve has led to an increase in the usage of portable devices to display augmented reality (AR) apps. AR apps may record video of the actual environment using the device's back-facing cameras, align and render

virtual data, and show the image on the screen. Additionally, portable AR devices like tablets and smartphones frequently include cameras on the rear with a wider field of view, which is crucial when the device is held at arm's length (Mallela et al., 2020). Adopting portable AR technology enables several users to see the same scene on a single device simultaneously. Some vendors have focused their efforts on portable, mobile devices for AR applications unique to the construction industry (Mallela et al., 2020).

2. 4.4 Mobile Mapping Systems

Image sensors have been entirely exploited for digital electrical components in current mobile mapping systems (Chiang et al., 2020). Digital cameras with image frames, multi-spectral line scanners using line-scan technology, and optical and IFSAR/INSAR image sensors are all examples of picture sensors. The evolution of digital image technology is intrinsically linked to the development of mobile mapping systems. The emergence of image-based digital cameras has had the most profound impact on imaging sensors.

The charged-coupled device (CCD) camera resolution and image size have been steadily increasing in recent years. For airborne mobile mapping systems, a number of high-performance digital reflex cameras with single lenses have been developed and tested, with promising results. To improve mapping efficiency, the user does not need to scan a film negative; digital image processing technology improves feature extraction automation and simplifies updating and storing digital photographs.

As digital imaging techniques have improved, the IFSAR aerial mapping method has gained appeal in the geospatial information business. It has a rapid deployment time, a weather-resistant operation mode, and excellent cloud penetration. The aerial hyperspectral imaging

system is another major advancement in digital imaging technology with an airborne mapping system.

In low-cost mobile mapping systems, kinetic depth cameras are gradually replacing sensors. Because they are low-cost and offer mass production for the consumer market, these approaches improve interior scenery. To produce indoor 3D models using mobile devices, Google and Apple are vying to develop inertial sensing, depth cameras, and CCD cameras.

2.5 Summary

The literature review findings reported in this chapter include the most important aspects of using technology for highway infrastructure inspection. This chapter contains essential information for comprehending the current state of practice for DOTs employing various technologies to assess highway infrastructure during construction and asset maintenance. The essential principles, typical uses, advantages, and issues linked to highway inspection of sample technologies in three primary areas are explored in detail: (1) geospatial technologies, (2) remote sensing & monitoring technologies, and (3) mobile devices & software applications. As stated at the outset of this chapter, the distinction between these three types of technology is hazy. Most technologies, in fact, may be categorized into many categories. The objective of this chapter is not to categorize technology used in highway inspection. The principles in this chapter, on the other hand, serve as the foundation for the survey and case example procedures used in this dissertation.

CHAPTER 3 : RESEARCH QUESTIONS AND METHODOLOGY

3.1 Introduction

This dissertation is the result of an intersection of the following three independent sources of information:

- Performing literature review on the type and uses of inspection technologies.
- Survey state DOTs on their use of these technologies.
- Conducting case studies of technology used in the inspection process.

First, a comprehensive literature review was conducted that explored innovative and advanced technologies and the associated current practices in use for inspection of new and existing highway infrastructure assets. The literature review included the following areas: (1) technologies used for inspection of new and existing highway infrastructure assets; (2) available assessment methods for the viability, efficiencies, and ROI of inspection technologies; and (3) relevant information on the use of technology for construction management, allocating resources and determining highway asset conditions. For example, the FHWA study on “Effective Use of Geospatial Tools in Highway Construction” identified a wide range of construction inspection and asset management technologies, including UASs, LIDAR, photogrammetry, GNSS, Robotic Total Stations, and others (FHWA, 2019). Similarly, the FHWA study on Automation in Highway Construction discussed a number of automation technologies, including remote sensing, underground utility location; machine control and automation; field technology and inspection (e.g., intelligent compaction and tablets); and digital data management) (FHWA, 2018). Based on the information gathered from the literature review, the author developed a questionnaire and conducted a survey of state DOTs. Finally, the case studies are conducted to supplement and validate the findings from the survey and obtain specific methods used to assess

the viability, efficiencies, and ROI of inspection technologies and how information obtained from these assessment methods is used.

3.2 Dissertation Structure

Figure 3.1 shows the dissertation's structure, including eight chapters, starting with the problem identification and the problem statement in addition to the main questions and purpose, which leads to the discussion of the needs and potential areas to investigate, in our case: "technology implementation in the inspection process."

3.2.1 Identifying the Research Problem and Establishing Research Questions

State DOTs historically have employed on-site inspectors to perform infrastructure inspection. However, over the past decades, many state DOTs have been experiencing an expanding highway construction program concurrently with a reduction in both the number and experience levels of inspectors. As a result, state DOTs are seeking approaches to achieve greater efficiencies in quality management. This part has set the stone for the rest of the dissertation. Accordingly, the main technologies used in highway project inspection were examined through literature and previous work to determine the best practice for each technology. This part helped in understanding the functions of each technology. All gathered insights and statistics were used for developing the survey. Later, the obtained data were analyzed and assessed. Patterns and trends in using the technologies were studied and analyzed. After that, the need to develop a systematic procedure depending on the ROI of each technology was proven to be needed. Therefore, a case study was conducted to investigate the effect of implementation environment factors on ROI.

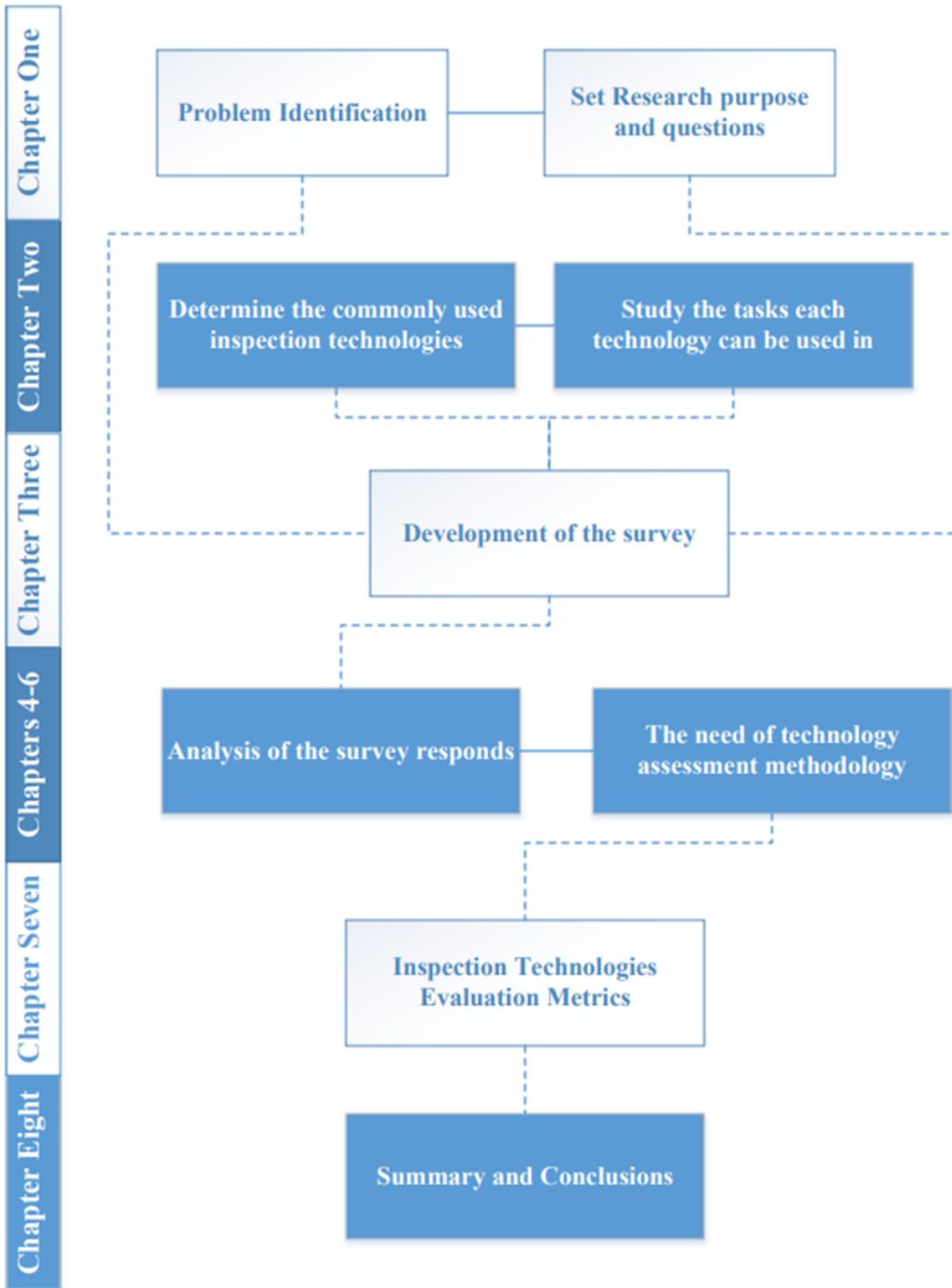


Figure 3.1: Overview of Research Methodology

3.2.2 Points of Departure

The dissertation starts by identifying the importance of implementing technologies in inspection and studying the involvement of all project parties in using these technologies usage by discussing the main aim of using technologies for inspection and how it will reflect the outcome of the project and the maintenance request at later stages.

This dissertation aims to alleviate the mistakes that may happen during the inspection of construction and maintenance projects and examine how to benefit from emerging technologies. The literature review and the survey are used to give a better image of how to leverage different emerging technologies and identify the barriers and shortcomings to use these technologies in highway projects.

3.2.3 Data Collection Survey

The purpose of the survey was to gather information on current nationwide practices, uses, and implementation of technologies for construction and to identify state DOTs with knowledge and experience that warrant additional investigation. In addition, the questionnaire allowed state DOT respondents to provide document links, references to websites, or attachments that offered specific DOT information on the investigated technologies.

The survey questionnaire was distributed electronically, the responses were then tabulated, evaluated, and supplemented with follow-up telephone calls and emails as needed for clarification. The survey questions aimed to present current practices of agency use of technologies for highway infrastructure inspection. To collect the most updated information on highway infrastructure inspection for the digital age, a web-based survey was distributed to the voting members of the American Association of State Highway and Transportation Officials

(AASHTO) Committee on Construction (COC), which includes representatives from all 50 state DOTs. After sending several requests to participate in the survey, 42 completed questionnaires were obtained (an 84% response rate). The purpose of the survey was to identify technologies currently in use by state DOTs for inspection of new and existing highway infrastructure assets and different document methods used to assess the viability, efficiencies, and return on investment (ROI) of inspection technologies. In addition, the survey result helped to determine state DOTs for further investigation as case examples, which are detailed in Chapter 4. Appendix A includes the survey questionnaire for reference. This survey questionnaire was distributed to each DOT's member of the AASHTO COC, or the AASHTO Technical Subcommittee on Integrated Construction Technologies. The individual privacy of the participants is maintained in all published and written data resulting from this study. Many technologies are covered in this questionnaire. The technologies covered were:

- Geospatial technologies.
- Remote sensing & Monitoring Technologies.
- Mobile Devices & Software Applications.

All the survey questions are shown in detail in Appendix A. However, this section will discuss some of the questions as examples. For each topic, the survey starts by stating their experience in this field, and from that point, people are classified into many criteria regarding their years of experience using specific technologies. This type of question served as data reliability depending on the user experience. After fulfilling other demographic questions, every technology has the same set of questions (either construction or maintenance process). This question allowed the classification of the most used applications of each technology, which indicates the improvement areas of how to make the applications with less helpful usage. For

example, mobile devices and software applications are BIM, AMG, or Handheld data collectors by analyzing this data and linking it to the years of experience using each technology.

The next segment shows an example from the survey regarding how the agencies are using technology applications for inspection (during construction), for example: “What was the Mobile technology they have been using for tracking the position of bulk materials (concrete, asphalt, aggregate loads)? This segment aims to gather knowledge regarding the most used technology application for specific tasks. The same question was asked for different phases of the project (Maintenance phase). This question helps the technology provider focus on some technologies that fit the inspection process more than the other technologies. The last part of each technology questionnaire is mainly concerned with barriers and the factors that hold back technology usage, considering cost, education, standards, and many other aspects. Finally, the survey asks questions that target the driving factors for selecting the technologies for highway inspection. The four following questions related to evaluation matrix include:

- “When evaluating the performance of the use of the technologies for highway infrastructure inspection, what metrics does your agency consider?”
- “Does your agency track the cost-effectiveness of implementing technologies for highway inspection?”
- “Approximately, what is the overall return on investment (ROI) from using the following technologies for highway infrastructure inspection in your agency?”
- “Which of the following technologies has been used by your agency to inspect highway infrastructure during construction or maintenance of assets?”

Tables and questions contain technologies used, obstacles, feasibility, and other metrics from analyzing the data obtained from the surveys to make the results less abstract and more comprehensible. Both qualitative and quantitative analysis methods were conducted.

3.2.4 Evaluation Metrics

In Chapter 7, this dissertation describes the different evaluation metrics that DOTs use to assess the usage of technologies in highway construction sites according to the survey responses. Chapter 7 also has an explanatory case study regarding ROI and calculating ROI using a systematic procedure that accounts for various costs and benefits. The theory of this case study is that ROI can differ drastically for the same technology implemented in a different environment. In this case study, an interview was conducted with an engineer from a reputable firm in the middle east to discuss the implementation procedure for mobile mapping technology in highway construction sites.

The explanatory case study is a research method that explores why something occurs when limited information is available. This method is suitable for a research topic that ascertains how or why a particular phenomenon is occurring and predicts future occurrences (Yin, 2009). The reason why this used a case study for calculating ROI is that by its nature, a case study gives more in-depth knowledge of the matter. According to Yin (2009), “choice depends in large part on your research question(s), the more that research questions seek to explain some present circumstance (e.g., “how” or “why”), the case study method is relevant. The method also is relevant when the research questions require an extensive and “in-depth” description of phenomena.

The data are calculated by studying the cost of several projects where that technology has been used and comparing the costs with similar projects in the same area that have been done without using that technology.

After that, the benefits, upfront, and yearly costs are calculated and used to obtain ROI. This is followed by comparing that ROI with an ROI for the same technology after being implemented in the Oregon DOT. Finally, the chapter dives through the factors that caused the ROI difference after studying the implementation environments.

CHAPTER 4 : GEOSPATIAL TECHNOLOGIES FOR HIGHWAY INSPECTION

4.1 Introduction

This chapter presents the results of agency use of geospatial technologies for highway infrastructure inspection. The findings presented in this chapter are a result of the 42 state DOT responses to the survey, which represents an 84% response rate. In addition, the content analysis results of DOT's manuals, guidelines, and relevant documents obtained from the survey are also included to support the findings. This chapter discusses the current practice of geospatial technologies category of inspection technologies. Additionally, this chapter discusses a statistical analysis to examine the impact of experience on choosing the proper technology for different inspection activities. It is important to note that the 42 state DOT respondents were not required to respond to all questions in the survey. As a result, the sample size (n) of each question likely varies. Finally, the chapter discusses the key findings from the interview with state DOTs with regard to the implementation of geospatial technologies for highway inspection during the construction and maintenance of assets.

4.2 Results of Using Geospatial for Highway Infrastructure Inspection

Figure 4.1 shows the application of geospatial technologies associated with different types of highway construction projects, including roadways, signage/roadside, earthwork/grading, bridges, drainage systems, and non-bridge structures. More than 50% of the 42 responded state DOTs have used geospatial technologies for inspection of roadways, signage/roadside, and earthwork/grading. Approximately 50% of the responded state DOTs have used geospatial technologies for inspection of bridges and drainage systems.

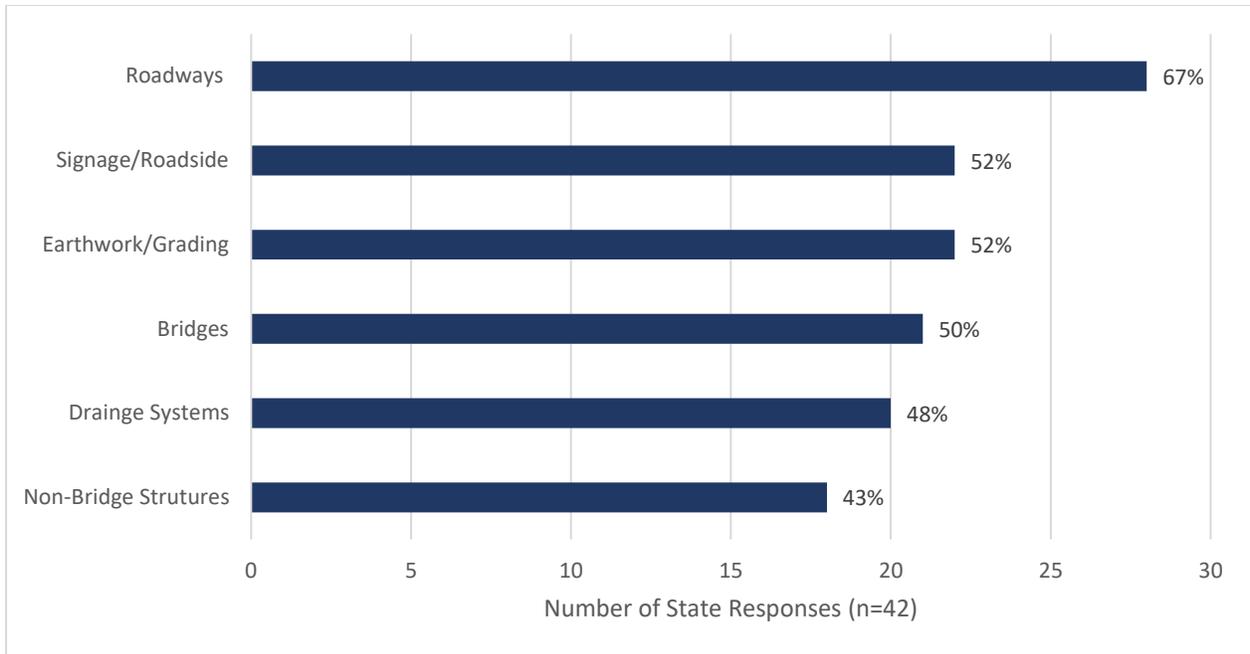


Figure 4.1: Use of Geospatial Technologies for Highway Infrastructure Inspection

4.2.1 Application of Geospatial Technologies for Highway Inspection during Construction

Figure 4.2 shows the main geospatial technologies used for highway infrastructure inspection during construction. Out of 32 valid responses, 26 state DOTs (81%) have used Global Navigation Satellite Systems (GNSS)/ Global Positioning System (GPS); 19 state DOTs (59%) have used e-Ticketing technologies, and nine state DOTs (28%) have used Terrestrial Photogrammetry for inspection of their highway infrastructure during construction. Figure 4.3 also indicates that approximately 50% of 32 responded DOTs have used unmanned aircraft systems (UASs), Robotic Total Stations, and Geographic Information Systems (GIS) for inspection of their highway infrastructure during construction.

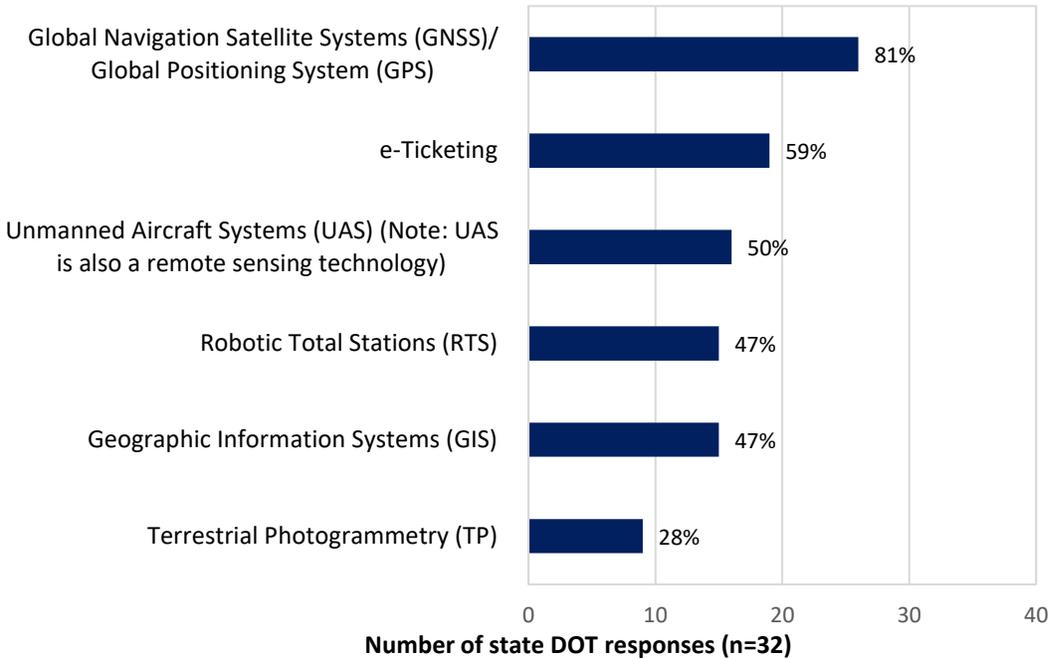


Figure 4.2: Types of Geospatial Technologies Used for Highway Infrastructure Inspection During Construction

Figure 4.3 shows the typical application of using GNSS/GPS for highway infrastructure inspection during construction. The top inspection activities that are suitable for using the GNSS/GPS technology agreed by more than one-thirds of 26 responded DOTs include:

- Earthwork inspection and quantities (17 DOTs, 65%);
- Collecting as-built information/Developing 3D as-built models (13 DOTs, 50%);
- Verification and documentation of work completed for payment (13 DOTs, 50%);
- Monitoring construction progress (11 DOTs, 42%); and
- General quality control and quality assurance activities (10 DOTs, 38%).

More than 20% of 26 responded DOTs also reported that they have used the GNSS/GPS technology for structural inspection and quantities; locating underground utilities and underground assets; and tracking position of bulk material (concrete, asphalt, aggregate loads)

during the construction of a highway project (Figure 4.3).

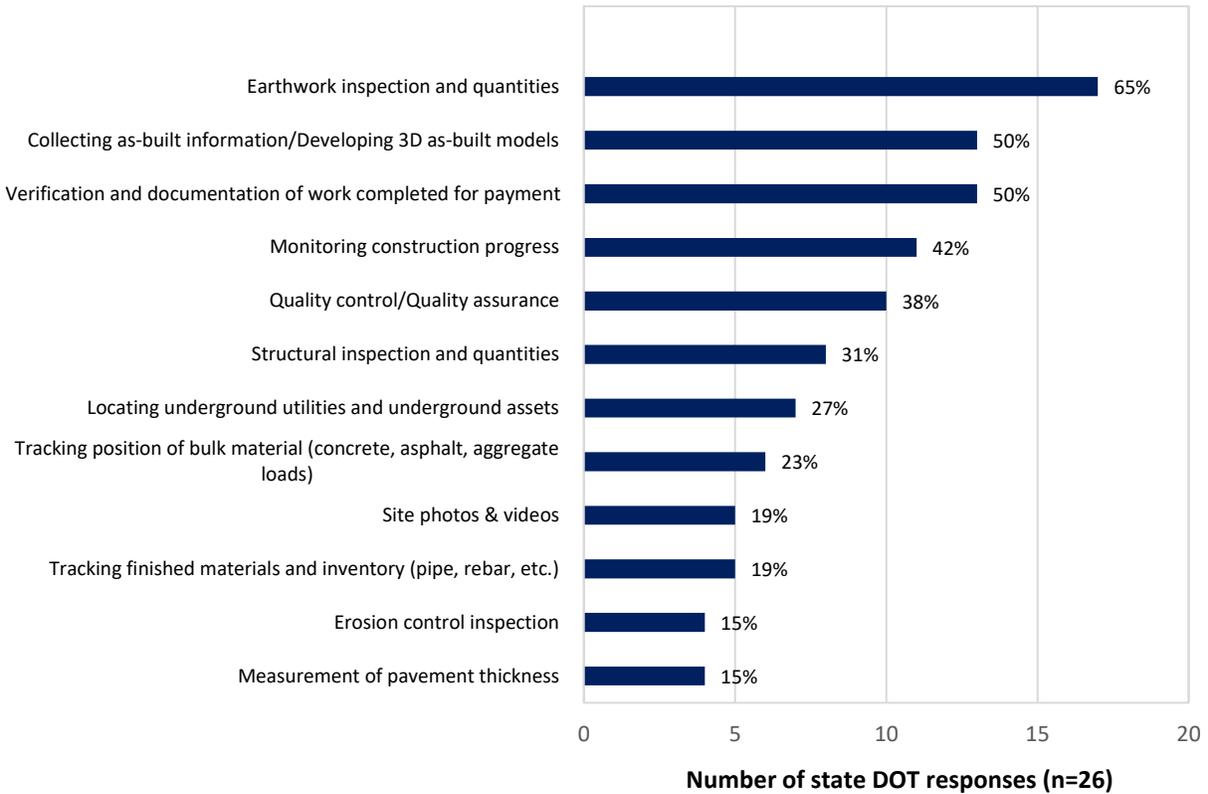


Figure 4.3: Application of GNSS/GPS for Highway Infrastructure Inspection During Construction

Figure 4.4 shows the typical application of using GIS for highway infrastructure inspection during construction. The top inspection activities that are suitable for using the GIS technology agreed by 20% or more of 15 responded DOTs include:

- Collecting as-built information/Developing 3D as-built models (5 DOTs, 33%);
- Site photos & videos (4 DOTs, 27%);
- Monitoring construction progress (4 DOTs, 27%);
- Locating underground utilities and underground assets (3 DOTs, 20%).
- Verification and documentation of work completed for payment (3 DOTs, 20%); and

- Structural inspection and quantities (3 DOTs, 20%).

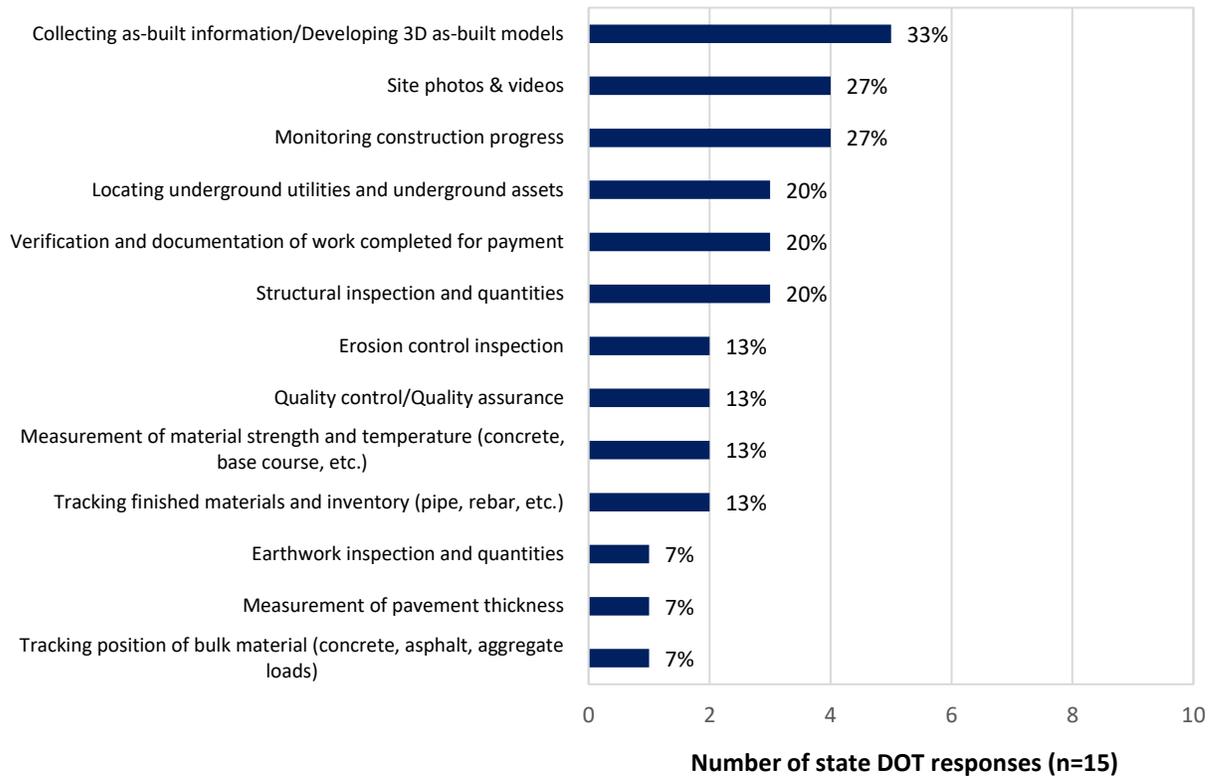


Figure 4.4: Application of GIS for Highway Infrastructure Inspection During Construction

Figure 4.5 shows the typical application of using UAS for highway infrastructure inspection during construction. The top inspection activities that are suitable for using the UAS technology agreed by more than one thirds of 16 responded DOTs include:

- Monitoring construction progress (14 DOTs, 88%);
- Site photos & videos (12 DOTs, 75%);
- Earthwork inspection and quantities (8 DOTs, 50%); and
- Structural inspection and quantities (6 DOTs, 38%).

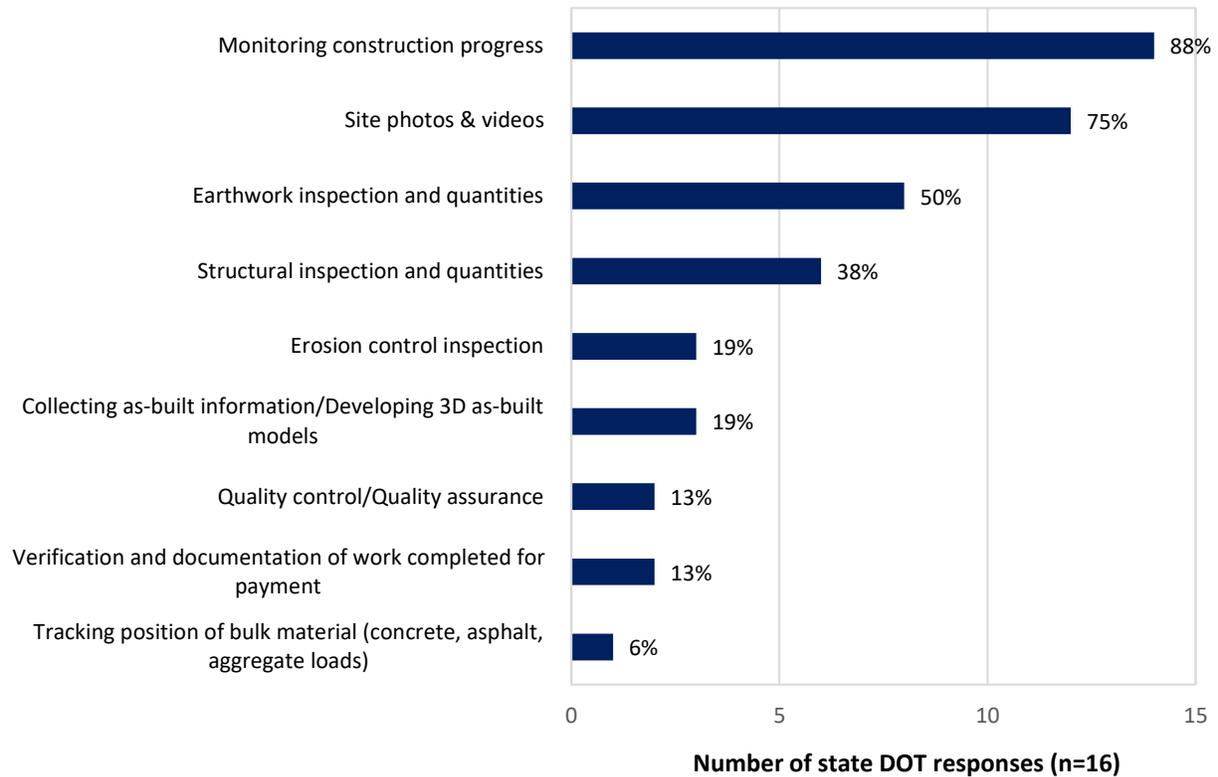


Figure 4.5: Application of UAS for Highway Infrastructure Inspection During Construction

Figure 4.6 shows the typical application of using Robotic Total Stations for highway infrastructure inspection during construction. The top inspection activities that are suitable for using the Robotic Total Stations agreed by 40% or more of 15 responded DOTs include:

- Earthwork inspection and quantities (9 DOTs, 60%);
- General quality control and quality assurance activities (6 DOTs, 40%);
- Collecting as-built information/Developing 3D as-built models (6 DOTs, 40%);
- Verification and documentation of work completed for payment (6 DOTs, 40%); and
- Monitoring construction progress (6 DOTs, 40%).

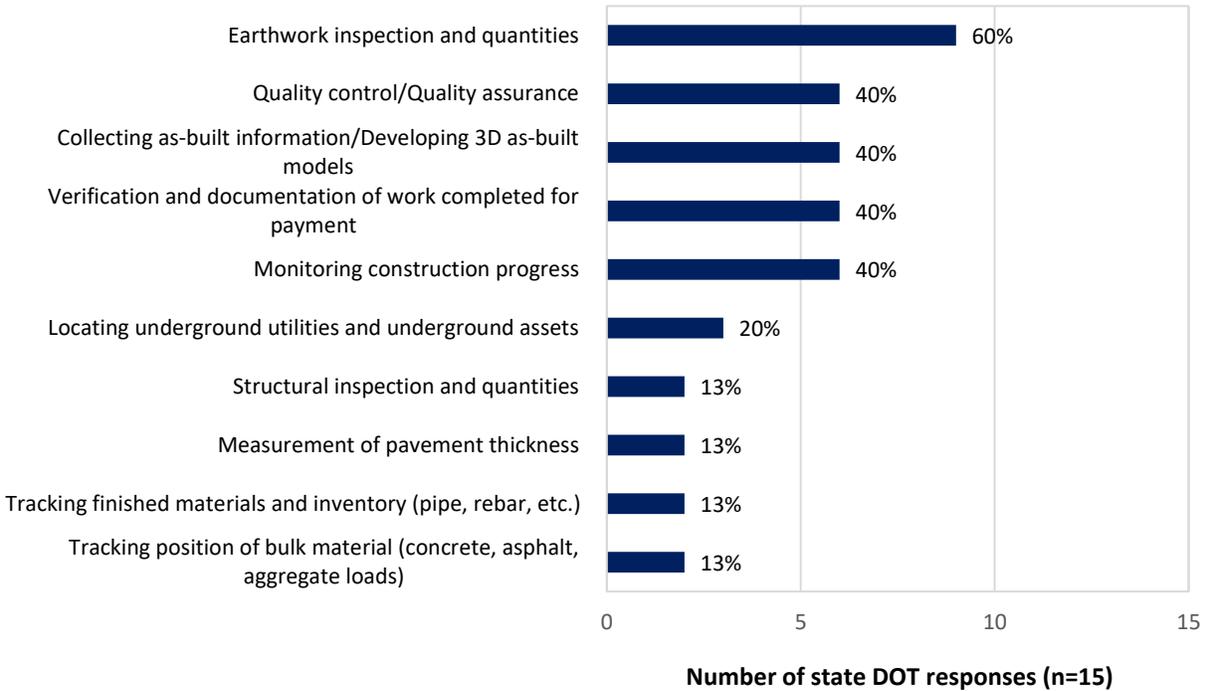


Figure 4.6: Application of Robotic Total Stations for Highway Infrastructure Inspection During Construction

Figure 4.7 shows the typical application of using Terrestrial Photogrammetry for highway infrastructure inspection during construction. The top inspection activities that are suitable for using the Terrestrial Photogrammetry technology agreed by more than one-thirds of nine responded DOTs include:

- Monitoring construction progress (4 DOTs, 44%);
- Earthwork inspection and quantities (4 DOTs, 44%);
- Site photos & videos (3 DOTs, 33%); and
- Collecting as-built information/Developing 3D as-built models (3 DOTs, 33%).

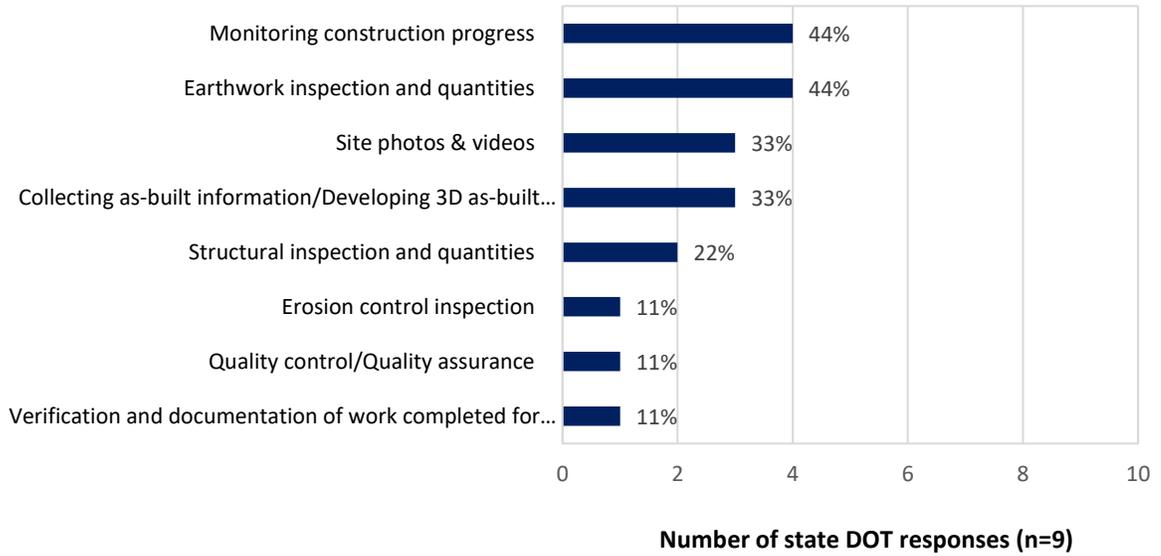


Figure 4.7: Application of Terrestrial Photogrammetry (TP) for Highway Infrastructure Inspection During Construction

Figure 4.8 shows the typical application of using e-Ticketing for highway infrastructure inspection during construction. The top two inspection activities that are suitable for using the e-Ticketing include:

- Tracking position of bulk material (concrete, asphalt, aggregate loads) (13 DOTs, 68%), and
- Verification and documentation of work completed for payment (6 DOTs, 32%).

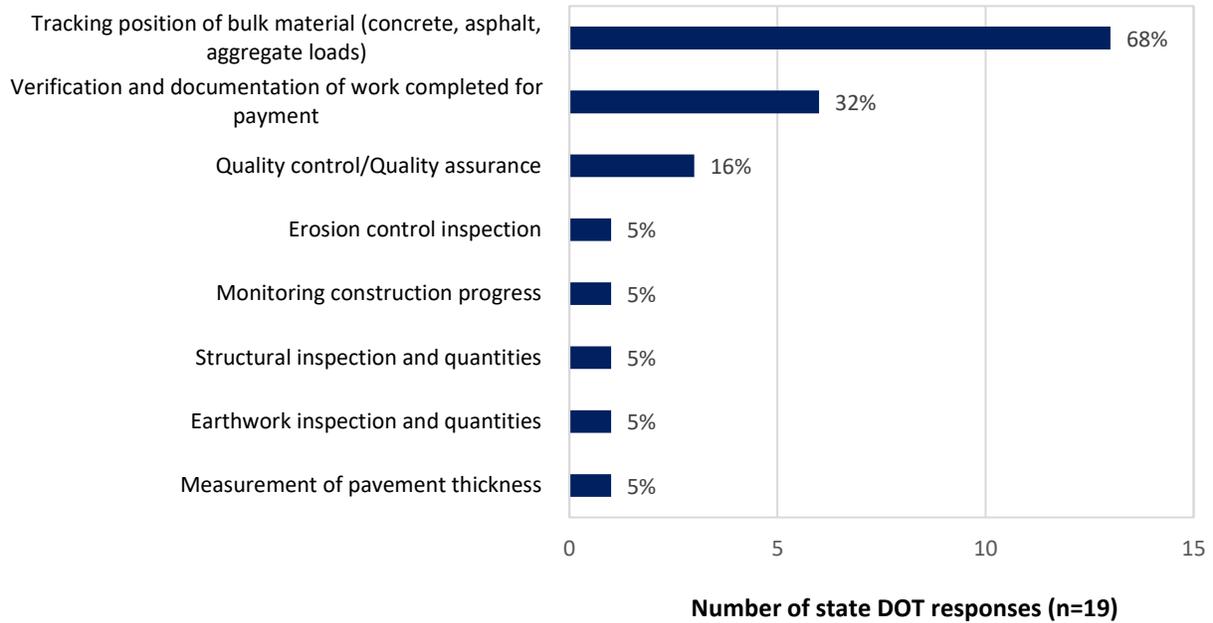


Figure 4.8: Application of e-Ticketing for Highway Infrastructure Inspection During Construction

4.2.2 Impact of Experience on Use of Geospatial Technologies During Construction

The hypothesis is the use of geospatial technology is not affected by the DOT’s years of experience. All responses were categorized and divided into two categories, more than five years of experience and less than five years of experience. Table 4.1 show a list of DOTs associated with these categories.

Table 4.1. Geospatial Technologies Years of Experience

Category	States
Less than 5 years (X)	Alabama, Arkansas, California, Delaware, Georgia, Hawaii, Illinois,
	Indiana, Minnesota, Mississippi, Montana, New Jersey, Pennsylvania, Utah, Vermont

More than 5 years (Y)	Colorado, Connecticut, Florida, Iowa, Missouri, Nebraska, New York,
	North Carolina, North Dakota, Oregon, South Carolina, Tennessee, Texas, South Dakota, Washington, West Virginia, Wisconsin

Figure 4.9 shows typical inspection activities for highway infrastructure during construction associated with experienced and less-experienced DOTs.

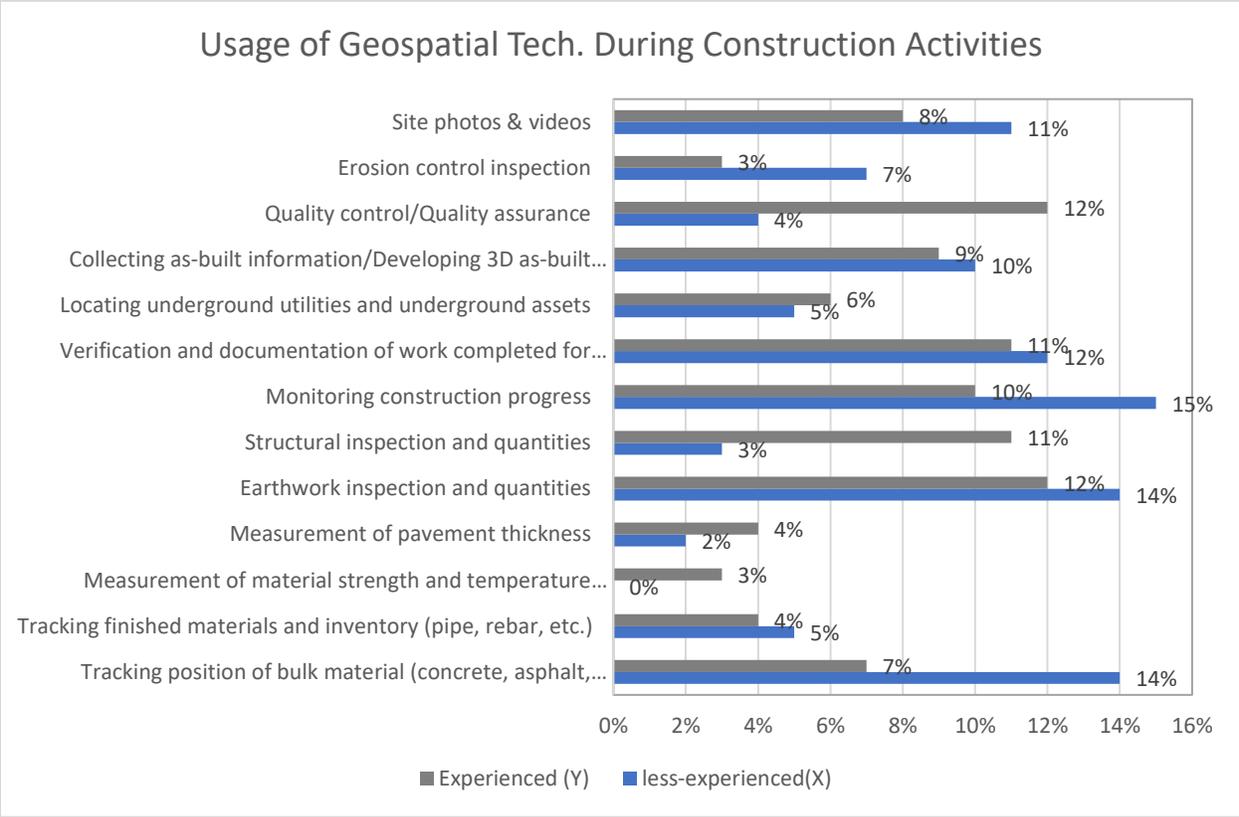


Figure 4.9: Usage of Geospatial Technologies for Highway Inspection During Construction Based on DOT’s Experience

The Pearson chi-square was used to determine whether there is a statistically significant difference in the technology usage by two groups of agencies. Table 4.2 shows the chi-square test result for the typical application of geospatial technologies for highway construction.

Table 4.2: Chi-Square Analysis Results for Geospatial Technologies During Construction

Applications Tested	Chi-Square (χ^2)	Significance (p)
Tracking position of bulk material (concrete, asphalt, aggregate loads)	46.903	0.001*
Tracking finished materials and inventory (pipe, rebar, etc.)	2.000	0.368
Measurement of material strength and temperature (concrete, base course, etc.)	0.200	0.655
Measurement of pavement thickness	3.000	0.392
Earthwork inspection and quantities	13.449	0.004*
Structural inspection and quantities	6.793	0.236
Monitoring construction progress	29.122	0.001*
Verification and documentation of work completed for payment	15.936	0.007*
Locating underground utilities and underground assets	2.462	0.292
Collecting as-built information/Developing 3D as-built models	4.889	0.299
Quality control/Quality assurance	48.106	0.001*
Erosion control inspection	3.091	0.543
Site photos & videos	15.606	0.001*

(*) Significant at 95%

In this statistical analysis result we look at the p-value. If this value is below 0.05, this means that prior experience is not a decisive factor in order to use this technology for the designated activity. Table 4.2 shows that there is a significant difference between experienced

state DOTs and less-experienced DOTs regarding the use of geospatial for highway infrastructure during construction of the following activities: Tracking position of bulk material; Earthwork inspection and quantities; Monitoring construction progress; Verification and documentation of work completed for payment; Quality control/Quality assurance; and Site photos & videos.

4.2.3 Application of Geospatial Technologies for Highway Inspection during Maintenance.

Figure 4.10 shows that out of 32 valid responses, 19 state DOTs (59%) have used GIS; 12 state DOTs (38%) have used GNSS/GPS; 10 state DOTs (31%) have used UAS; and six state DOTs (19%) have used Terrestrial Photogrammetry; and four state DOTs (13%) have used Robotic Total Stations for inspection of their highway infrastructure during maintenance of assets or asset management.

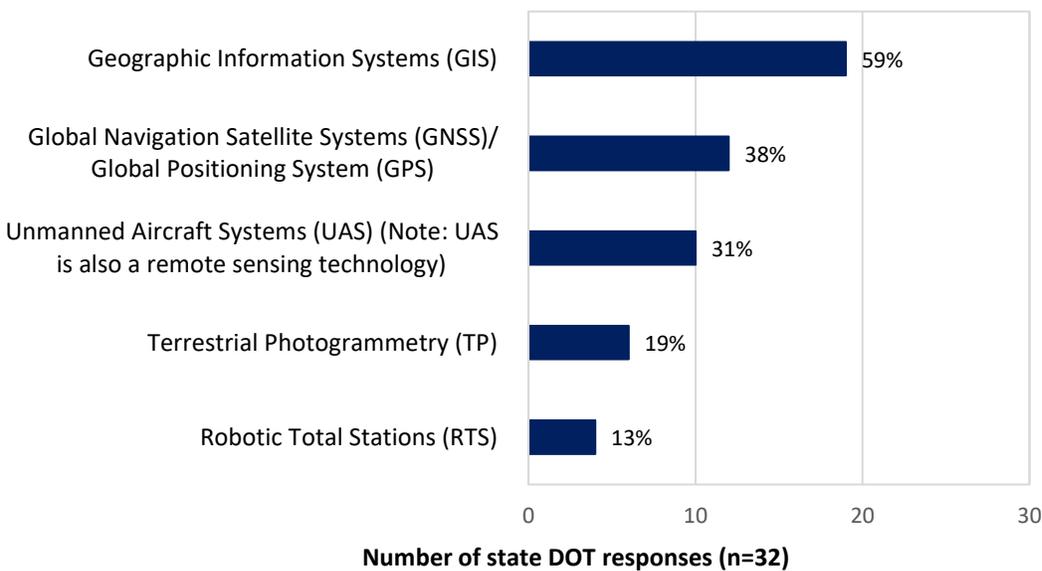


Figure 4.10: Types of Geospatial Technologies Used for Highway Infrastructure Inspection During Maintenance or Asset Management

Figure 4.11 shows the typical application of using GNSS/GPS for highway infrastructure inspection during maintenance or asset management. The top inspection activities that are suitable for using the GNSS/GPS technology agreed by more than half of 12 responded DOTs include:

- Signage, culvert, guardrail& other asset inventories and inspection (10 DOTs, 83%);
- Sharing asset information between different functional units (7 DOTs, 58%);
- Structural inspection (6 DOTs, 50%);
- Pavement crack and defect detection (6 DOTs, 50%); and
- Location of pavement/ material placement for performance tracking (6 DOTs, 50%).

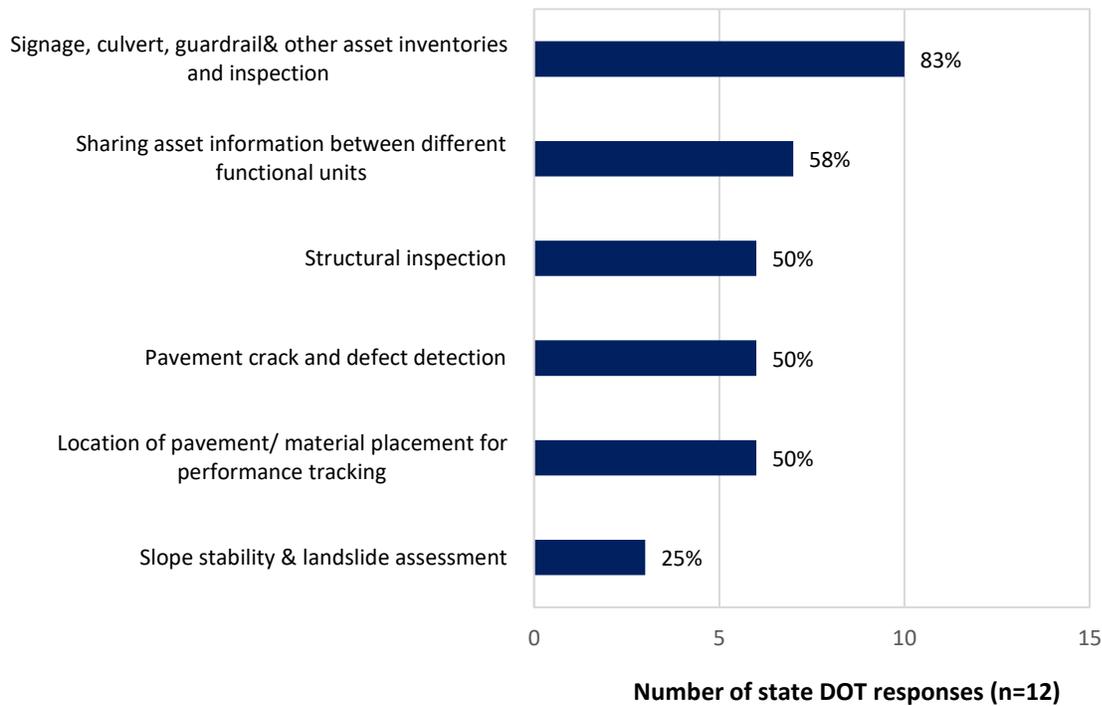


Figure 4.11: Application of GNSS/GPS for Highway Infrastructure Inspection During Maintenance or Asset Management

The West Virginia, South Dakota, and North Dakota DOTs also mentioned that they have

used GNSS/GPS for slope stability and landslide assessment. New York DOT indicated that it has used GNSS/GPS for inspection of secondary highway assets during maintenance. Nebraska DOT mentioned that it used GNSS/GPS for capturing video/pictures with GEO Tags during maintenance and asset management.

Figure 4.12 shows the typical application of using GIS for highway infrastructure inspection during maintenance or asset management. The top inspection activities that are suitable for using the GIS technology agreed by more than 20% of 19 responded DOTs include:

- Signage, culvert, guardrail& other asset inventories and inspection (16 DOTs, 84%);
- Sharing asset information between different functional units (15 DOTs, 79%);
- Location of pavement/ material placement for performance tracking (6 DOTs, 32%);
- Slope stability & landslide assessment (4 DOTs, 21%); and
- Structural inspection (4 DOTs, 21%).

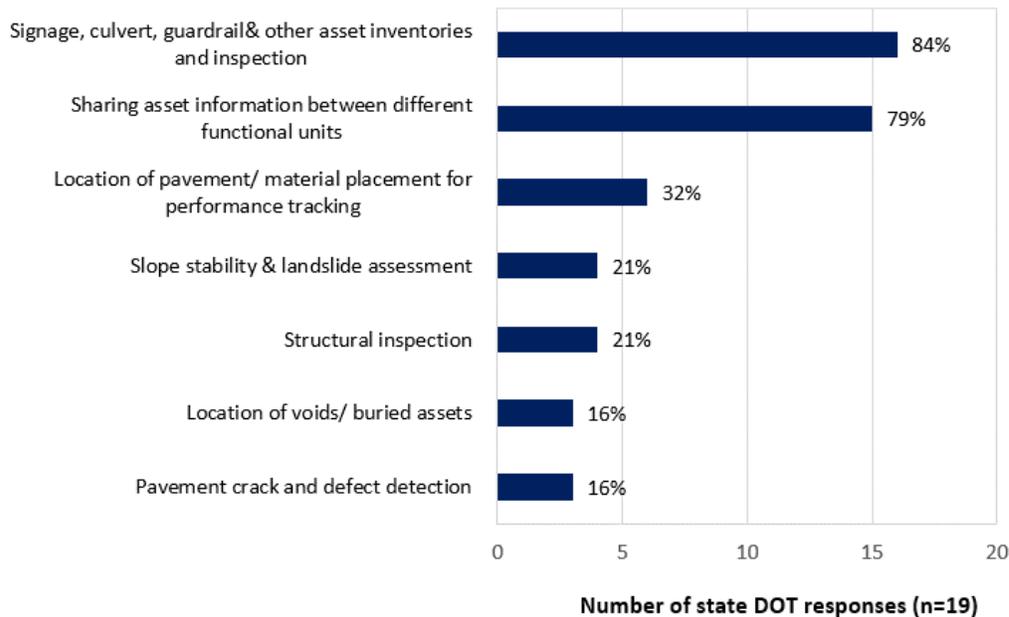


Figure 4.12: Application of GIS for Highway Infrastructure Inspection During Maintenance or Asset Management

Figure 4.13 shows the typical application of using UAS for highway infrastructure inspection during maintenance or asset management. The top three inspection activities that are suitable for using the UAS technology during asset management include:

- Structural inspection (10 DOTs, 100%);
- Slope stability & landslide assessment (5 DOTs, 50%); and
- Signage, culvert, guardrail& other asset inventories and inspection (3 DOTs, 30%);

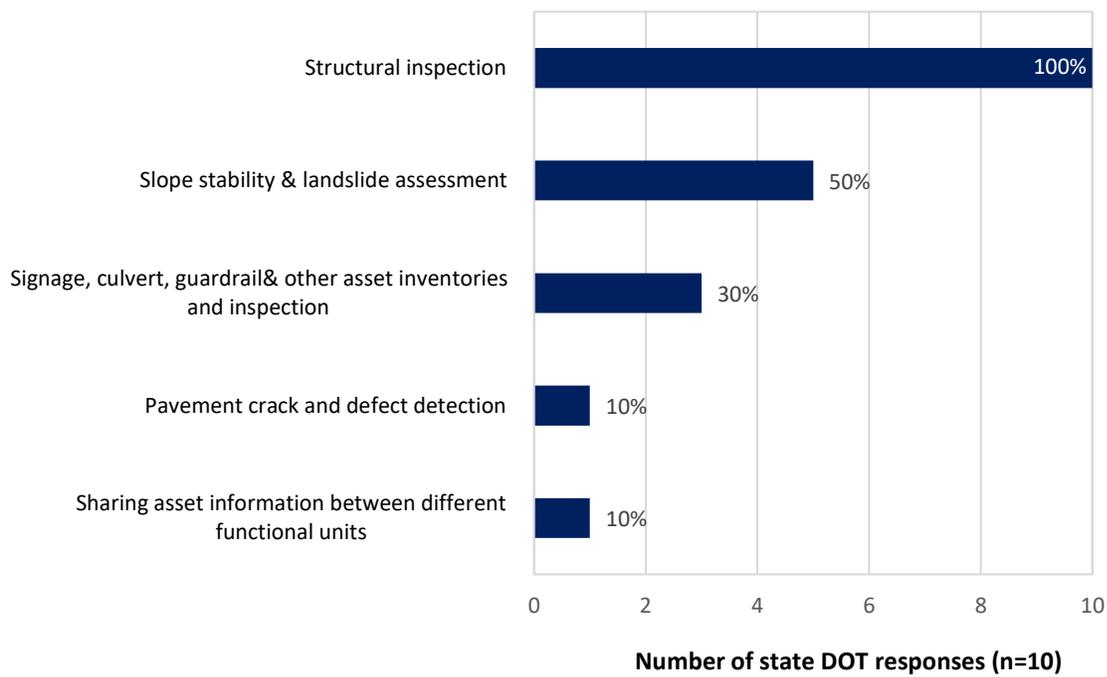


Figure 4.13: Application of UAS for Highway Infrastructure Inspection During Maintenance or Asset Management

4.2.4 Impact of Experience on Use of Geospatial Technologies During Maintenance

Similar to the inspection during construction, the hypothesis is the use of geospatial technology is not affected by the DOT’s years of experience during maintenance. All responses were categorized and divided into two categories, more than five years of experience and less than five

years of experience. Figure 4.14 shows typical inspection activities for highway infrastructure during maintenance associated with experienced and less-experienced DOTs.

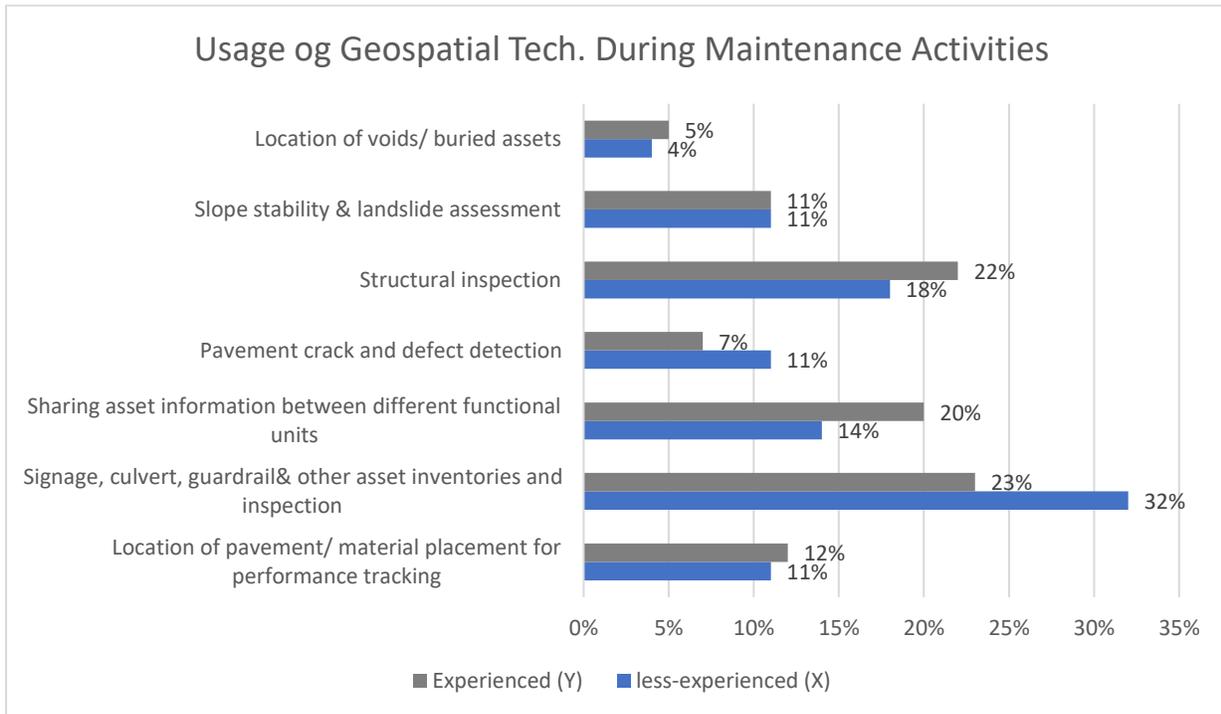


Figure 4.14: Usage of Geospatial technologies for Maintenance Activities in Different States DOTs Based on Years of Experience

The Pearson chi-square was used to determine whether there is a statistically significant difference in the technology usage by two groups of agencies. Table 4.3 shows the chi-square test result for the typical application of geospatial technologies for highway inspection during maintenance.

Table 4.3: Geospatial Technologies Chi-Square Analysis Results for the Maintenance Phase

Applications Tested	Chi-Square (χ^2)	Significance
Location of pavement/ material placement for performance tracking	10.000	0.040*
Signage, culvert, guardrail& other asset inventories and inspection	28.069	0.001*
Sharing asset information between different functional units	27.667	0.001*
Pavement crack and defect detection	5.818	0.213
Structural inspection	13.083	0.011*
Slope stability & landslide assessment	1.429	0.699
Location of voids/ buried assets	0.200	0.655

(*) Significant at 95%

In this statistical analysis result we look at the p-value. If this value is below 0.05, this means that prior experience is not a decisive factor in order to use this technology for the designated activity. Table 4.3 shows that there is a significant difference between experienced state DOTs and less-experienced DOTs regarding the use of geospatial for highway infrastructure during maintenance of infrastructure assets of the following activities: Signage, culvert, guardrail& other asset inventories and inspection; Sharing asset information between different functional units; and Structural inspection.

4.3 Key Findings from Interviews

This section summarizes the key findings from interviews with two state DOTs (one DOT with

less than five years of experience and two DOTs with more than five years of experience) on the use of geospatial technologies for highway infrastructure inspection.

4.3.1 Illinois DOT (IDOT)

Application for highway inspection during construction

For construction inspection, IDOT crews use GPS rovers and robotic total stations, primarily Trimble systems, to perform project layouts and check alignments and grades as construction is performed. While not programmatically implemented, UAS has been used to collect photos and video of project sites. While this UAS use may be performed by the contractor in most instances, IDOT does have a Division of Aeronautics with UASs capable of performing these activities. IDOT's investigation into e-ticketing has been according to the reception of their contractors. Where contractors have been receptive, or even at times promoted its use, IDOT has collaborated with vendors and the contractor to implement e-ticketing on a project-by-project basis. As new vendors continue to enter the market, IDOT will still require paper tickets if they do not have a comfort level with the e-ticketing system being used. IDOT is not moving toward a requirement to use e-ticketing, but they feel this technology will become the industry standard based on the benefits the technology provides to both the contractor and state agency.

IDOT noted that in general, procuring technologies can be very difficult in a government agency. This is especially true in construction where the ownership of the specified technology could be IDOT or their construction contractor. The policies and specifications controlling these procurements can be problematic when piloting technology on a project-by-project basis. Additionally, IDOT noted that staff training and use of the technology presents challenges as

change in general is not always welcome. In fact, learning new technologies is sometimes viewed as a distraction even if efficiencies are an expected outcome. Nonetheless, IDOT sees technology implementation as necessary to cope with staffing reductions and to collect data in an efficient and usable method for improved decision making now and in the future.

Application for highway infrastructure inspection during maintenance of assets

IDOT's use of GIS for asset management is quite mature as they began using that technology in the 1990's. In fact, GIS is the primary tool complemented by use of GPS for asset collection. IDOT uses GIS with their pavement assessment data creating georeferenced shapefiles to share pavement smoothness (IRI/international roughness index) and rutting information. GIS is also used to share other forms of IDOT data. The publicly available Illinois Roadway Analysis Database System (IROADS) shares pavement conditions, the multi-year highway improvement plan, traffic counts, and more. This system, along with dashboards sharing roadway performance metrics, has been very well received especially by the Metropolitan Planning Organizations (MPOs) in Illinois. As mentioned, IDOT has been using GIS since the 1990's but they are currently procuring and working toward a significant system transition to the Deighton dTIMS infrastructure asset management software system. They are also investigating the use of UAS for bridge and pavement inspections.

IDOT noted that there are several challenges in developing the GIS linear referencing for their system and in keeping it updated. The linear referencing of the roadways is the backbone of the GIS system. As the IDOT roadway system changes, the linear referencing must be kept up to date. Another challenge is also related to system benefits. IDOT noted the amount of data being

collected for the GIS system is great but the storage, access, and analysis of that amount of information presents unique challenges.

Another challenge noted by IDOT is in regard to data already collected. Not only can the volume of new data collected by technology present a challenge, but the connection of this data with an existing dataset can present a challenge. Legacy data may be difficult or costly to transfer, and in some cases, it may not even be in a digital or digitized form. Conversions and migrations of this type of data need to be handled with caution to ensure the intent and understanding of the data is well communicated. IDOT noted that as their databases are becoming more complicated and are being moved from databases managed and well-understood, within a specific business unit, to more centrally managed IT systems. IDOT notes that the knowledge of the data collected and how it should be reported must be well communicated and validated. They also note that this concern is exacerbated by knowledge loss through attrition.

4.3.2 Oregon DOT (ODOT)

Application for highway inspection during construction

The geospatial technologies used by ODOT for construction inspections include GNSS/GPS, UAS, and robotic total stations. In addition, ODOT is starting to explore the use of e-ticketing. For GPS use, ODOT has a statewide GNSS network that is used for a variety of tasks including construction inspections. GNSS allows for RTK handheld devices to provide survey grade accuracy. Tablets with GNSS antennas are used by inspectors to check lines and grades and measure quantities in real-time. As stated by ODOT staff, the software that ties with GNSS is easy to use and ODOT trains all inspectors to use the software and associated field equipment.

UASs used for construction inspections at ODOT include taking videos, checking elevation data, tracking progress, and verifying payment quantities. UASs provide construction staff with volumetric information, point clouds, and orthomosaics. In addition, UASs are used for geotechnical work to monitor slides near construction sites and to create surface models that are then used with ground-based radar to track the movement of slides.

Robotic total stations are used for most surveying and inspection processes on ODOT projects. Robotic total stations are used to monitor construction, stake the project, measure quantities, and check vertical clearances. Consultants also employ robotic total stations when using AMG, the data is then provided to ODOT for inspection. Furthermore, ODOT uses robotic total stations when GNSS is not working or only has limited connectivity because of the mountainous areas.

Application for highway infrastructure inspection during maintenance of assets

Asset management at ODOT has been using the GNSS network for 15 years for tasks such as inventory of culverts and signs and the GNSS location data is then fed into their asset GIS system. ODOT is now in the process of replacing their current mapping grade handheld devices with survey grade units that are tied to the GNSS network. The data collected from the inventory of assets is then stored within the individual divisions of ODOT that manage those assets. Along with GNSS, GIS is also used to inventory the ODOT highway assets across the state. The use of GNSS and GIS allows for ODOT to be accurate in their tracking and monitoring of their inventory of assets. Finally, UASs are used for asset management, but only to measure material stockpiles at ODOT material locations.

There are several challenges in using geospatial technologies at ODOT. As mentioned previously, one limitation is the use of the GNSS network in mountainous terrain. Limited or no connection still occurs in some areas, which then does not allow for the use of the GNSS network. The connectivity issues impact asset management more than construction. Another challenge for ODOT is how to contractually require contractors to use geospatial technologies and provide appropriate data to ODOT for inspection purposes. Additionally, it is important to evaluate the effective use of technologies by proving the worth of these technologies, the costs to purchase and update/upgrade equipment, and the change from a linear reference system based on mile markers to a coordinate correct system based on actual positions.

ODOT noted that they may get push back to the use of a technology at first because inspectors perceive that the technology will complicate their tasks and take longer to complete their work. Proof of concepts needs to be conducted to show the value and efficiency in using these technologies. Cost is a concern and ODOT continually looks for grants and other resources to help offset the costs to purchase the required equipment and update them as the technologies advance. Moving from a linear reference system for locations to GNSS and a coordinate correct system has been difficult, but ODOT mentioned that a benefit from the coordinate correct system is that the geospatial positions can be used on more than a static straight-line chart. In summary, as stated by ODOT, the benefits of using geospatial technologies for construction inspection and asset management outweigh the challenges as technology saves resources for ODOT to use on other important work.

Finally, ODOT mentioned that it is important to gain buy-in from the staff and inspectors prior to the implementation of inspection technologies. Providing proof of the technology and showing that the implementation will make their work more efficient tends to help gain that buy-in and allows ODOT staff and inspectors to be more open-minded about changes in their daily tasks. Providing effective training on the use of technologies also helps to overcome the stigma of “this is how we always do it” and “why do we need to change.”

4.3 Summary

Geospatial technologies are mainly used in roadways, signage, and earthwork. GNSS and GPS are the most common geospatial technologies used by state DOTs for inspection of highway infrastructure during construction and maintenance of assets. For construction inspection, GNSS and GPS technologies are mostly used for earthwork inspection and quantities, verification and document of work complete, and collecting as-built information. For inspection of existing highway assets, GNSS and GPS technologies are mostly used for inventories and inspection of signage, culvert, guardrail and other highway assets. E-ticketing is increasingly used by many state DOTs to track the position of bulk materials such as concrete, asphalt, and aggregate loads for the inspection purposes of highway construction. Additionally, State DOTs are increasingly using UASs for inspection of highway infrastructure during construction and maintenance of assets. UASs are mostly used for monitoring construction progress and capturing site photos. Finally, GIS is typically used in tandem with GNSS/GPS or other geospatial technologies to share asset information between different functional units within a DOT.

CHAPTER 5 : REMOTE SENSING & MONITORING TECHNOLOGIES

5.1 Introduction

This chapter presents the results of agency use of remote sensing and monitoring technologies for highway infrastructure inspection. The findings presented in this chapter are a result of the 42 state DOT responses to the survey, which represents an 84% response rate. In addition, the content analysis results of DOT's manuals, guidelines, and relevant documents obtained from the survey are also included to support the findings. This chapter discusses the current practice of remote sensing & monitoring technologies category of inspection technologies. Additionally, this chapter discusses a statistical analysis to examine the impact of experience on choosing the proper technology for different inspection activities. It is important to note that the 42 state DOT respondents were not required to respond to all questions in the survey. As a result, the sample size (n) of each question likely varies. Finally, the chapter discusses the key findings from the interview with state DOTs with regard to the implementation of remote sensing & monitoring technologies for highway inspection during the construction and maintenance of assets.

5.2 Results of Using Remote Sensing and Monitoring Technologies for Highway Infrastructure Inspection

Figure 5.1 shows the application of remote sensing & monitoring technologies associated with different types of highway construction projects, including roadways, signage/roadside,

earthwork/grading, bridges, drainage systems, and non-bridge structures. Remote sensing & monitoring technologies are typically used for the inspection of roadways (45%), and bridges (45%), and earthwork or grading (19%). Only 10% of the 42 responded state DOTs indicated that they have used remote sensing & monitoring technologies for inspection of non-bridge structures. It is worth mentioning that Remote Sensing & Monitoring technologies are not used in inspecting drainage systems according to the responses from the DOTs.

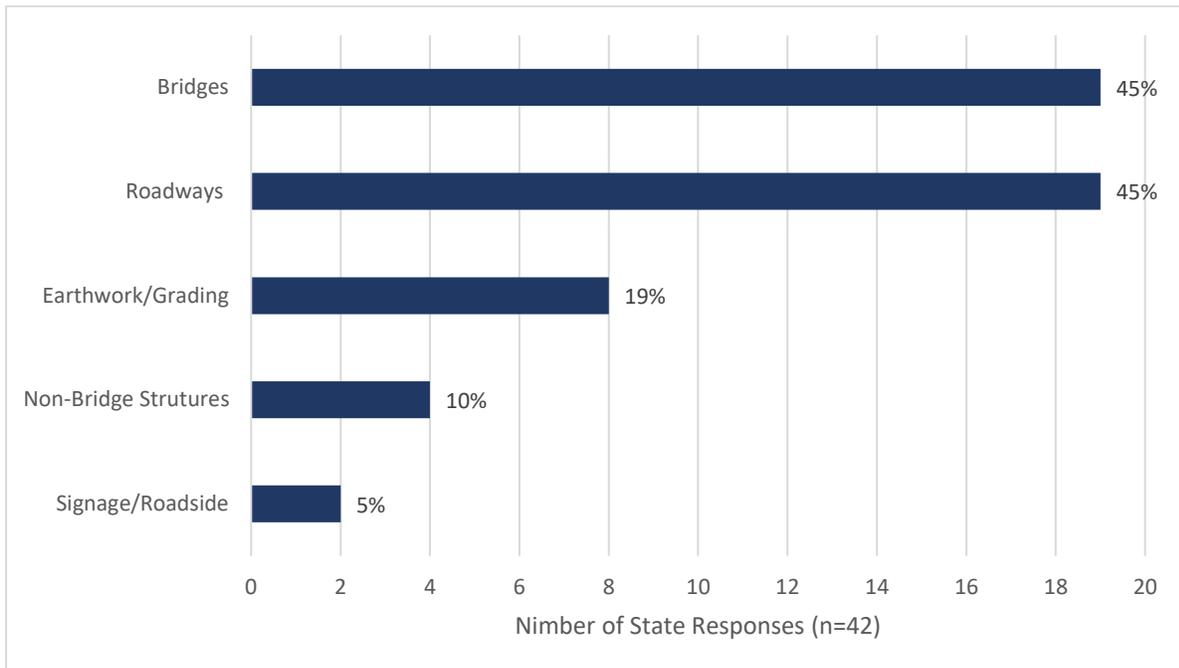


Figure 5.1: Use of Remote Sensing and Monitoring Technologies for Highway Infrastructure Inspection

5.2.1 Application of Remote Sensing & Monitoring Technologies for Highway Inspection during Construction.

Figure 5.2 shows that out of 28 valid responses, 21 DOTs (75%) have used remote sensors (e.g., accelerometers, maturity meter sensors, or strain gauges); 15 DOTs (54%) have used remote cameras; 14 DOTs (50%) have used intelligent compaction and Light Detection and Ranging (LIDAR)/ 3D laser scanning; and 13 DOTs (46%) have used infrared sensors (e.g., thermal, motion detectors, object detection, thermal profiling) for inspection of their highway

infrastructure during construction. Figure 5.2 also indicates that four DOTs (14%) have used Barcodes & Readers and three DOTs (11%) have used Radio-frequency identification (RFID) for inspection of their highway infrastructure during construction.

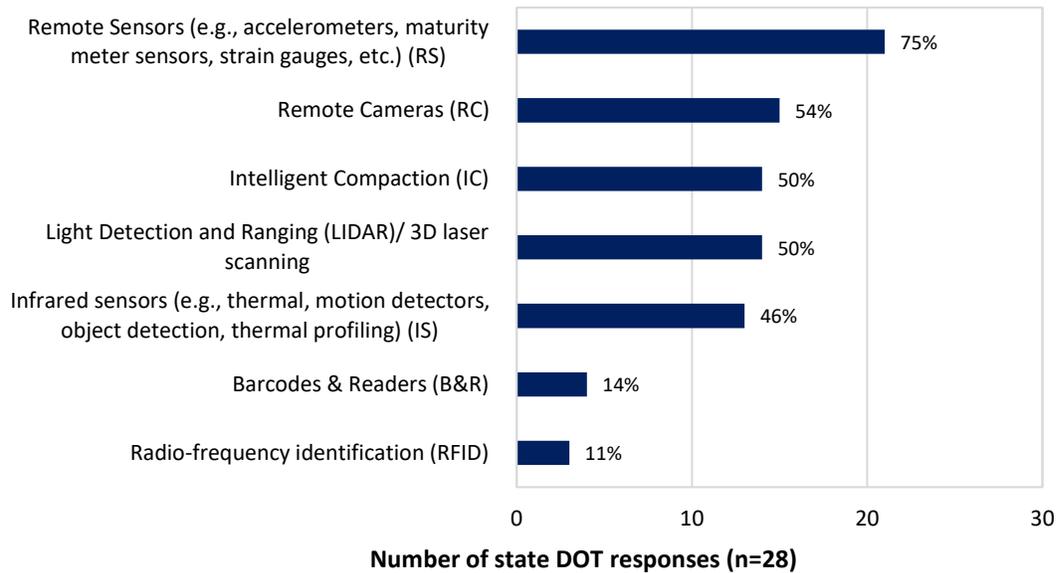


Figure 5.2: Types of Remote Sensing & Monitoring Technologies Used for Highway Infrastructure Inspection During Construction

Figure 5.3 shows the typical application of using LiDAR/3D Laser Scanning Technologies for highway infrastructure inspection during construction. The top inspection activities that are suitable for using the LiDAR/3D Laser Scanning technologies agreed by more than one-thirds of 14 responded DOTs only includes collecting as-built information/Developing 3D as-built models (5 DOTs, 36%). More than 20% of 14 responded DOTs also reported that they have used the LiDAR/3D Laser Scanning technologies for structural inspection and quantities and earthwork inspection quantities (Figure 5.3).

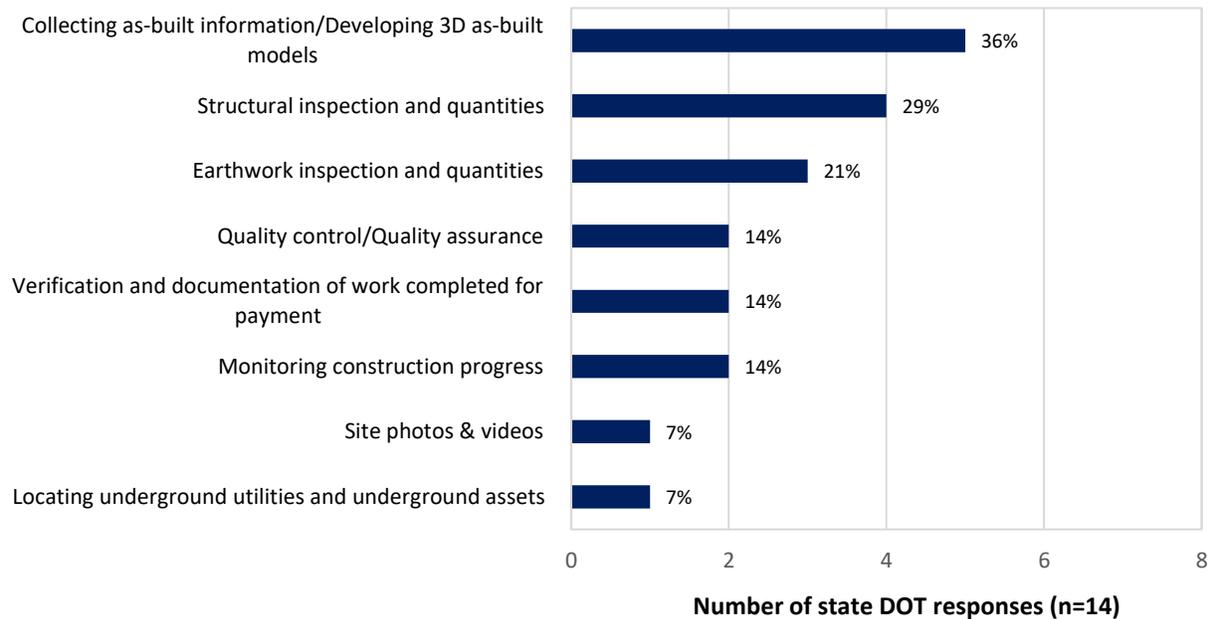


Figure 5.3: Application of LiDAR/3D Laser Scanning Technologies for Highway Infrastructure Inspection During Construction

Figure 5.4 shows the typical application of using Intelligent Compaction for highway infrastructure inspection during construction. The top inspection activities that are suitable for using the Intelligent Compaction technology agreed by 20% or more of 14 responded DOTs include:

- Quality control/Quality assurance (6 DOTs, 43%);
- Earthwork inspection and quantities (3 DOTs, 21%); and
- Measurement of pavement thickness (3 DOTs, 21%).

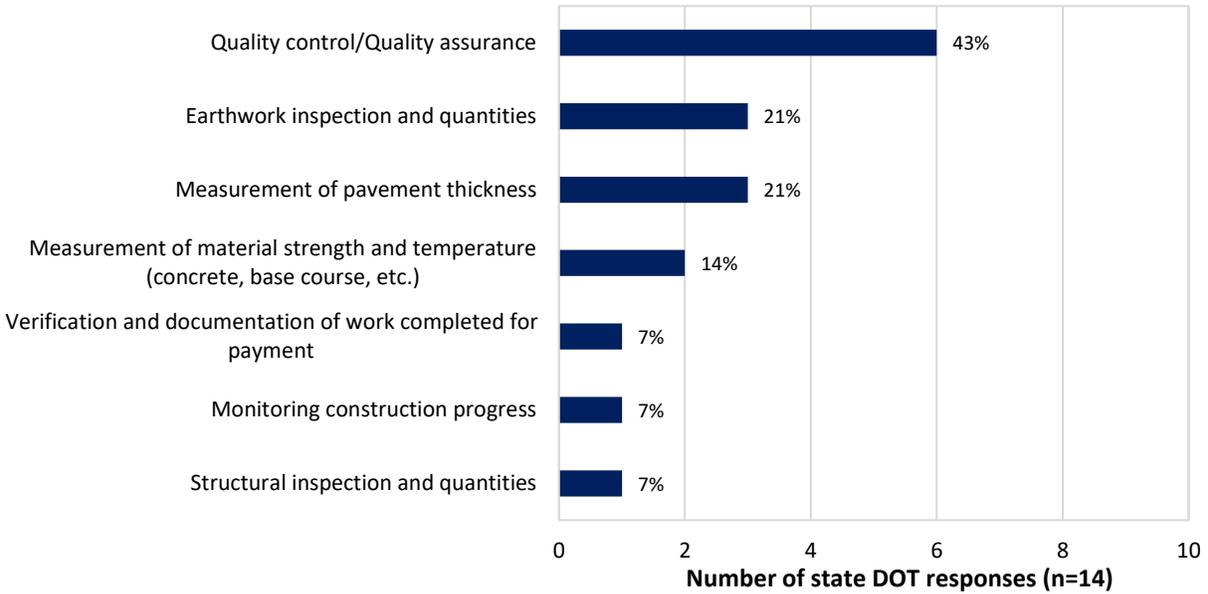


Figure 5.4: Application of Intelligent Compaction for Highway Infrastructure Inspection During Construction

Figure 5.5 shows the typical application of using remote sensors for highway infrastructure inspection during construction. The top three inspection activities that are suitable for using remote sensors during construction include:

- Measurement of material strength and temperature (7 DOTs, 33%);
- Quality control and quality assurance (6 DOTs, 29%); and
- Measurement of pavement thickness (3 DOTs, 14%).

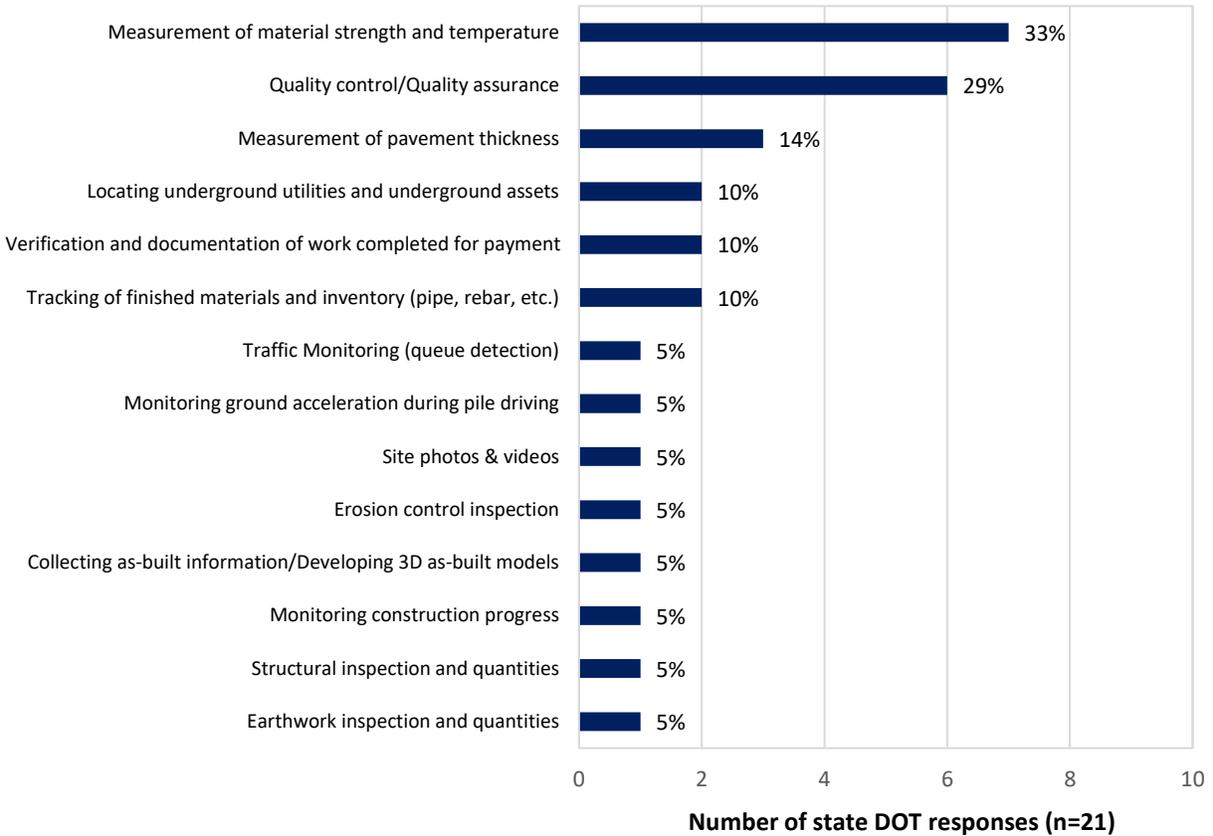


Figure 5.5: Application of Remote Sensors for Highway Infrastructure Inspection During Construction

Figure 5.6 shows the typical application of using infrared sensors for highway infrastructure inspection during construction. The top two inspection activities that are suitable for using infrared sensors during construction include:

- Measurement of material strength and temperature (10 DOTs, 77%);
- Locating underground utilities and underground assets (2 DOTs, 15%).

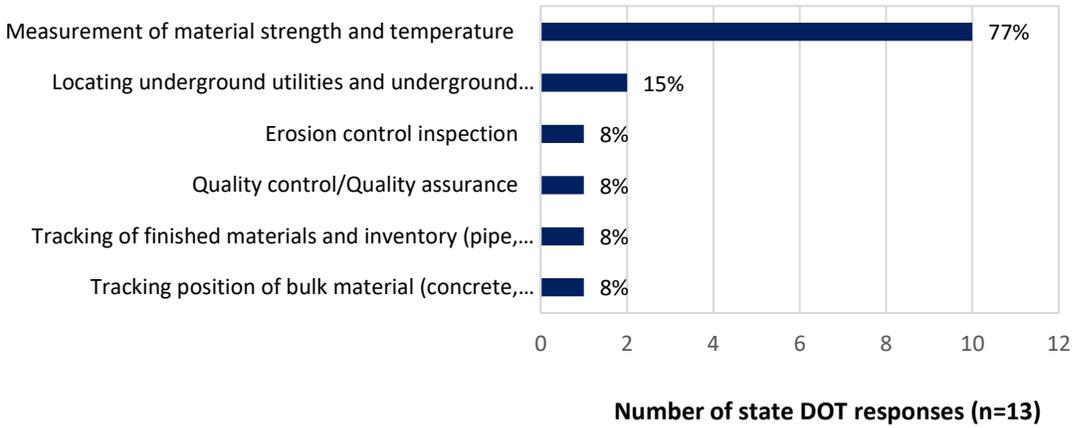


Figure 5.6: Application of Infrared Sensors for Highway Infrastructure Inspection During Construction

Figure 5.7 shows the typical application of using Remote Cameras for highway infrastructure inspection during construction. The top inspection activities that are suitable for using the Remote Cameras technology agreed by more than one-thirds of 15 responded DOTs include:

- Capturing site photos & videos (12 DOTs, 80%);
- Monitoring construction progress (10 DOTs, 67%).

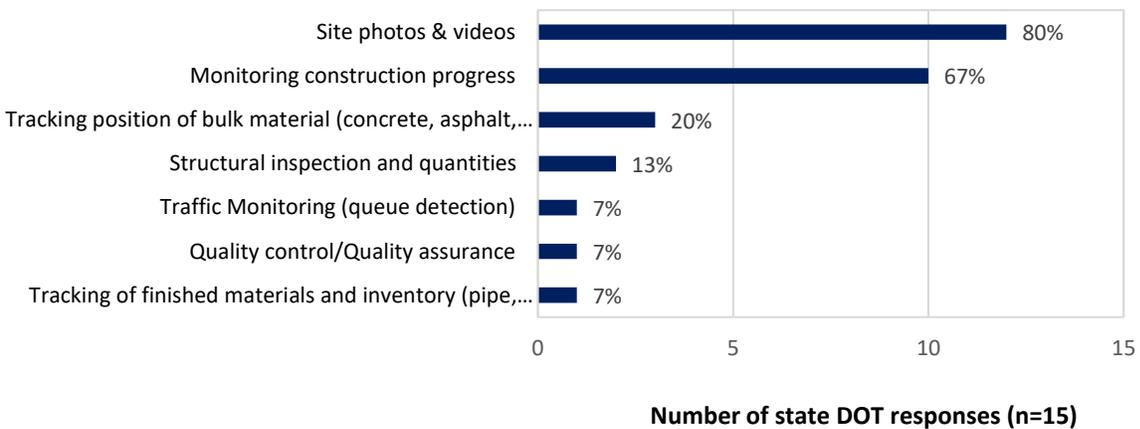


Figure 5.7: Application of Remote Cameras for Highway Infrastructure Inspection During Construction

5.2.2 Impact of Experience on Use of Remote Sensing and Monitoring Technologies During Construction

The hypothesis is the use of remote sensing & monitoring technology is not affected by the DOT's years of experience. All responses were categorized and divided into two categories, more than five years of experience and less than five years of experience. Table 5.1 show a list of DOTs associated with these categories.

Table 5.1: Remote Sensing& Monitoring Technologies Years of Experience

Category	States
Less than five years	Alabama, Arkansas, Delaware, Kentucky, Massachusetts, New Jersey, New Mexico, North Carolina, North Dakota, Pennsylvania, Virginia, and Washington.
More than five years	Colorado, Florida, Hawaii, Illinois, Indiana, Iowa, Minnesota, Missouri, Montana, Nebraska, New York, Oregon, South Carolina, Tennessee, Texas, and West Virginia.

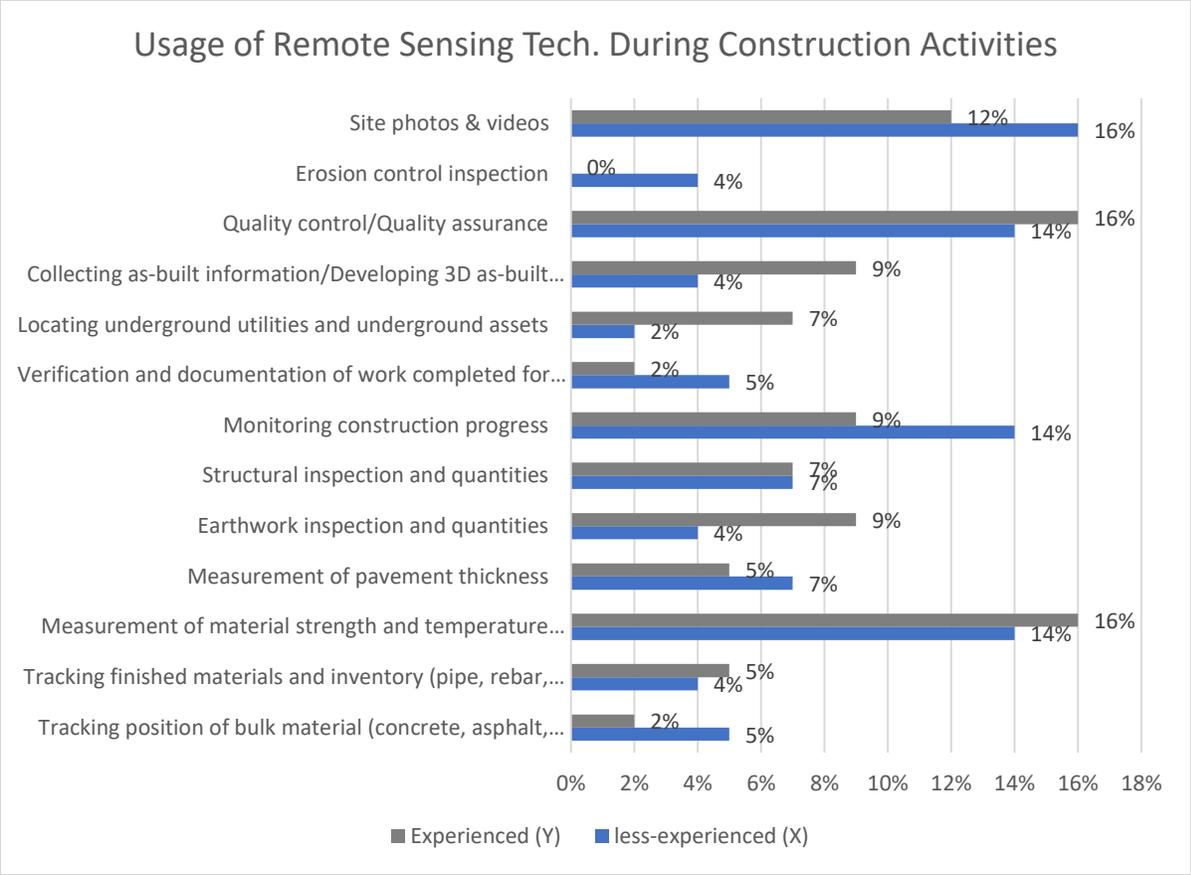


Figure 5.8: Usage of Remote Sensing & Monitoring Technologies for Highway Inspection During Construction Based on DOT’s Experience

The Pearson chi-square was used to determine whether there is a statistically significant difference in the technology usage by two groups of agencies. Table 5.2 shows the chi-square test result for the typical application of remote sensing & monitoring technologies for highway construction.

Table 5.2: Chi-Square Analysis Results for Remote Sensing & Monitoring Technologies During Construction

Applications Tested	Chi-Square (χ^2)	Significance (p)
Tracking position of bulk material (concrete, asphalt, aggregate loads)	1.600	0.449
Tracking finished materials and inventory (pipe, rebar, etc.)	0.600	0.896
Measurement of material strength and temperature (concrete, base course, etc.)	26.000	0.001*
Measurement of pavement thickness	0.000	1.000
Earthwork inspection and quantities	1.000	0.607
Structural inspection and quantities	3.000	0.392
Monitoring construction progress	16.286	0.001*
Verification and documentation of work completed for payment	0.400	0.819
Locating underground utilities and underground assets	0.400	0.819
Collecting as-built information/Developing 3D as-built models	2.667	0.102
Quality control/Quality assurance	13.308	0.038*
Erosion control inspection	0.000	1.000
Site photos & videos	26.889	0.001*

(*) Significant at 95%

In this statistical analysis result we look at the p-value. If this value is below 0.05, this means that prior experience is not a decisive factor in order to use this technology for the

designated activity. Table 5.2 shows that there is a significant difference between experienced state DOTs and less-experienced DOTs regarding the use of remote sensing for highway infrastructure during construction of the following activities: Measurement of material strength and temperature (concrete, base course, etc.); Monitoring construction progress; and Site photos & videos.

5.2.3 Application of Remote Sensing & Monitoring Technologies for Highway Inspection During Maintenance

Figure 5.9 shows the typical remote sensing and monitoring technologies used for highway infrastructure inspection during maintenance of assets or asset management. Out of 28 valid responses, 10 state DOTs (36%) have used remote cameras; nine state DOTs (32%) have used LIDAR/3D laser scanning technologies; seven state DOTs (25%) have used remote sensors; three state DOTs (11%) including Kentucky, South Carolina, and Nebraska have used Barcodes & Readers; and three state DOTs (11%) including Wisconsin, Florida, and Nebraska have used infrared sensors. Virginia DOT mentioned that it has used RFID for inspection of its highway infrastructure during maintenance of assets or asset management.

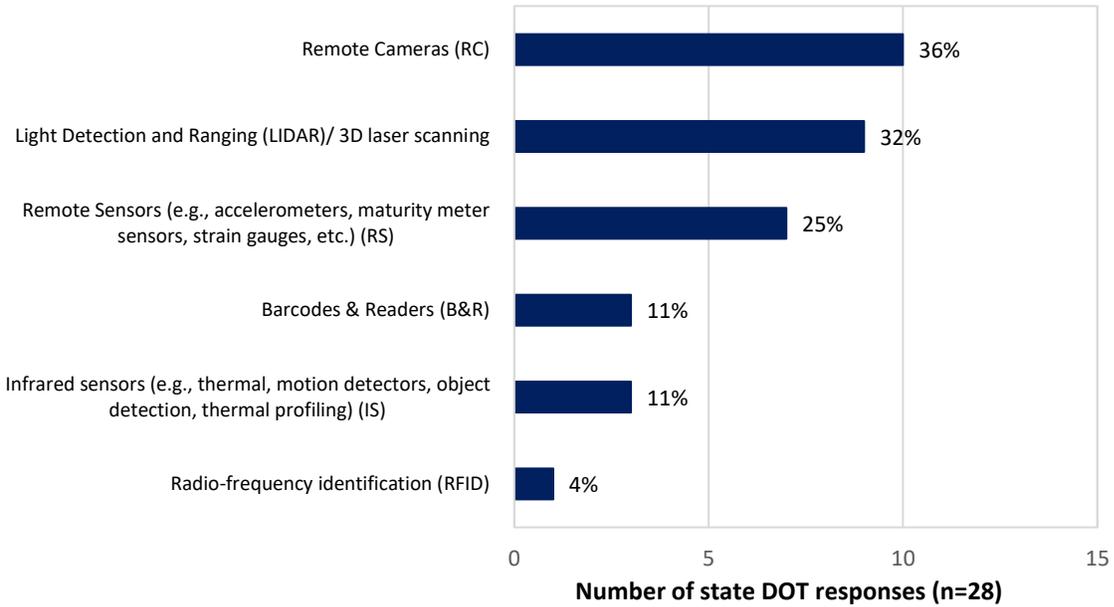


Figure 5.9: Types of Remote Sensing & monitoring Technologies Used for Highway Infrastructure Inspection During Maintenance or Asset Management

Figure 5.10 shows the typical application of using Remote Sensors for highway infrastructure inspection during maintenance or asset management. The top inspection activities that are suitable for using the Remote Sensors technology agreed by more than 20% of 7 responded DOTs include:

- Structure Inspection (3 DOTs, 43%);
- Slope stability and landslide assessment (2 DOTs, 29%); and

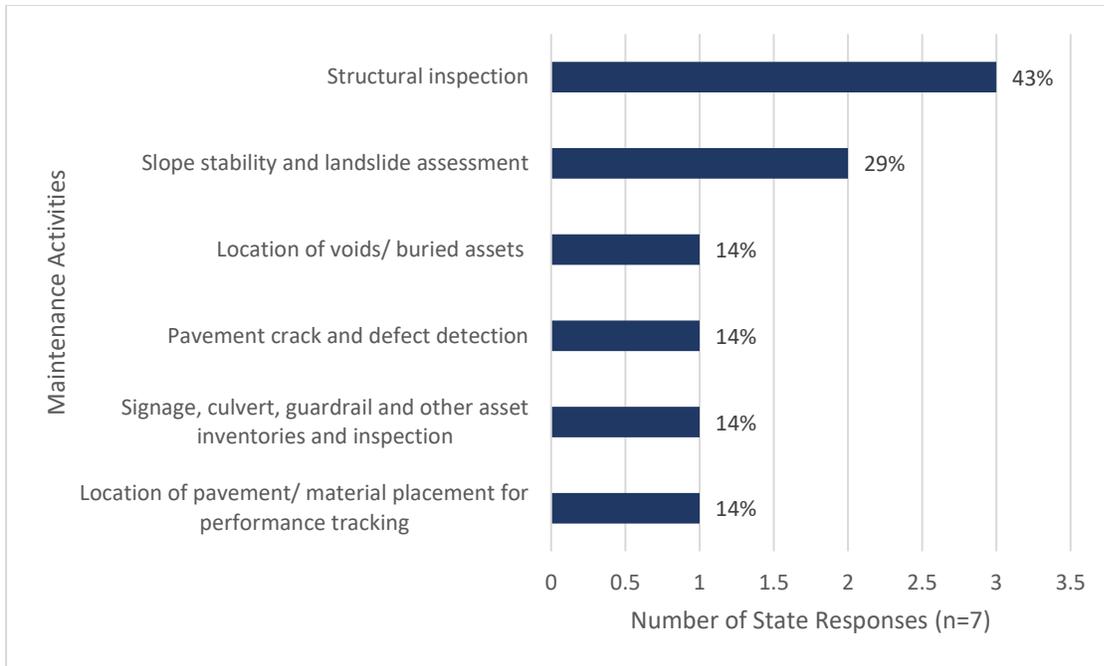


Figure 5.10: Application of Remote Sensors for Highway Infrastructure Inspection During Maintenance or Asset Management

Figure 5.11 shows the typical application of using LIDAR/3D for highway infrastructure inspection during maintenance or asset management. The top inspection activities that are suitable for using the LIDAR/3D technology agreed by more than 20% of 9 responded DOTs include:

- Pavement crack and defect detection (4 DOTs, 45%);
- Slope stability and landslide assessment (3 DOTs, 34%); and
- Location of pavement / material placement for performance tracking (2 DOTs, 22%);

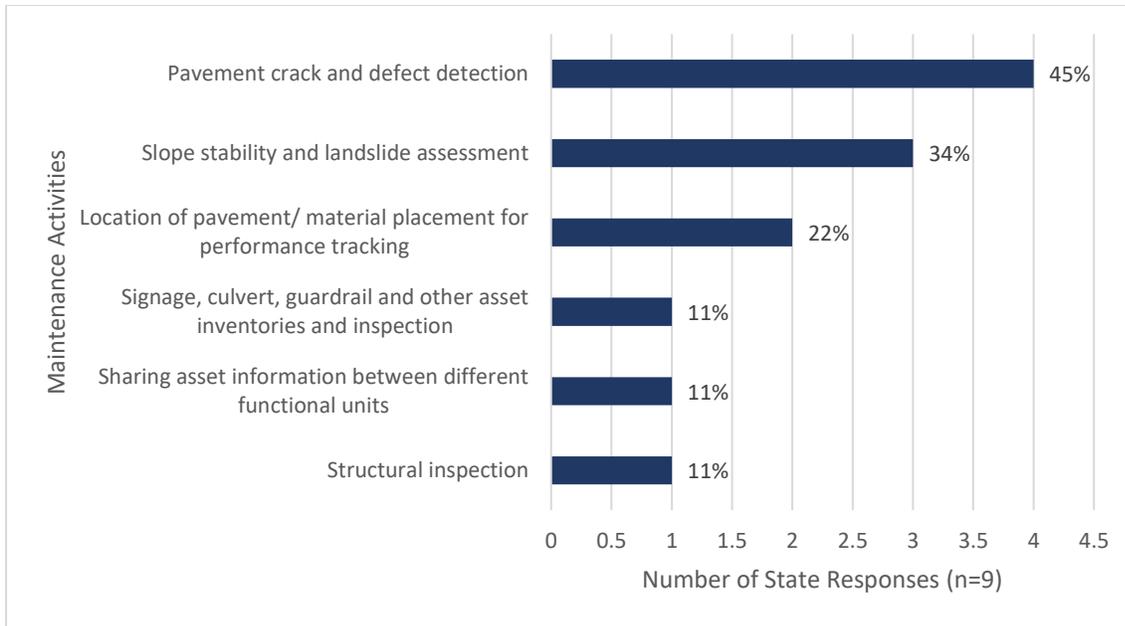


Figure 5.11: Application of LiDAR/3D for Highway Infrastructure Inspection During Maintenance or Asset Management

5.2.4 Impact of Experience on Use of Remote Sensing and Monitoring Technologies During Maintenance

Similar to the inspection during construction, the hypothesis is the use of remote sensing & monitoring technology is not affected by the DOT's years of experience during maintenance. All responses were categorized and divided into two categories, more than five years of experience and less than five years of experience. Figure 5.12 shows typical inspection activities for highway infrastructure during maintenance associated with experienced and less-experienced DOTs.

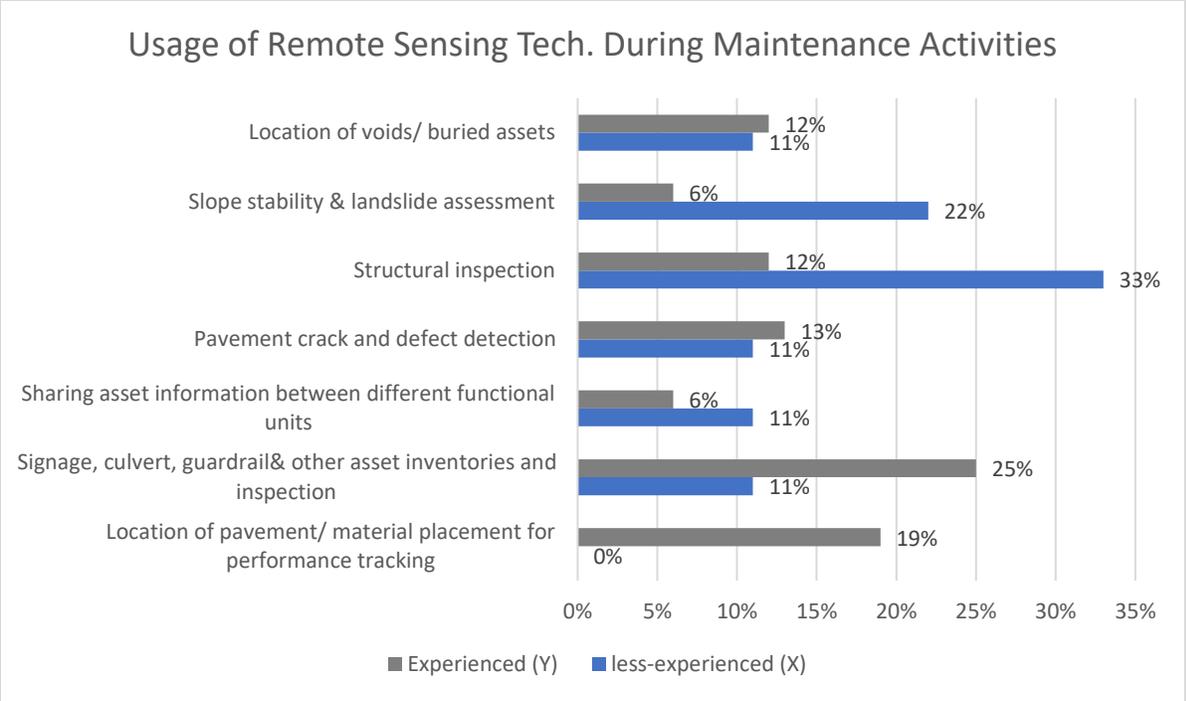


Figure 5.12: Usage of Remote Sensing & Monitoring Technologies for Maintenance in Different States DOTs Based on years of Experience

The Pearson chi-square was used to determine whether there is a statistically significant difference in the technology usage by two groups of agencies. Table 5.3 shows the chi-square test result for the typical application of remote sensing & monitoring technologies for highway inspection during maintenance.

Table 5.3: Remote Sensing Technologies Chi-Square Analysis Results for Maintenance Phase

Applications Tested	Chi-Square (χ^2)	Significance (p)
Location of pavement/ material placement for performance tracking	0.333	0.564
Signage, culvert, guardrail& other asset inventories and inspection	0.600	0.896
Sharing asset information between different functional units	0.000	1.000
Pavement crack and defect detection	1.000	0.317
Structural inspection	1.600	0.449
Slope stability & landslide assessment	0.200	0.655
Location of voids/ buried assets	0.000	1.000

(*) Significant at 95%

In this statistical analysis result we look at the p-value. If this value is below 0.05, this means that prior experience is not a decisive factor in order to use this technology for the designated activity. Table 5.3 shows that there is no significant difference between experienced state DOTs and less-experienced DOTs regarding the use of remote sensing & monitoring for highway infrastructure during maintenance of infrastructure assets of the activities.

5.3 Key Findings from Interviews

This section summarizes the key findings from interviews with two state DOTs (one DOT with less than five years of experience and two DOTs with more than five years of experience) on the use of remote sensing technologies for highway infrastructure inspection.

5.3.1 Florida DOT (FDOT)

Application for highway inspection during construction

FDOT uses LiDAR, remote sensors, infrared sensors and remote cameras for a variety of construction inspection. For example, infrared sensors are used to monitor temperatures for mass concrete pours, and with drilled shaft construction work, which ties with thermal integrity testing. LiDAR is used for earthwork tasks and measuring quantities for construction inspections.

Remote cameras are used on construction sites and the consultant inspectors use the cameras to visualize the progress of work over a specific period of time. Remote cameras are also used in construction of special activities, such as sliding in a bridge to its permanent location from the construction location, to document the operations.

Application for highway infrastructure inspection during maintenance of assets

For asset management, FDOT is exploring the use of bar codes and readers, specifically for sign inventory. Similarly, LiDAR is being investigated for drainage assets as LiDAR can be used to see where the drainage is going. FDOT mentioned that discussions are taking place on expanding the use of LiDAR for construction and maintenance.

Specific applications of sensors and camera use is the monitoring of rest area assets and the number of parking spaces available, and the maintenance aspects required for the Skyway Bridge in Tampa, FL. In rest areas, FDOT placed sensors in the pavement to note whether a parking space is occupied or not. Remote cameras visually show which spots are available for truckers to use. This helps the traveling public and improves FDOT's operations. Stress and strain gauges along with accelerometers are placed along the Skyway bridge to monitor its movement.

Monitoring the bridge remotely helps maintenance to determine needs without inspectors physically having to measure and check movement on a regular basis.

Finally, FDOT mentioned that they have a robust ITS system that includes video cameras on limited access roadways. For crashes, maintenance can make sound decisions on repairing the infrastructure and associated equipment even prior to visiting the site.

5.3.2 Pennsylvania DOT (PennDOT)

Application for highway inspection during construction

Remote sensing technologies used by PennDOT for construction inspections includes LiDAR, RFID, IC, remote sensors, infrared sensors, remote cameras, and barcodes and readers. LiDAR currently is used for surveying and for monitoring work. The PennDOT representative noted that IC was used by PennDOT in the past with asphalt paving projects. However, IC is rarely used by PennDOT currently because of concerns related to not achieving the compaction specified. As the technologies improve, PennDOT may revisit the use of IC in the future.

Remote cameras are used on projects to collect time-lapse information on the progress of work that helps PennDOT check the conditions of a project for inspection purposes as well as for claims filed by contractors. In addition, PennDOT employed the use of live cameras with audio during the COVID-19 pandemic at asphalt testing sites. Traditionally, PennDOT requires an inspector to be onsite during the entire paving test. During the pandemic, this was not allowed. Therefore, remote cameras were set up at the testing site with paving contractors and inspectors were able to access the video feed and communicate live with the contractor. Inspectors could remotely monitor the asphalt sample testing without having to be on site. Finally, PennDOT

currently uses barcodes and readers and RFID technologies to provide necessary information about the particular material to the inspector.

Application for highway infrastructure inspection during maintenance of assets

For asset management, PennDOT uses remote sensors, such as strain gauges and accelerometers, for evaluating highway infrastructure assets. Sensors are used in pavement structures to help inspectors observe how the structures flex and move over time. This information helps inspectors make timely decisions on the maintenance of pavement structures. In addition, accelerometers are used by PennDOT maintenance staff on bridges when performing maintenance work. Accelerometers provide information related to the stresses impacting the bridge required for maintenance.

One of the challenges in using technologies to replace traditional methods is gaining buy-in from users and providing proper training to the staff and inspectors. PennDOT requires classroom training, but more importantly, PennDOT focuses on hands-on training in the field. Training also varies depending on the staff being trained and the work that is to be performed with a specific technology. Additionally, PennDOT trains experts across the state that can assist users in using specific technologies on a project site.

5.4 Summary

State DOTs are increasingly using remote and infrared sensors to measure material strength and temperature. LiDAR and 3D laser scanning are often used for the inspection of highway infrastructure during the construction and maintenance of assets. For construction inspection, LiDAR and 3D laser scanning are typically used for collecting as-build information and

developing 3D as-built models. For inspection of existing highway assets, LiDAR and 3D laser scanning are typically used for detecting pavement cracks and defects and slope stability and landslide assessment.

Technologies for construction inspections and asset management are not cheap, and if not maintained, the technologies can become limited as to what they can do. For example, FDOT realizes that they have to support and maintain their equipment so that personnel can perform their responsibilities correctly and efficiently. Further, it is important that technologies used for highway inspection be compatible with other devices used by DOT inspectors, contractors, and consultant inspectors. For example, FDOT has experienced incompatibility issues, such as incompatible GPS rovers that cannot communicate with the contractor's base station, which has led FDOT toward a statewide network that broadcasts correction information for those devices instead of communicating with the base station. Overcoming incompatibilities has been a challenge. Finally, training plays an important role in overcoming challenges in the transition from comfortable /traditional inspection approaches to tech-based inspection approaches. The staff inspectors and end-users of the technology must be trained properly and have the buy-in of the implementation process.

CHAPTER 6 : MOBILE DEVICES AND SOFTWARE APPLICATIONS

6.1 Introduction

This chapter presents the results of agency use of mobile devices and software applications for highway infrastructure inspection. The findings presented in this chapter are a result of the 42 state DOT responses to the survey, which represents an 84% response rate. In addition, the content analysis results of DOT's manuals, guidelines, and relevant documents obtained from the survey are also included to support the findings. This chapter discusses the current practice of mobile devices and software applications category of inspection technologies. Additionally, this chapter discusses a statistical analysis to examine the impact of experience on choosing the proper technology for different inspection activities. It is important to note that the 42 state DOT respondents were not required to respond to all questions in the survey. As a result, the sample size (n) of each question likely varies. Finally, the chapter discusses the key findings from the interview with state DOTs with regard to the implementation of mobile devices and software applications for highway inspection during the construction and maintenance of assets.

6.2 Results of Using Mobile Devices and Software Applications for Highway Infrastructure Inspection

Figure 6.1 shows the use of mobile devices & software applications for highway infrastructure inspection. According to Figure 6.1, More than 70% of the 42 responded state DOTs indicated that they had used mobile devices and software applications for inspection of all project types.

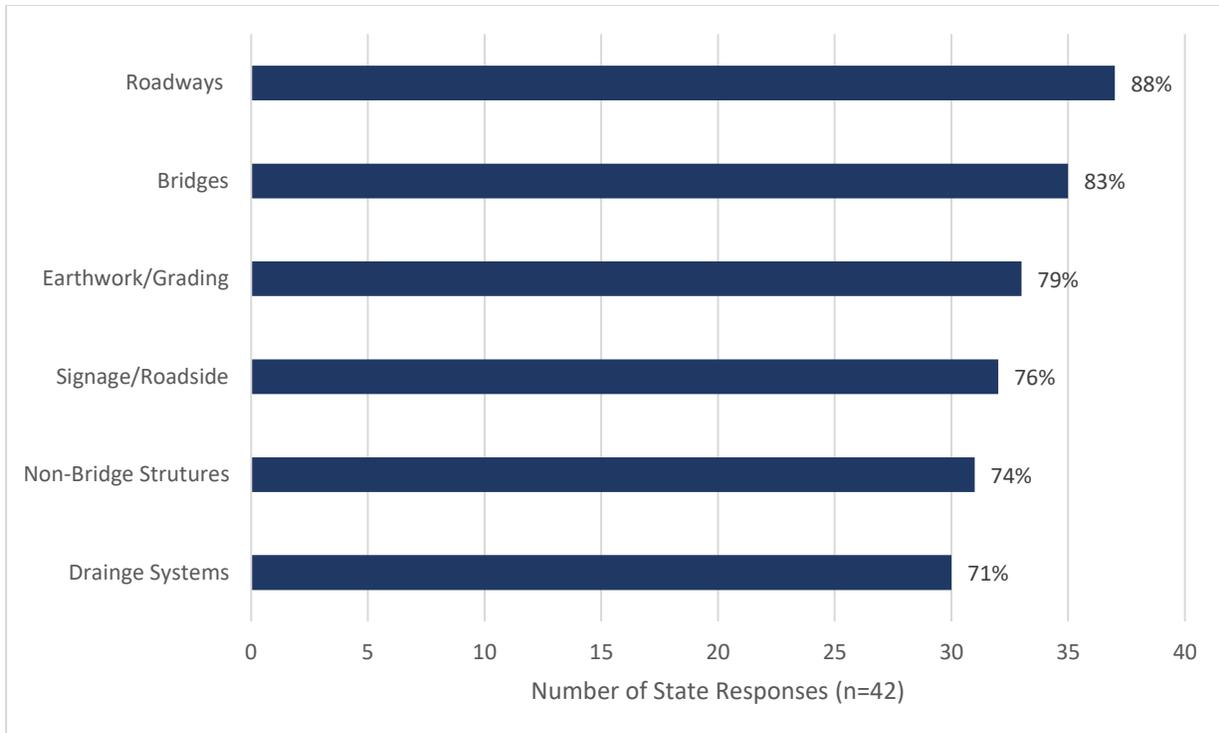


Figure 6.1: Use of Mobile Devices & Software Application for Highway Infrastructure Inspection

6.2.1 Application of Mobile Devices & Software Applications for Highway Inspection during Construction

Figure 6.2 shows the typical mobile devices & software applications used for highway infrastructure inspection during construction. Out of 41 responses, 37 DOTs (90%) have used tablet computers and smartphones; 22 DOTs (54%) have used handheld data collectors (e.g., Real-time Kinematics (RTK), Trimble Yuma); and 17 DOTs (41%) have used automated machine guidance and 3D Engineered Models/BIM for inspection of their highway infrastructure during construction. Figure 6.2 also indicates that only two DOTs (California and Connecticut) have used Virtual Reality/Augmented Reality for inspection of their highway infrastructure during the construction.

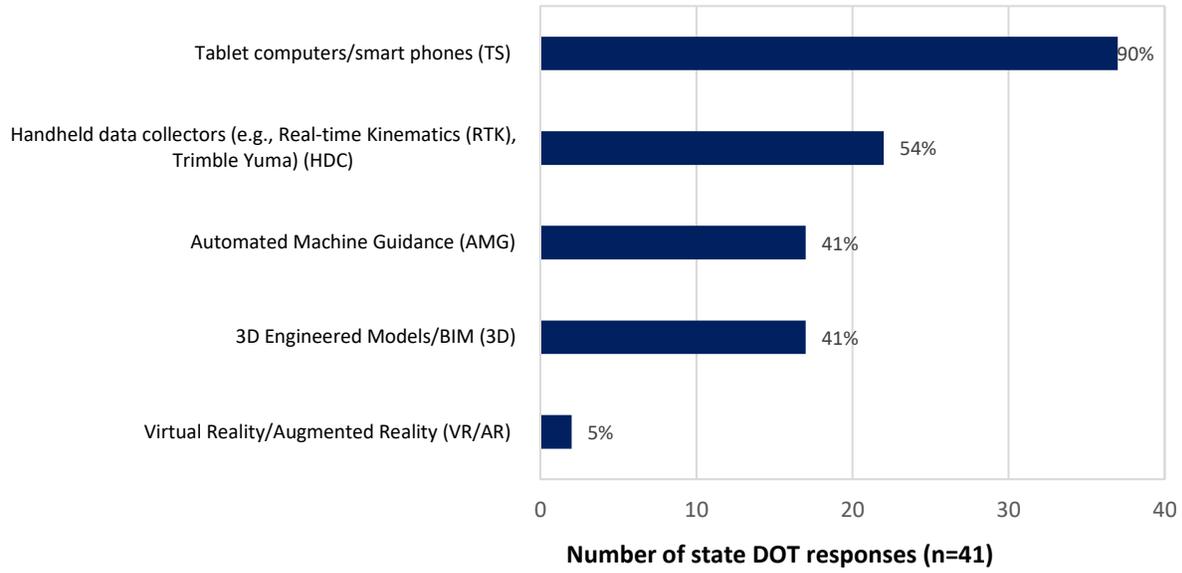


Figure 6.2: Types of Mobile Devices & Software Applications Used for Highway Infrastructure Inspection During Construction

Figure 6.3 shows the typical application of using 3D Engineered Models/BIM for highway infrastructure inspection during construction. The only inspection activity that was agreed upon by 20% of 41 respondents was earthwork inspection and quantities (10 DOTs, 24%).

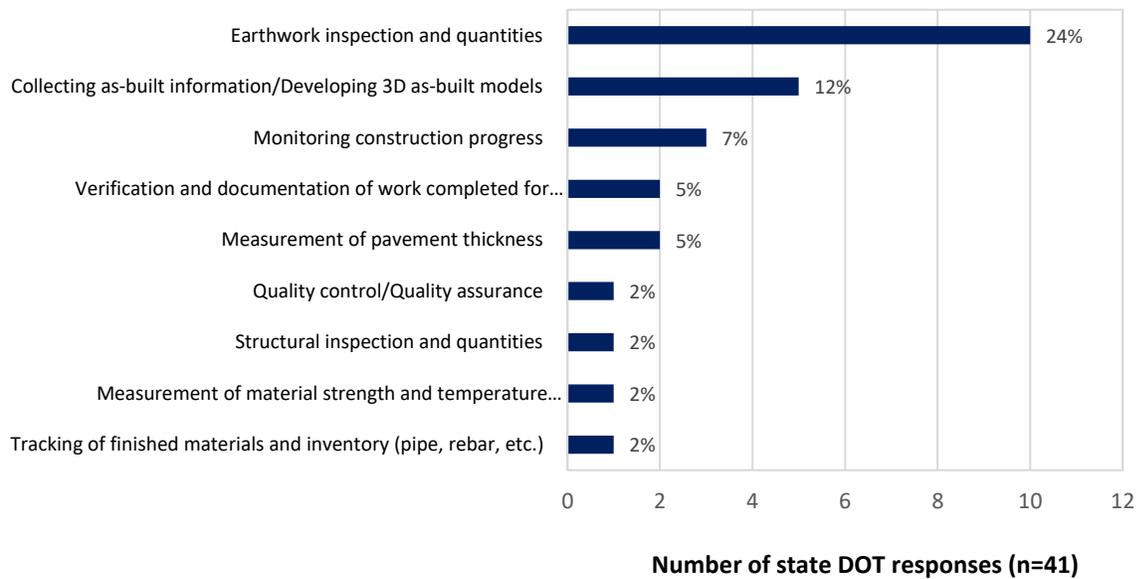


Figure 6.3: Application of 3D Engineered Models/BIM for Highway Infrastructure Inspection During Construction

Figure 6.4 shows the typical application of using Automated Machine Guidance for highway infrastructure inspection during construction. The inspection activities that are agreed upon by more than 10% of 41 responded DOTs include:

- Earthwork inspection and quantities (7 DOTs, 17%).
- Monitoring construction progress (4 DOTs, 10%);

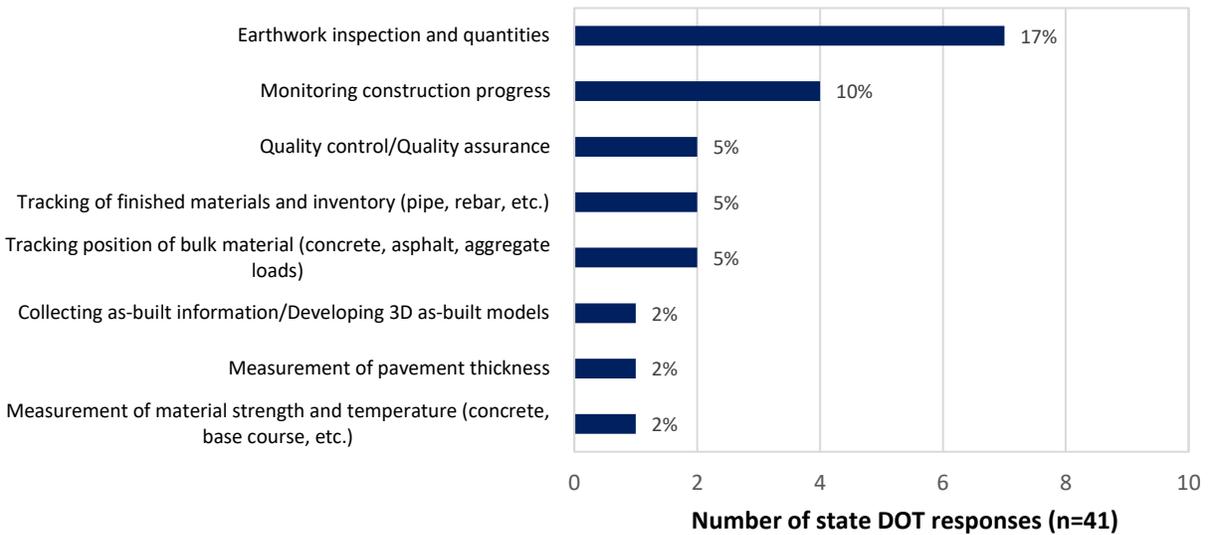


Figure 6.4: Application of Automated Machine Guidance for Highway Infrastructure Inspection During Construction.

Figure 6.5 shows the typical application of using tablet computers/smartphones for highway infrastructure inspection during construction. The top five inspection activities that are suitable for using tablet computers/smartphones include:

- Verification and documentation of work completed for payment (33 DOTs, 80%);
- Monitoring construction progress (32 DOTs, 78%);
- Site photos & videos 3D as-built models (26 DOTs, 63%);
- Quality control/Quality assurance (24 DOTs, 59%); and

- Erosion control inspection (22 DOTs, 54%).

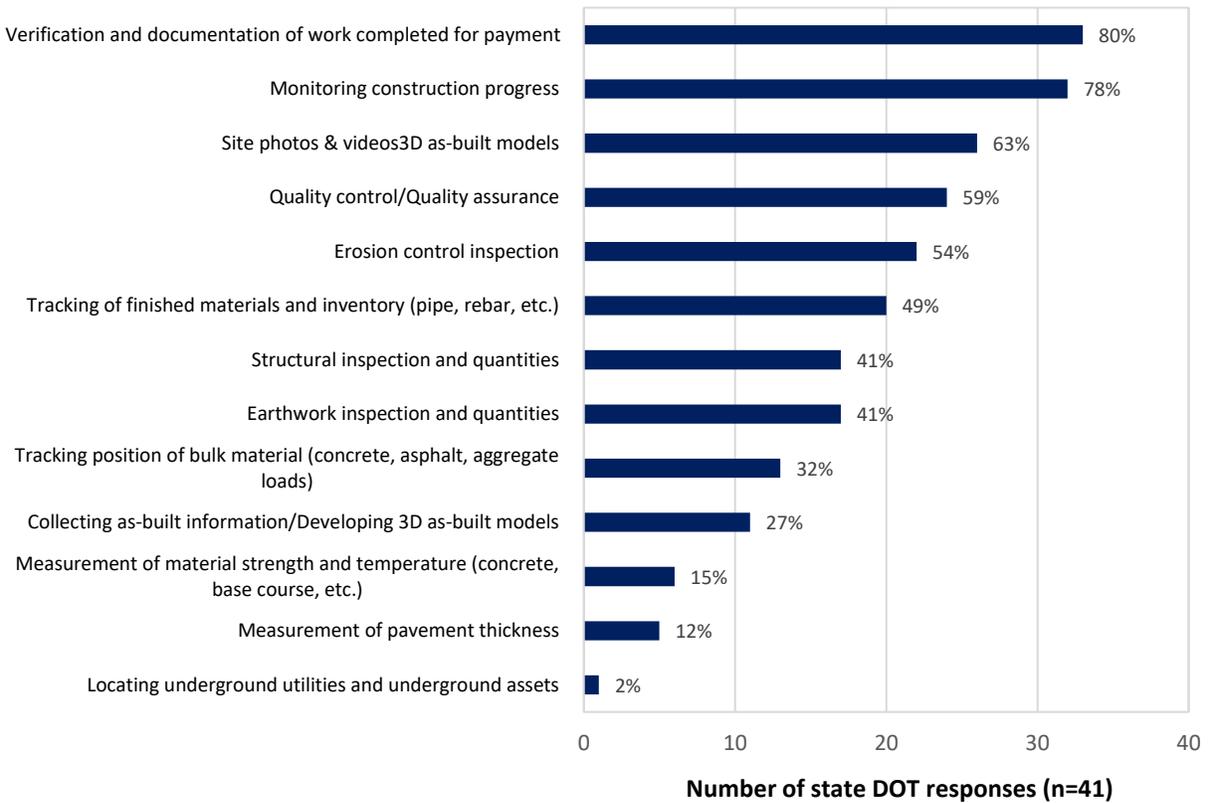


Figure 6.5: Application of Tablet Computers/Smart Phones for Highway Infrastructure Inspection During Construction

Figure 6.6 shows the typical application of using handheld data collectors for highway infrastructure inspection during construction. The inspection activities that are by more than 15% of 41 responded DOTs include:

- Monitoring construction progress (12 DOTs, 29%);
- Quality control/Quality assurance (9 DOTs, 22%);
- Earthwork inspection and quantities (9 DOTs, 22%);
- Verification and documentation of work completed for payment (6 DOTs, 15%); and
- Tracking position of bulk material (concrete, asphalt, aggregate loads) (6 DOTs, 15%).

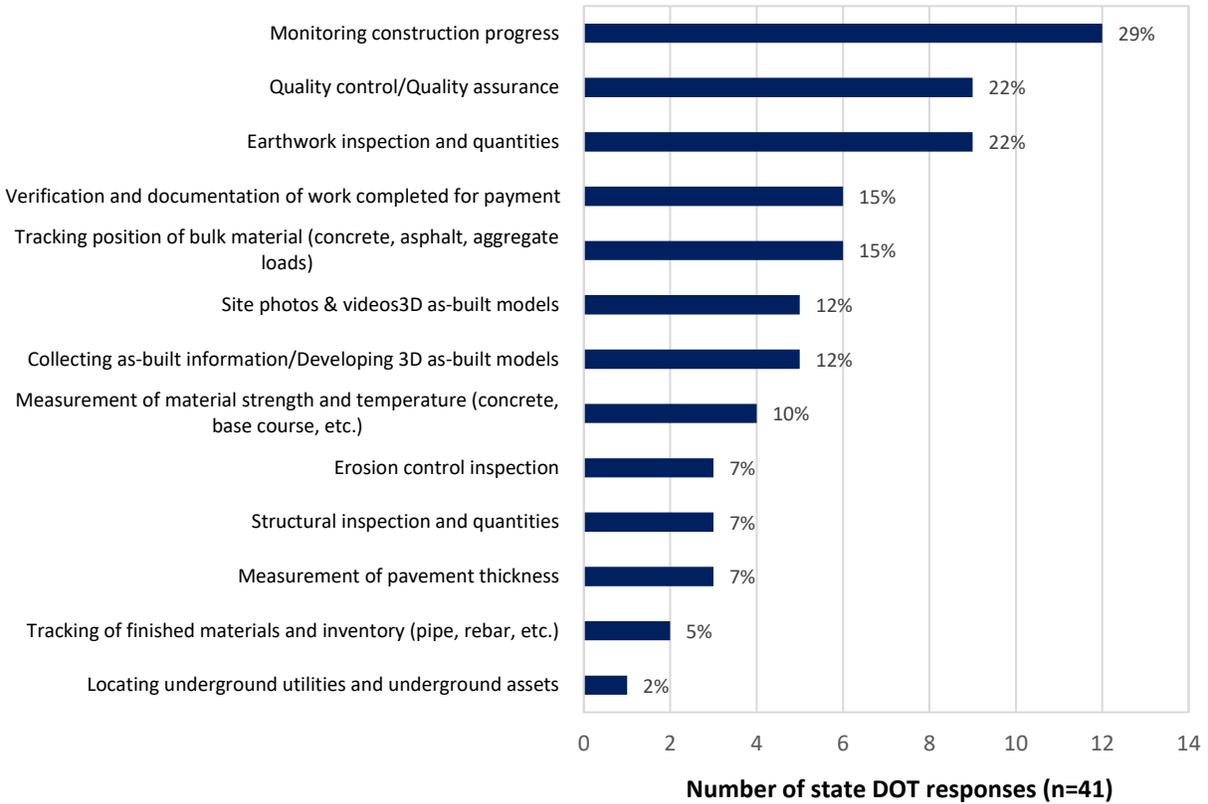


Figure 6.6: Application of Handheld Data Collectors for Highway Infrastructure Inspection During Construction

6.2.2 Impact of Experience on Use of Mobile Devices & Software Technologies During Construction

The hypothesis is the use of mobile devices & software applications is not affected by the DOT's years of experience. All responses were categorized and divided into two categories, more than five years of experience and less than five years of experience. Table 6.1 show a list of DOTs associated with these categories.

Table 6.1: Mobile Devices & Software Application Years of Experience

Category	States
Less than 5 years	Alabama, Arkansas, California, Colorado, Delaware, Georgia, Hawaii, Illinois, Kansas, Kentucky, Maryland, Minnesota, Montana, Nebraska, New Hampshire, New Mexico, Rhode land, Utah, Vermont, Virginia, and Washington.
More than 5 years	Connecticut, Florida, Indiana, Iowa, Massachusetts, Missouri, New Jersey, New York, North Carolina, North Dakota, Pennsylvania, Oregon, Oklahoma, South Carolina, South Dakota, Tennessee, Texas, West Virginia, Wisconsin, and Wyoming.

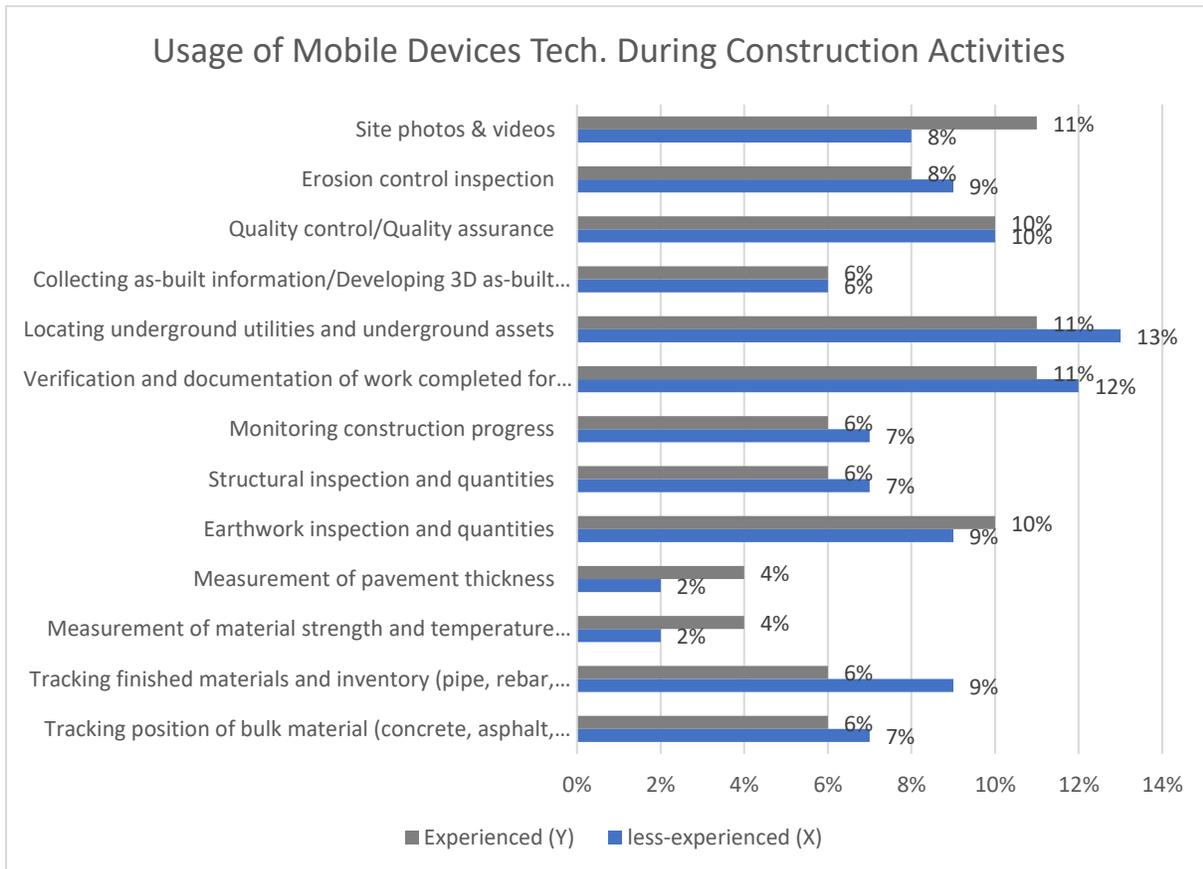


Figure 6.7: Usage of Mobile Devices & Software Application for Highway Inspection During Construction Based on DOT’s Experience

The Pearson chi-square was used to determine whether there is a statistically significant difference in the technology usage by two groups of agencies. Table 6.2 shows the chi-square test result for the typical application of mobile devices & software for highway construction.

Table 6.2: Chi-Square Analysis Results for Mobile Devices & Software Application During Construction

Applications Tested	Chi-Square (χ^2)	Significance (p)
Tracking position of bulk material (concrete, asphalt, aggregate loads)	8.0857	0.012*
Tracking finished materials and inventory (pipe, rebar, etc.)	40.655	0.001*
Measurement of material strength and temperature (concrete, base course, etc.)	6.000	0.112
Measurement of pavement thickness	3.182	0.364
Earthwork inspection and quantities	20.639	0.001*
Structural inspection and quantities	21.714	0.001*
Monitoring construction progress	25.391	0.001*
Verification and documentation of work completed for payment	83.639	0.001*
Locating underground utilities and underground assets	54.918	0.001*
Collecting as-built information/Developing 3D as-built models	8.826	0.032*
Quality control/Quality assurance	45.392	0.001*
Erosion control inspection	9.966	0.002*
Site photos & videos	10.756	0.001*

(*) Significant at 95%

In this statistical analysis result we look at the p-value. If this value is below 0.05, this means that prior experience is not a decisive factor in order to use this technology for the designated activity. Table 6.2 shows that there is a significant difference between experienced state DOTs and less-experienced DOTs regarding the use of mobile devices & software application for highway infrastructure during the construction of all activities except measurement of pavement thickness.

6.2.3 Application of Mobile Devices & Software Application for Highway Inspection during Asset Management

Figure 6.8 shows the typical mobile devices & software applications used for highway infrastructure inspection during maintenance of assets or asset management. Out of 41 responses, 16 state DOTs (39%) have used tablet computers and smartphones, and seven state DOTs (17%) have used handheld data collectors (e.g., Real-time Kinematics (RTK), Trimble Yuma). Florida DOT mentioned that it has used 3D Engineered Models/BIM for inspection of its highway infrastructure during maintenance of assets or asset management.

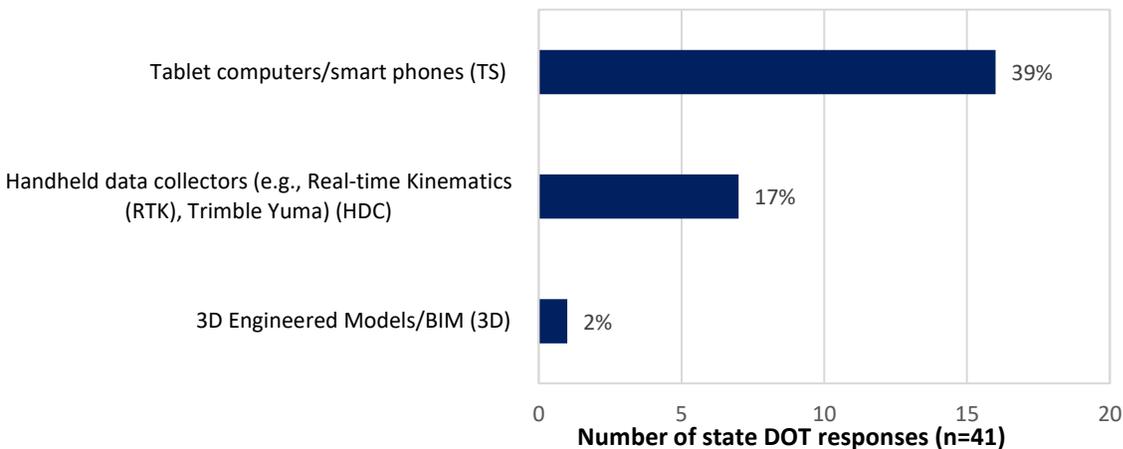


Figure 6.8: Types of Mobile Devices & Software Applications Used for Highway Infrastructure Inspection During Maintenance or Asset Management

Figure 6.9 shows the typical application of using the application of tablet computers / smartphones for highway infrastructure inspection during maintenance or asset management. The top inspection activities that are suitable for using the TS technology agreed by more than 20% of 16 responded DOTs include:

- Signage, culvert, guardrail& other asset inventories and inspection (16 DOTs, 100%);
- Sharing asset information between different functional units (14 DOTs, 88%);
- Structural inspection (10 DOTs, 63%).
- Slope stability & landslide assessment (6 DOTs, 38%); and
- Location of pavement/ material placement for performance tracking (6 DOTs, 38%).

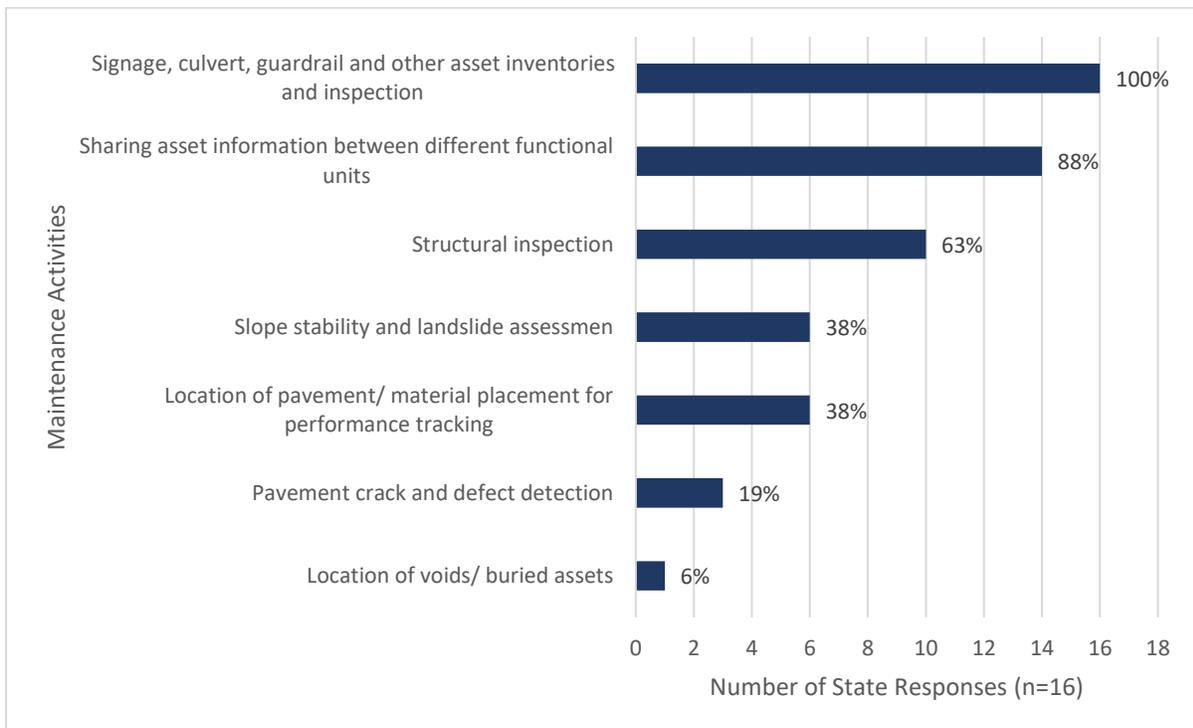


Figure 6.9: Application of TS for Highway Infrastructure Inspection During Maintenance or Asset Management

Figure 6.10 shows the typical application of using handheld data collectors for highway infrastructure inspection during maintenance or asset management. The top inspection activities that are suitable for using the HDC technology agreed by more than 15% of 7 responded DOTs include:

- Signage, culvert, guardrail & other asset inventories and inspection (4 DOTs, 58%);
- Slope stability & landslide assessment (2 DOTs, 29%); and
- Sharing asset information between different functional units and Pavement crack and defect detection (1 DOTs, 15%).

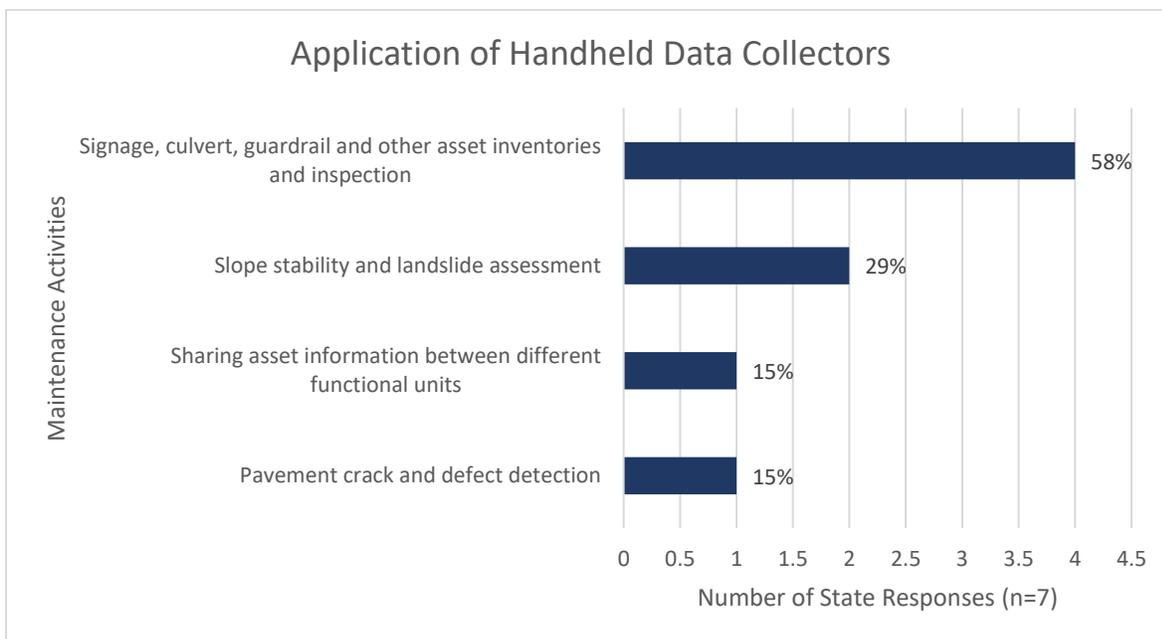


Figure 6.10: Application of HDC for Highway Infrastructure Inspection During Maintenance or Asset Management

6.2.4 Impact of Experience on Use of Mobile Devices & Software Application During Maintenance

Similar to the inspection during construction, the hypothesis is the use of mobile devices & software applications is not affected by the DOT's years of experience during maintenance. All responses were categorized and divided into two categories, more than five years of experience and less than five years of experience. Figure 6.11 shows typical inspection activities for highway infrastructure during maintenance associated with experienced and less-experienced DOTs.

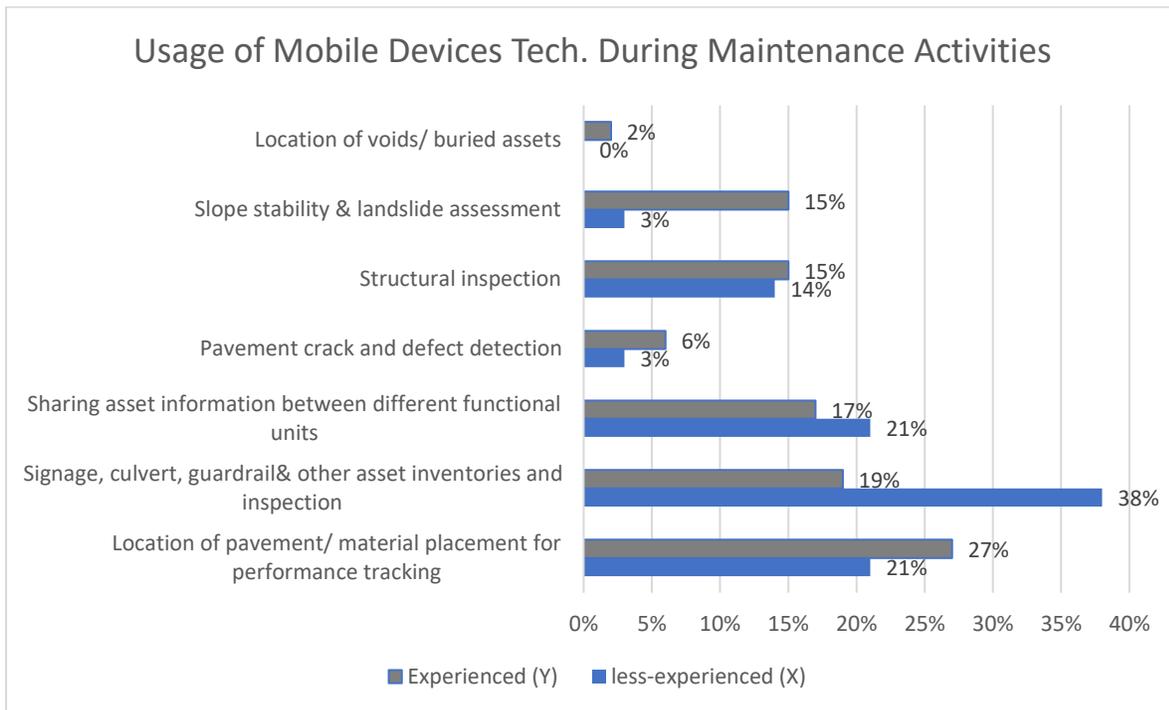


Figure 6.11: Usage of Mobile Devices & Software Application for Maintenance Activities in Different States DOTs Based on Experience

The Pearson chi-square was used to determine whether there is a statistically significant difference in the technology usage by two groups of agencies. Table 6.3 shows the chi-square test result for the typical application of mobile devices & software applications for highway inspection during maintenance.

Table 6.3: Mobile Devices & Software Application Chi-Square Analysis Results for

Maintenance Phase

Applications Tested	Chi-Square (χ^2)	Significance (p)
Location of pavement/ material placement for performance tracking	8.909	0.003*
Signage, culvert, guardrail& other asset inventories and inspection	14.727	0.001*
Sharing asset information between different functional units	9.000	0.003*
Pavement crack and defect detection	1.000	0.317
Structural inspection	7.364	0.007*
Slope stability & landslide assessment	4.667	0.097
Location of voids/ buried assets	0.000	0.000

(*) Significant at 95%

In this statistical analysis result we look at the p-value. If this value is below 0.05, this means that prior experience is not a decisive factor in order to use this technology for the designated activity. Table 6.3 shows that there is a significant difference between experienced state DOTs and less-experienced DOTs regarding the use of mobile devices & software application for highway infrastructure during maintenance of infrastructure assets of the following activities: Location of pavement/ material placement for performance tracking; Signage, culvert, guardrail& other asset inventories and inspection; Sharing asset information between different functional units; and Structural inspection.

6.3 Key Findings from Interviews

This section summarizes the key findings from interviews with two state DOTs (one DOT with less than five years of experience and two DOTs with more than five years of experience) on the

use of mobile devices and software applications for highway infrastructure inspection.

6.3.1 Minnesota DOT (MnDOT)

Application for highway inspection during construction

MnDOT uses 3D engineered models, automated machine guidance (AMG), tablet/smartphones, and RTK handheld devices for construction inspection. The 3D engineered models and AMG use has been driven by the contractors that work with MnDOT, which has helped them advance in these technology areas. Using 3D models and AMG-equivalent inspection technologies provides inspectors with Realtime data that is easy to access on the tablet they have in the field. Inspectors also use a collector app on tablet devices when conducting field inspections. Handheld rover devices are provided to inspectors to collect data on specific aspects of a project.

Challenges that MnDOT experiences with using mobile devices and software applications is incompatibility issues, training staff, and keeping device hardware current. Internally, different departments and offices use different software and mobile devices. Externally, contractors may use different software and mobile devices as well. Finding common or universal files to share data tends to cause issues in some cases. Personnel need to be trained so that they use the mobile devices and associated software properly and accurately, and for changes in the processes they perform. For example, MnDOT staff mentioned that surveyors may spend more time in the office today than in the past processing and analyzing data, which is a change for experienced surveyors that used to spend most or all their time in the field. Keeping devices current can be expensive when replacing technologies on a regular basis as the technologies continue to improve. However, the use of mobile field devices at MnDOT provides the benefit of real-time and accurate data collection, improving the efficiency of inspection operations.

Application for highway infrastructure inspection during maintenance of assets

For asset management, MnDOT uses 3D engineered models, tablets/smartphones, and handheld devices. MnDOT is not currently inspecting assets within operations and maintenance using 3D engineered models. However, a large pilot project in District 3 is ongoing in which hydraulic asset data is being used for design and utilizing a digital twin to track through construction and back to maintenance/asset management. The digital twin will allow MnDOT to recognize more accurate costs for assets and pay items for contractor work, and the ability to update the model to recognize the real-time changes made to a physical asset.

MnDOT has used windows mobile field devices for over ten years to collect asset information. In the last four years, MnDOT has moved to tablet devices and smartphones in the field (paired with a receiver if needed) to apply field devices for multiple needs, such as phone calls, email, or network access.

6.3.2 New York State DOT (NYSDOT) ***Application for highway inspection during construction***

Mobile devices and software applications in use for construction inspections include 3D engineered models, AMG equivalent inspection equipment, tablets/smartphones, handheld RTK devices, VR/AR, and various mobile apps and software programs to collect, view, and analyze the data collected with the mobile digital devices. NYSDOT noted that 3D models are used along with a BIM specification on large design-build projects. The specification requires the contractor to update the 3D model throughout the project and produce 3D as-builts and 3D GIS models at the conclusion of the project. Currently, NYSDOT is implementing 4D and 5D models that allow project staff and management to account for and verify time and costs associated with overall project schedules as well as specific components of a project.

The majority of contractors are using AMG on projects that make work more efficient and NYSDOT is able to inspect AMG work using technologies. All construction inspectors have a

tablet or laptop and a cell phone, including in-house and external third-party consultant inspectors. Handheld data collectors are used with RTK GPS units for collecting data on inspections and progress of work and note the actual location of the work being inspected. NYSDOT is testing out a simplified GPS system that can be connected to a tablet or smartphone. The accuracy may not be survey grade, but its accuracy is acceptable for construction purposes. Further, NYSDOT has a virtual reality and augmented reality department, which is a part of design. In construction, the virtual and augmented reality information is used to develop 4D and 5D animations to illustrate the work progress.

Application for highway infrastructure inspection during maintenance of assets

For asset management, NYSDOT noted that a system of engagement in NYSDOT allows for the use of asset-centric viewers that permits anyone within NYSDOT to view the information collected on assets in their asset management system. The viewers provide NYSDOT staff with information about assets including items such as accurate location, pavement conditions, and previous three years of maintenance history from their maintenance management system, and other relevant information. Feedback from NYSDOT staff shows that the viewers are really helpful and provide better information and accuracy than previous methods used. Along with the viewers, NYSDOT also has in development specific asset class applications that can be used on smartphones and tablet devices to keep the geospatial warehouse of asset information updated.

6.4 Summary

The 3D engineered model allows for faster, more accurate and more efficient planning and construction. AMG is a suitable tool for projects that involve large amounts of earthwork or paving, new alignments, or projects requiring accurate digital terrain models. In addition, the main benefits of using handheld devices in highway infrastructure inspection include better

organizing field-generated data; reducing the cycle time to obtain the data; improving accuracy for material delivery; and enhancing electronic documentation and digital inspection. State DOTs have used tablet computers and smartphones for inspection of highway infrastructure during construction. The top inspection activities utilizing tablets and smart phones during highway construction include verifying and documenting work completed for payment, monitoring construction progress, and capturing site photos and videos. State DOTs have used tablet computers and smartphones for inspection of highway infrastructure during the maintenance of assets. The top inspection activities for using tablets and smartphones during maintenance of highway infrastructure assets include inventories and inspection of signage, culverts, guardrails and other highway assets and sharing asset information between different functional units. Finally, the top inspection activities that use handheld data collectors during highway construction include monitoring construction progress, earthwork inspection and quantities, and quality control/quality assurance activities.

CHAPTER 7 : INSPECTION TECHNOLOGIES EVALUATION METRICS

7.1 Introduction

This chapter aims to examine the inspection technologies evaluation metrics that are considered by DOTs and determine ROI for mobile mapping. First, this chapter discusses the evaluation metrics of implementing technologies for highway infrastructure inspection based on the responses from the national survey. This is followed by a discussion regarding the calculation of ROI. Next, the chapter presents a case study result from a contractor in Jordan (Middle East) that used mobile mapping technologies for highway construction projects. This is followed by examining the differences between the ROI in a developed country (USA) versus a developing country (Jordan) by comparing the ROI case study to that already performed in the Oregon DOT.

7.2 Evaluation Metrics for Inspection Technologies Metrics

The survey respondents were asked to identify the performance metrics that their state DOTs use to evaluate the implementation of technologies for highway infrastructure inspection. Figure 7.1 summarizes the result of this question. The four metrics used by more than two thirds of the 42 responding DOTs include: (1) efficiencies gained when using technologies; (2) increase in quality of a project; (3) overcoming limited inspection resources; and (4) cost-benefit analysis.

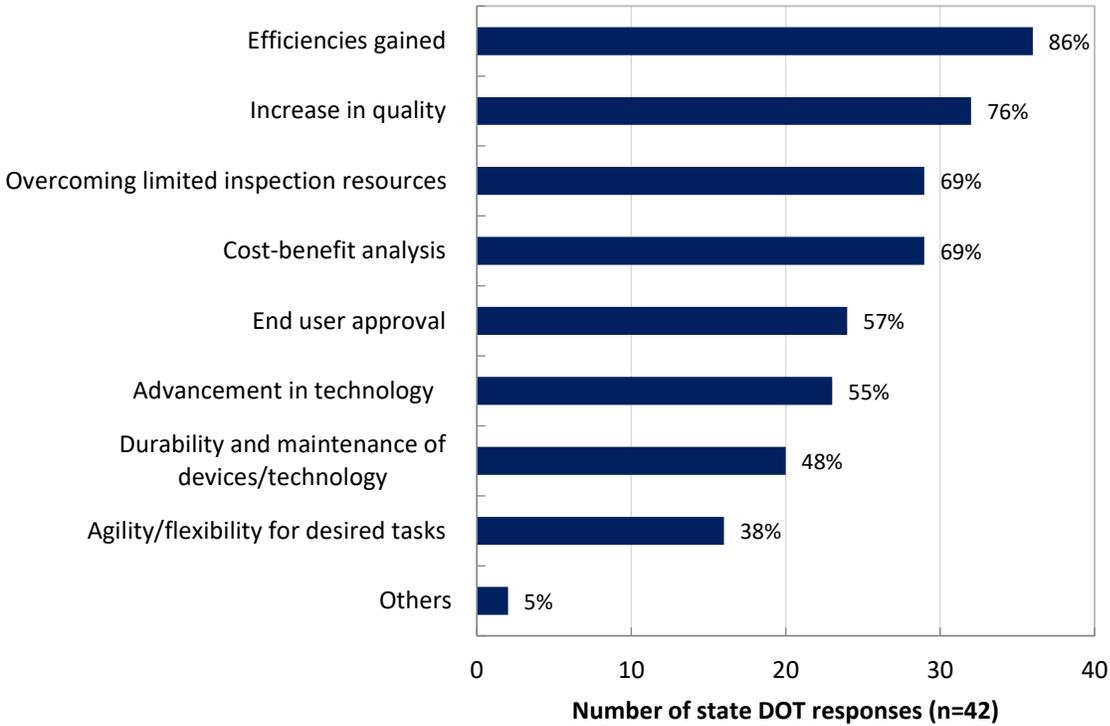


Figure 7.1 Performance Metrics to Evaluate the use of Technologies for Inspection

It is important to note that the cost-benefit analysis performance shown in Figure 7.1 is based on a specific case project or the perception of the user. Specifically, when the survey respondents were asked to identify the overall return on investment (ROI) from using the technologies for highway infrastructure inspection, most state DOTs (32 out of 42 responding DOTs) stated that the information required to calculate the ROI is not available (See Table 7.1).

Table 7.1 Overall return on investment (ROI) from using the technologies for highway infrastructure inspection (n = 42)

Technologies	< 0%	0-10%	10%-20%	20%-50%	50%-100%	> 100%	Unsure/Information is not available
Geospatial Technologies	0	0	0	2	1	3	32
Remote sensing and Monitoring Technologies	0	0	1	1	1	2	33
Mobile Devices and Software Applications	0	0	2	1	2	3	33
Nondestructive Evaluation Methods	0	0	1	2	2	0	34

The survey results also indicated that most state DOTs currently do not track the cost-effectiveness of implementing technologies for highway inspection during construction and maintenance of assets. Figure 7.2 indicates that 53% of the 42 responding DOTs do not track the cost-effectiveness of implementing technologies.

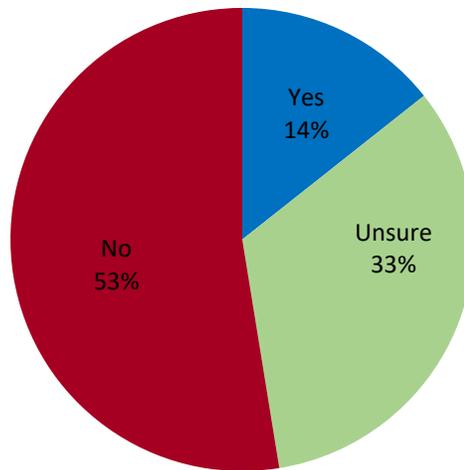


Figure 7.2 Agency track the cost-effectiveness of implementing technologies (n =42)

Six state DOTs (14%) including California, New York, New Mexico, Oregon, Pennsylvania, and Wisconsin mentioned that they have tracked cost-effectiveness of implementing technologies for highway inspections. Specifically, the Oregon DOT indicated that independent studies were

conducted to evaluate and track cost-effectiveness of implementing technologies. The Oregon DOT also indicated that the ROI of geospatial technologies, remote sensing and monitoring technologies, and mobile devices and software applications are greater than 100%.

The Pennsylvania DOT mentioned that ROI is analyzed for proposed technologies based on the cost to develop and incorporate efficiency gains or quality improvements. The Pennsylvania DOT indicated that the ROI for geospatial technologies and remote sensing and monitoring technologies, mobile devices and software applications, and nondestructive evaluation methods is approximately 50-100%, greater than 100%, and 20-50%, respectively.

The Wisconsin DOT indicated that they track savings during pilot projects, but the ongoing implementation is not tracked. The Wisconsin DOT estimated that the ROI of geospatial technologies, remote sensing and monitoring technologies, and mobile devices and software applications is greater than 100%.

The California DOT mentioned that they have tracked the cost-effectiveness of implementing technologies by comparing cost using conventional methods versus using inspection technologies. The California DOT estimated that the ROI of geospatial technologies, remote sensing and monitoring technologies, mobile devices and software applications, and nondestructive evaluation methods is approximately 20-50%.

Lastly, the New Mexico DOT stated that they have tracked the cost-effectiveness of implementing mobile devices and software applications by comparing time spent in the field

versus time spent going back to the office to enter quantities for payment and daily work reports. The New Mexico DOT estimated that the ROI of implementing mobile devices and software applications is approximately 10-20%.

Finally, to further identify different methods used to assess the viability and efficiencies of inspection technologies, the survey respondents were asked to determine the primary drivers for selecting the technologies for highway inspection. Figure 7.3 shows the result of this question based on the responses from 42 state DOTs.

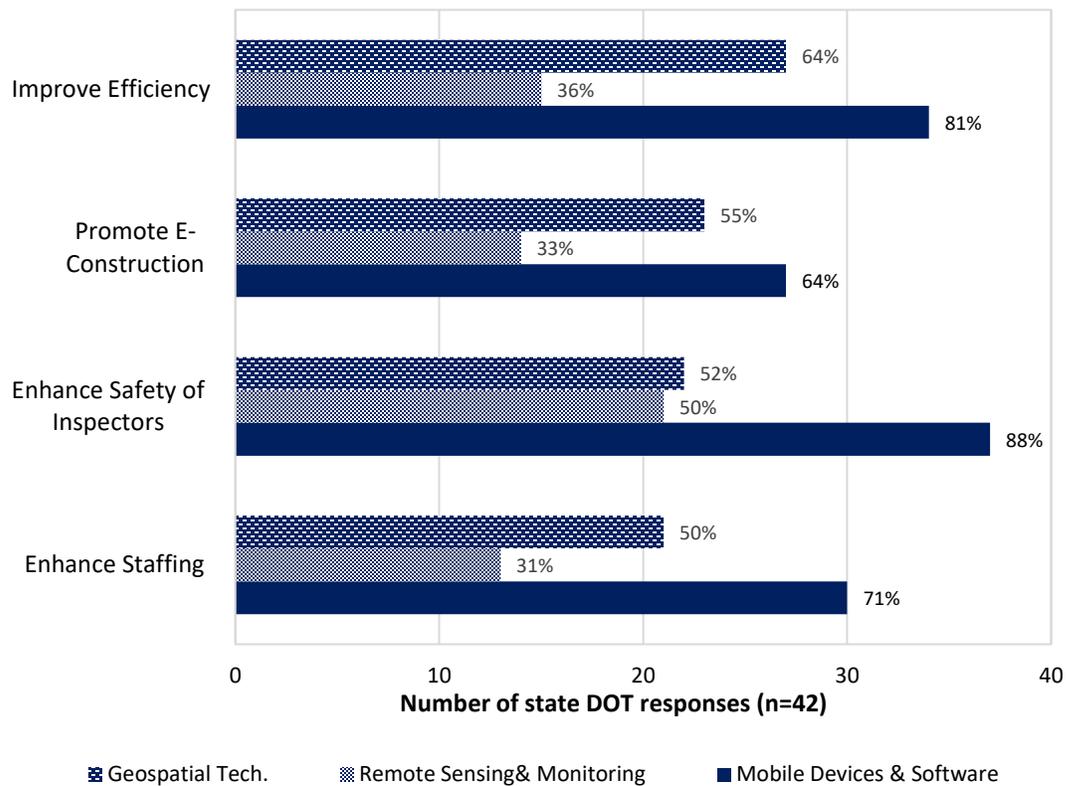


Figure 7.3 Primary drivers for selecting technologies for highway inspection

Figure 3.24 indicates that more than 70% of the 42 responding DOTs indicated that the main driving factors for using mobile devices and software applications are to (1) enhance the safety of inspectors; (2) improve efficiency; and (3) enhance staffing (e.g., using mobile devices and software applications reduces the need of inspection staff). Similarly, more than half of 42 DOT responded that the main driving factors of using geospatial technologies are to (1) improve efficiency; (2) promote e-Construction; and (3) enhance the safety of inspectors. Figure 7.3 also indicates that the main driver of using remote sensing and monitoring technologies and nondestructive evaluation methods is to enhance the safety of inspectors.

7.3 Case Study

As mentioned in the previous section, it is challenging to determine ROI for an organization to use technologies for highway inspection because the ROI depends on a case-by-case basis. Therefore, a case study regarding the methodology of calculating ROI and investigating the effect of the implementation environment factors is presented in this section.

7.3.1 Selection of Case Study

An interview was conducted with a professional engineer at a renowned firm in Jordan. This particular firm was chosen because of its extensive portfolio and multi-disciplinary projects. Moreover, this firm has deep knowledge of inspecting technologies and is counted as a leader in obtaining all new technologies and devices. The focus of this case study is on the mobile mapping technology because of its data-collecting nature that combines multiple inspection technologies with sufficient and accurate systems.

After the interview, it was managed to understand the ROI calculations and answered the question of “How to estimate the benefits and impact of using mobile mapping technologies and measuring the feasibility of technology usage in the construction field.” This interview discusses

the bases of ROI calculations in these projects. It calculates the direct and the indirect costs by mentioning the extra-governmental costs (as fees) and the cost increment due to shipping, tutoring, and deploying mobile mapping devices.

Since the prototype development stage, which professional research institutions performed before 2005, enabled an innovative solution in the geospatial information industry, the geospatial industry has seen an increase in demand for mapping process automation, which has made it commercially viable products. Furthermore, the robotics industry uses identical principles and sensors to build perception technologies that assist robots in navigating new environments. Compared to existing mobile mapping systems developed by the geospatial information business, environmental perception technology generated by the robotic industry has the benefit of low pricing, but its precision is insufficient to fulfill the requirements for geospatial applications. As a result, mobile mapping technology continues to advance in response to customers' fundamental requirements, such as lower hardware costs, more accuracy, and higher profits. The mobile mapping system includes digital imaging technologies, location and orientation systems, and multiple practice platforms and application scenarios. The evolution of mobile mapping systems, hardware costs, and accuracy requirements are linked.

7.3.2 Case Study Interview

The interview is an important data-gathering technique involving verbal communication between the interviewee and the researcher. Regarding the mobile mapping subject, an engineer from a renowned construction company in Jordan, Middle East was the interviewee. The structure of the questions was clear and straight to the point. While some questions covered his professional background and previous projects, others focused on mobile mapping usage within As-Salt's (Jordanian city) ring road and many other projects. The interviewee's answers illustrated the

experience using mobile mapping, the cost of implementation, and output quality. It is noted that many technologies were used alongside mobile mapping in these projects, and many working hours were saved, which led to a noticeable increase in productivity.

7.3.3 Challenges and Barriers

The main barrier faced by the company is the overall cost of the technology. While it is feasible in the long term, companies had to pay the entire cost at once, which causes financial turbulence. Another factor that affected the cost of the equipment is the high customs fees. In Jordan, the customs fees for technologies and vehicles are high. As a result, the benefits of mobile mapping were not significant in some aspects of projects.

Additionally, the cost of labor in Jordan is low. Therefore, the reduction in the labor cost after using the technology will not be as significant as in a country with high labor costs. This factor might affect the magnitude of benefits obtained from using the device. This factor may also lead to a higher breakeven than the use of technology in the U.S.

7.3.4 Benefits Gained

The interviewee noted that mobile mapping technology helped increase the accuracy of measurements required for all projects. It also helps maintain the assets in highway sites easier and more effective.

The interviewee highlighted, "Projects in Jordan have special nature. In Jordan, any project with a cost beyond \$5 million is considered big". The interviewee added: "Customs and taxes are huge, which lead to neglect some important pillars that eliminate some critical quality tests. To uplift their reputation and work, a contractor/consultant may invest in their tools and product quality for long-term investment."

Projects like “As Salt’s ring road” are counted as the biggest in Jordan as a commercial hub connecting Asia, Africa, Europe, and the gate of the Arabian Gulf. Thus, each neighboring country is trying to upgrade the infrastructure to ease land transportation, keeping their cargo, fleet, and passengers safe from road accidents or delays.

7.3.5 Finances and Technical Point of View

As per the setup cost, there are three main factors, including 1- Work station, 2- Scan Processors, 3- Virtual Geomatics LiDAR Explorer. The cost was around 8000 JODs adding up to 16810 JODs as training fees for (3+1) engineers. The device price is the chunk. It cost JOD 415689 (USD 585,477), and the fees are 16%.

For the deployment cost, the interviewee stated: “Three simple terms shaped the deployment cost, Maintenance, Technical support, and Calibration and the cost is 29684, 23772, and 10490 Jordanian Dinars respectively... To sum up, the entire adoption cost is JOD 570934”.

For training, according to the interviewee, the effect of having engineers take courses on how to use this technology impacted the efficiency and accuracy of results. It reduced the time needed at first when there was minimal experience.

Finally, the interviewee was asked to break down the transportation and surveying benefits and the calculation process based on six projects (three with LiDAR technology and three without technology).

7.4 Case Study Analysis

Figure 7.4 shows a summary of the systematic procedure for calculating ROI of mobile mapping.

The process of calculating ROI is based on Equations (1) to (4). From Figure 7.4, one should calculate the Adjusted Annual Deployment Cost (AADC) using Equation 7.2. After that, the Total Cost (TC) is calculated using Equation 7.3. Then, the Direct Return of Investment (DROI) can be determined using Equation 7.4.

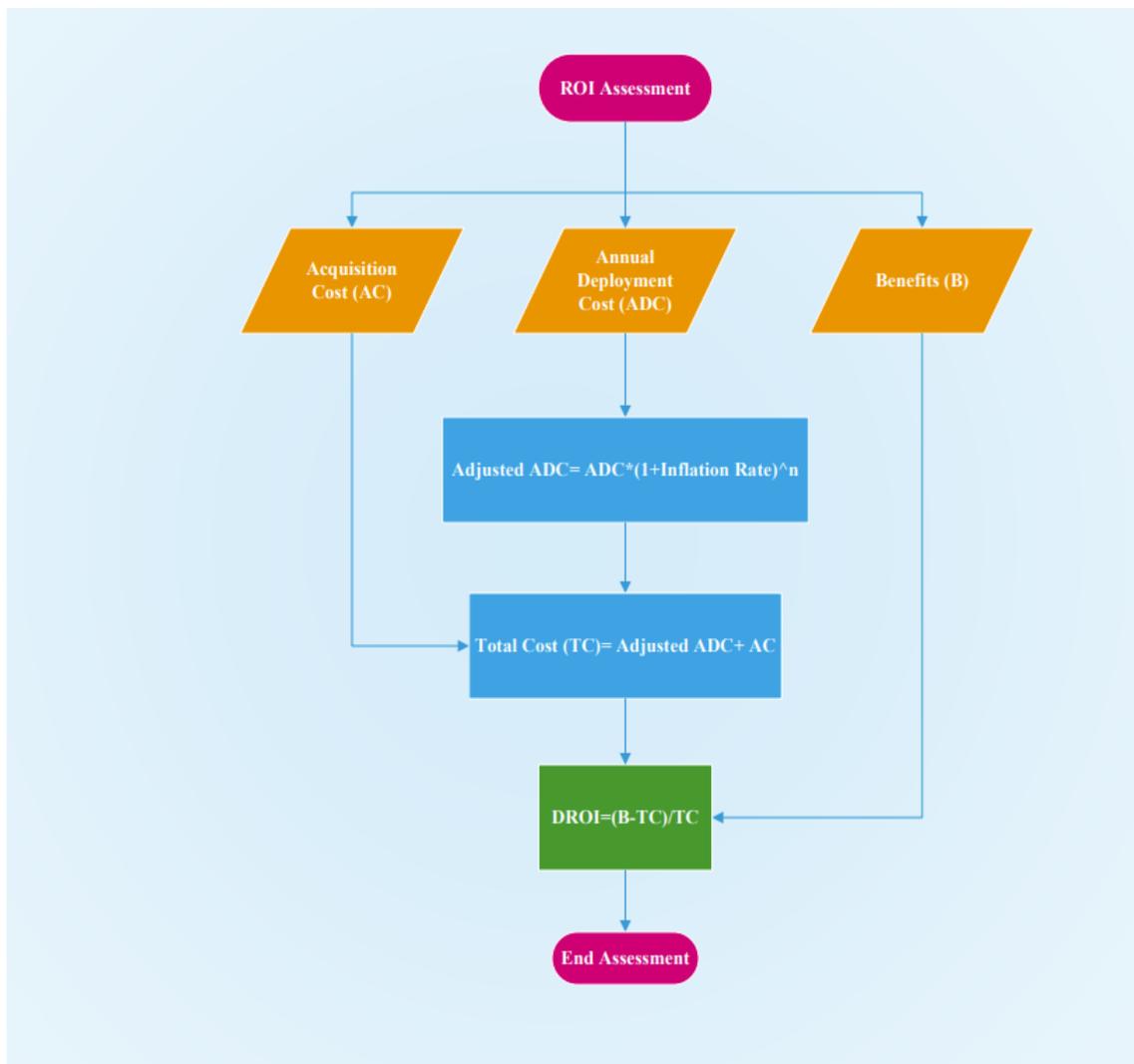


Figure 7.4: Systematic Procedure of Calculating ROI

$$ROI = \frac{\text{Benefits}-\text{Cost}}{\text{Cost}} * 100\% \quad (7.1)$$

$$AADC = ADC(1 + \text{Inflation Rate})^n \quad (7.2)$$

$$TC = AADC + AC \quad (7.3)$$

$$DROI = \frac{B-TC}{TC} \quad (7.4)$$

The data for this case study were collected via interviewing an engineer in a big construction firm in Jordan. The interview questions helped describe the benefits and challenges of using mobile mapping technologies. The interview also helped illustrate the ROI differences when using the same technology in different countries, as illustrated in the previous sections. As for numeric data, the interviewee provided the data regarding the cost and benefits via follow-up emails. The cost category included the acquisition and deployment costs summarized in Table 7.2.

Table 7.2: Summary of Mobile Mapping Adoption Cost for five years

No.	Item	Present Value of Cash Flow (USD)
Acquisition Cost		
1	Purchase Price: Topcon IP-S3 HD1	566,311.00
2	Work Station	2,300.00
3	Scan Processors	1,890.00
4	Virtual Geomatics LiDAR Explorer	7,064.00
5	Mobile LiDAR Company Training	21,710.00
6	Custom fees (16%)	95,884.00
Deployment Cost		
1	Software Maintenance	41,688.00
2	Technical Software Support	33,529.00
3	Calibration and Tune Up	14,796.00
4	Inflation Rate (5%)	25,204.00
Total Company Cost		810,376.00

As for the benefits, the interviewee was able to find projects with similar scopes and sizes where mobile mapping technologies were not used (traditional scenario) and compared it to the cost of projects where mobile mapping was used (technology scenario). Table 7.3 summarizes the costs of surveying and transportation. These costs were used to calculate the benefits by subtracting the cost of transportation and surveying of projects with mobile mapping used from associated costs from projects using mobile mapping.

Table 7.3: Summary of Surveying and Transportation Expenses for five years

Project Name	Mobile Mapping Used	Surveying Expenses (USD)	Transportation expenses (USD)
Irbid Ring Road	No	795,876.00	77,928.00
Umari - Azraq Highway (Saudi Borders)	No	1,577,256.00	105,073.00
Amman Development Corridor	No	728,156.00	73,166.00
Amman BRT	Yes	270,458.00	14,638.00
As Salt Ring Road	Yes	199,908.00	15,536.00
Amman-Aqaba Kings Highway (Desert Rd.)	Yes	2,422,810.00	41,971.00

From Table 7.3, the surveying cost for projects without using mobile mapping is calculated to be \$3,101,257.68 compared to \$2,893,176.07 for the ones with mobile mapping. This shows a benefit or reduction in the cost of surveying equal to \$208,081.61. Similarly, the benefit measured in the cost of transportation is equal to \$184,022.06. Table 7.4 summarizes the benefits of mobile mapping for this case study.

Table 7.4: Summary of Mobile Mapping Benefits for five years

No.	Item	Present Value of Cash Flow (USD)
1	Total Projects Scan	152,570.00
2	Transportation Benefits	184,022.00
3	Surveying Benefits	208,082.00
4	Leasing of the device (avg/year)	5*(183,359.00)

Total Company Benefits	1,156,329.00
-------------------------------	---------------------

$$ROI = \frac{1,156,330 - 810,376}{810,376} * 100\% = 43\%$$

The ROI calculated using Equation 7.1 for our case study resulted in 43%. These calculations are based on the assumption that the device's useful life is five years. The leasing of the device helped the company overcome the high initial and customs costs and achieve a higher ROI.

7.5 Oregon State Mobile Mapping ROI

To compare the findings from the Jordanian case study, a similar project from Oregon DOT aimed to implement and measure the performance of mobile mapping technologies was investigated. The following sections briefly discuss the Oregon case study.

7.5.1 Mobile Mapping Expenses and Cost in Oregon DOT

The bulk of the expenses associated with asset inventory is labor and vehicle-related. Through mobile mapping for assets, inventory might cut down the number of hours that crews spend on the road collecting these inventories, reducing labor, fuel, and vehicle maintenance costs. However, since mobile mapping cannot fully replace on-the-ground asset structural integrity assessments, certain fieldwork hours will be essential. Likewise, utilizing mobile mapping will almost undoubtedly demand more office hours. Ultimately, however, it is likely that mobile mapping will reduce overall labor hours for all asset inventories. Finally, enhanced reliability and collaboration from a centralized point cloud of assets would likely benefit ODOT by making data more accessible and shareable. This improved usability and ease of access to all

data in one place. Cost-wise, it was divided into direct and indirect ROI by calculating the inflation rate and the 5-year project life-cycle returns.

Table 7.5 shows the initial cost flow followed by the annual cash flow for the prospected life-cycle of five years. Acquisition costs are the upfront purchase costs of the equipment and software required for mobile mapping. These are one-time costs with a useful life of 5 years. Deployment costs are mobile mapping equipment and software maintenance and operation costs. These are annual costs with a useful life of one year. All agency costs for mobile mapping were annualized across the technology’s 5-year useful life.

Table 7.5. Summary of Mobile Mapping Costs for Oregon State Case Study (Sillars et al. 2017)

	Present Value of Cash Flow	Yr 1	Yr 2	Yr 3	Yr 4	Yr5
Acquisition Cost						
Purchase Price (Pegasus: two)	\$749,800	\$163,722	\$163,722	\$163,722	\$163,722	\$163,722
WorkStations	\$16,538	\$3,611	\$3,611	\$3,611	\$3,611	\$3,611
Dell Precision Scan processors	\$5,764	\$1,259	\$1,259	\$1,259	\$1,259	\$1,259
Virtual Geomatics LiDAR Explorer	\$46,500	\$10,153	\$10,153	\$10,153	\$10,153	\$10,153
Mobile LiDAR Company Training	\$17,289	\$3,775	\$3,775	\$3,775	\$3,775	\$3,775
Deployment Cost						
Software Maintenance	\$254,432	\$53,337	\$54,457	\$55,601	\$56,768	\$57,960
Technical Software Support	\$210,554	\$44,139	\$45,066	\$46,012	\$46,978	\$47,965
Calibration and Tune Up	\$97,409	\$20,420	\$20,849	\$21,287	\$21,734	\$22,190
Total Agency Cost	\$1,398,286	\$300,416	\$302,892	\$305,420	\$308,001	\$310,636

The Pegasus: Two mobile mapper was the most costly acquisition cost for mobile mapping. The Pegasus: Two had an initial purchase price of \$749,800. The portable sensor platform, the 2015 GMC Yukon vehicle upon which the mobile sensor is mounted, software, and initial ODOT scanning training were all included. The cost of this upgrade is not included in the agency's mobile mapping acquisition expenses. In addition, three computer workstations for \$16,538 were purchased. Each workstation is fitted with a high computer desktop that can process mobile mapping data.

ODOT employees underwent initial training on using mobile mapping software from the Mobile LiDAR company. The cost of this training is \$24,565, and the price of the software. The data storage system currently used for mobile mapping was purchased for \$11,528 along with the Topcom IP-S2 and is not included in this analysis. However, this system is old and overloaded, and it will need to be upgraded shortly.

In addition to the financial acquisition costs, ODOT has annual deployment costs for mobile mapping. It is expected that deployment costs will increase each year due to inflation. Therefore, deployment costs were adjusted for inflation using the Equation below, where n represents the year.

$$\textit{Adjusted deployment cost} = \textit{Annual deployment cost} * (1 + \textit{inflation rate})^n$$

The annual maintenance cost for the Virtual Geomatics LiDAR Software was determined to be \$52,240 without adjusting for inflation. ODOT receives quarterly upgrades to the Leica software used for mobile mapping. The cost of these upgrades is included in ODOT's software maintenance agreement with Leica. This agreement does not cover technical support of the software, which costs \$43,231 annually, without adjusting for inflation. In 2016, ODOT's mobile

mapping hardware and software had not required the previous calibration and tune-up. This calibration and tune-up were estimated at \$20,000 based on annual service averages for similar software before adjusting for inflation as a future annual cost.

The total agency costs for mobile mapping were calculated as the acquisition and deployment cost sum. The net present value of the total agency costs was \$1,398,286. The annualized cost of the technology was \$300,416 in Year 1 and increased to \$310,636 in Year 5 due to inflation.

7.5.2 Oregon State Mobile Mapping Benefits

The overall benefits of survey for design can be divided into two categories: 1) surveying benefits; and 2) transportation benefits. In addition, due to its agency-wide character, the statewide mobile scan is separated as a “global” cost (or negative benefit). A summary of ODOT benefits of mobile mapping in the survey for design is shown in Table 7.6.

Table 7.6. Summary of Mobile Mapping Benefits for Oregon State Case Study (Sillars et al., 2017)

	Annual Cash Flow					
	Present Value of Cash Flow	Yr1	Yr 2	Yr 3	Yr4	Yr5
Geometronics Statewide Mobile Mapping Scan						
Total Statewide Scan	(\$595,401)	\$0	(\$160,000)	(\$163,360)	(\$166,791)	(\$170,293)
Transportation Benefits	\$2,290,438	\$476,256	\$491,247	\$501,563	\$512,096	\$522,850
Preservation projects are limited to non-structural applications	\$132,572	\$26,057	\$28,828	\$29,433	\$30,051	\$30,682
Surveying Benefits	\$2,641,940	\$551,907	\$565,967	\$577,853	\$589,987	\$602,377
Total ODOT Benefits	\$4,778,171	\$1,118,245	\$992,272	\$1,013,110	\$1,034,385	\$1,056,107

Each of the benefits was calculated separately by region to adjust for regional differences, given the size and project scope differences, and then aggregated for a composite agency evaluation. The amounts were calculated assuming that survey crews are located at regional technical centers and dispatched from the technical center closest to the project. It was also believed that survey crews do not work on projects outside of their region. The mobile mapping ROI for the case study in Oregon DOT is 242% (Sillars et al., 2017).

7.6 Discussion of Case Study Findings

The results show that the ROI from the case study in Jordan is much lower than that of Oregon DOT (43% vs. 242%) for the mapping technology. There are several factors that affect the costs and benefits related to calculating ROI. First, the use of mobile mapping technologies tends to reduce the number of workers, hence, lower labor costs. Because the labor cost in Jordan is much cheaper than that in the USA. Thus, the benefits or reduction in labor work will not play a significant role in the use of technology in Jordan. Another factor that played a role in the big gap in the two case studies is the transportation benefits. Jordan is a small country. Therefore, the savings on transportation is not significant compared to the case study in ODOT. The small scale of transportation benefits in Jordan leads to reducing the ROI.

7.7 Conclusion

Evaluation of technologies varies widely among state DOTs. Most state DOTs do not have a formal cost-benefit analysis approach to the evaluation of inspection technologies. Rather, state DOT often uses pilot projects and anecdotal approaches to evaluate new technologies. The main evaluation metrics used by state DOTs to evaluate the use of technologies for highway inspection

include efficiencies gained when using technologies, improving project quality, and the ability to overcome limited inspection resources. Most state DOTs noted that there is not enough information to perform return on investment (ROI) to evaluate the use of technologies for highway inspection.

This chapter also presents the result of ROI for a specific case study in Jordan. The result shows that although mobile mapping technologies help the construction firm improve accuracy and effectively manage transportation systems, the ROI of this case study is not as high as that of technology used in Oregon DOT. It is evident that Jordan needs arduous work and substantial governmental support to implement various technologies in projects to enhance the quality of work and raise production.

CHAPTER 8 : SUMMARY AND CONCLUSION

8.1 Summary

Highway infrastructure inspection is critical in any transportation system. With the latest technological advancements, the inspection landscape has been rapidly changing through the incorporation of technologies. This dissertation aims to examine the benefits of the various technologies used by DOTs to inspect highway infrastructure during the construction and maintenance of assets. As the research evolved, case studies were reviewed and examined to provide an accurate overview regarding the use of technology in highway construction in the US compared to other sides of the globe by comparing the ROI in a developed country (USA) to that in a developing country (Jordan). It was noticed that developing countries are striving and competing against time to follow up with the developed countries in terms of technology usage and understanding the technology fundamentals. Therefore, data accuracy and many areas were covered by breaking down the current technology usage scene into small fragments. It showed the importance of ROI metrics, the learning curve, and the educational journey for the technology users. Additionally, it was shown how the technology had an immersive impact on productivity and the project's timeline. It played a significant role in deciding whether it is a successful technological implementation or not by measuring all the previous factors.

The research methodology of this study includes a literature review, national survey, interviews, and case studies. The key findings from this study are summarized below.

- GNSS and GPS are the most common geospatial technologies used for inspection of highway infrastructure during the construction and maintenance of assets. For

construction inspection, GNSS and GPS technologies are mostly used for earthwork inspection and quantities, verification and document of work complete, and collecting as-built information. For inspection of existing highway assets, GNSS and GPS technologies are mostly used for inventories and inspection of signage, culvert, guardrail and other highway assets.

- E-ticketing is increasingly used to track the position of bulk materials such as concrete, asphalt, and aggregate loads for the inspection purposes of highway construction.
- State DOTs are increasingly using UASs for inspection of highway infrastructure during construction and maintenance of assets. UASs are mostly used for monitoring construction progress and capturing site photos.
- GIS is typically used in tandem with GNSS/GPS or other geospatial technologies to share asset information between different functional units.
- LiDAR and 3D laser scanning are often used for inspection of highway infrastructure during construction and maintenance of assets. For construction inspection, LiDAR and 3D laser scanning are typically used for collecting as-built information and developing 3D as-built models. For inspection of existing highway assets, LiDAR and 3D laser scanning are typically used for detecting pavement cracks and defects and slope stability and landslide assessment.
- State DOTs are increasingly used remote and infrared sensors for measuring material strength and temperature. Remote cameras are typically used for monitoring construction progress and capturing site photos and videos. 3D models and AMG are typically used for earthwork inspection and quantities for highway construction projects.
- For construction inspection, tablets and smartphones are typically used to verify and

document work completed for payment and to monitor construction progress. For inspection of existing highway assets, tablets and smartphones are typically used for inventories and inspection of signage, culvert, guardrail and other highway assets and for sharing asset information between different functional units.

- Handheld data collectors such as real-time kinematics are commonly used for inspection of highway infrastructure during construction and maintenance of assets. For construction inspection, handheld data collectors are typically used for monitoring construction progress, earthwork inspection and quantities, and enhancing quality control and quality assurance activities. For inspection of existing highway assets, handheld data collectors are typically used for inventories and inspection of signage, culvert, guardrail, and other highway assets.
- The main challenges in implementing technologies for inspection of highway infrastructure during construction and maintenance of assets include cost issues; lack of training, knowledge, and skills to use technologies; and requirements for device maintenance and user support.
- The main performance metrics used by state DOTs to evaluate the use of technologies for highway inspection include efficiencies gained when using technologies; improving project quality; and the ability to overcome limited inspection resources.
- Most state DOTs noted that there is not enough information to perform cost-benefit analysis and ROI to evaluate the use of technologies for highway inspection.
- The main driving factors for using inspection technologies are to enhance inspectors' safety, improve efficiency, and enhance staffing (e.g., using mobile devices and software applications reduces the need for inspection staff).

8.2 Conclusion

Various technologies exist that convey efficient approaches for completing specific tasks and assignments. Emerging new and innovative technologies are changing how state DOTs deliver, inspect and maintain their highway construction projects. In particular, with the latest technological advancements, the inspection landscape has been rapidly changing through the incorporation of technologies. The following conclusions may help the industry better understand how to implement technologies for highway infrastructure inspection.

- Maintaining technologies and associated equipment and keeping the software application up to date is critical to ensure that inspectors can perform their work correctly and efficiently. Additionally, it is important that technologies used for highway inspection be compatible with other devices used by DOT inspectors, contractors, and consultant inspectors.
- Training plays an important role in overcoming challenges in the transition from comfortable /traditional inspection approaches to tech-based inspection approaches. The staff inspectors and end-users of the technology must be trained properly and have a buy-in of the implementation process. It is important to offer training to employees regularly to learn the technology as well as refresher training to keep inspectors up to date. Participation in webinars, presentations, and peer exchanges provides ample opportunities to share experience in the implementation of technology.
- It is challenging for state DOTs to keep up with the rapidly changing hardware and software of technology. It was noted that technology evolution will not stop to allow a DOT to catch up and that a mindset of continuous improvement is needed to stay current

with technologies and the potential value they can provide. Thus, it is essential to enhance coordination across the departments to collect and share pertinent information collected from technologies.

- It is important to consult with contractors and consultants to identify and evaluate appropriate inspection technologies. Partnership, communication, and collaboration with the industry are vital to the implementation of inspection technologies.
- It is important to gain leadership support to implement technologies for highway inspection. This support is necessary to overcome initial barriers or to back the cost of implementing the innovation.
- Evaluation of technologies varies. It is challenging to develop a formal cost-benefit analysis approach to the evaluation of inspection technologies. As shown in the case study and comparison, implementing the same technology in two different areas can have a drastically different ROI due to the various factors playing a role in the implementation process.

8.3 Contribution

The findings from this study contribute to both theory and practice. Specifically, this study is one of the first attempts to investigate the use of technologies for highway infrastructure inspection in the construction and asset management phases. The findings from this study may contribute to the construction body of knowledge by adding new information on the implementation of three technology areas (geospatial technologies, remote sensing and monitoring technologies, and mobile devices and software applications) for the highway inspection process. For practitioners, the use of different technologies associated with various inspection activities may help identify the

proper tool and techniques when given specific projects or inspection of existing assets. Additionally, the effect of the implementation of environmental factors on ROI has been shown and illustrated in this dissertation.

8.4 Limitations

There are several limitations of this study. The main limitations are:

- Lack of technical knowledge from some respondents: some are not aware of the technical part of using the technology, and they may not have enough experience using it to assess it accurately.
- Lack of technology availability: Some technologies were unavailable due to budget allocation or state regulations.
- It is noted that there is a blurred boundary among these four technology areas. As a result, most technologies can be classified in more than one area. For example, some technologies in the geospatial technology area are also used as remote sensing technologies or within mobile devices. Similarly, nondestructive evaluation methods are often developed and used along with remote sensing devices.

8.5 Future Work

To promote the effective use of technologies for inspection of highway infrastructure during construction and maintenance of assets, future research is suggested in the following areas:

- Barriers of automation and technological transformation in highway projects: Study the factors holding back the adaptation of inspection technologies in highway construction projects and the possible criteria that can be implemented to overcome the barriers.

- Many state DOTs have lost experienced construction inspection staff while the number of projects is increased with a high level of inspection required. One of the strategies to address this challenge is to employ inspection technologies. However, there is a lack of understanding and guidance on how inspection technologies can effectively use to offset the limited inspection resources. Future research is needed to develop a framework to empirically investigate the relationships between inspection technologies and the allocation of inspection resources during construction and asset management.
- Tracking benefit-cost analysis and performing return on investment are essential to evaluate the effectiveness of the technology implementation. However, most state DOTs, if not all, do not have a formal framework to perform quantitative return on investment analysis when investigating the value of technology for inspections. Future research is suggested to develop guidance on conducting benefit-cost analysis and a return on investment of inspection technologies for highway infrastructure. The guidance will also provide the value of using technologies in comparison with the value of traditional means used for inspections.

REFERENCES

- Alizadehsalehi, S., Yitmen, I., Celik, T., & Arditi, D. (2018). The effectiveness of an integrated BIM/UAV model in managing safety on construction sites. *International Journal of Occupational Safety and Ergonomics*, DOI: 10.1080/10803548.2018.1504487
- Azar, E. R., & Kamat, V. R. (2017). Earthmoving equipment automation: A review of technical advances and future outlook. *Journal of Information Technology in Construction*, 22, 247-265.
- Baron, W., & DaSilva, M. (2019). *Using an unmanned aerial vehicle to produce accurate grade crossing profile data (Report No. DOT-VNTSC-FRA-20-02)*. U.S. Department of Transportation.
- Brooks, C., Dobson, R., Banach, D., Dean, D., Oommen, T., Wolf, R., Havens, T., Ahlborn, T., & Hart, B. (2015). *Evaluating the use of unmanned aerial vehicles for transportation purposes*. Michigan Department of Transportation.
- Burgett, J. M., Bausman, D. C., & Commert, G. (2019). *Unmanned aircraft systems impact on operational efficiency and connectivity (Project C2M2 No. 1)*. South Carolina Department of Transportation.
- Castro-Martínez, R. E., Jang, S., Kim, J., & Wentworth, A. (2019). Experimental evaluation of a low-cost RFID-based sensor to crack propagation. *Journal of Aerospace Engineering*, 32(2), 04019003.
- Chiang K. W., Tsai G. J., & Zeng J. C. (2021) Mobile mapping technologies. In W. Shi, M. F. Goodchild, M. Batty, M. P. Kwan, & A. Zhang (Eds.), *Urban Informatics. The Urban Book Series*. Springer. https://doi.org/10.1007/978-981-15-8983-6_25

- Cho, Y. K. (2019). *Assessment of construction points for grade control and reference in 3D* (Report No. FHWA-GA-19-1618). Georgia Department of Transportation.
- Conver, J. (2019). *Unmanned aerial systems: Construction research project*. Montana Department of Transportation.
- Dadi, G. B., Sturgill, R. E., Jr., Patel, D., Van Dyke, C., & Mulder, G. (2020). *Electronic ticketing of materials for construction management (NCHRP Synthesis 545)*. Transportation Research Board.
- Darby, P., & Gopu, V. J. (2018). *Bridge inspecting with unmanned aerial vehicles, R&D*. U.S. Department of Transportation.
- Darby, K. (2015). *Quantitative cost-benefit analyses of the use of automated machine guidance in construction: An examination of current practice. Preliminary investigation*. Caltrans Division of Research, Innovation and System Information.
- de Melo, R. R. S., Costa, D. B., Álvares, J. S., & Irizarry, J. (2017). Applicability of unmanned aerial system (UAS) for safety inspection on construction sites. *Safety Science*, 98, 174-185.
- Domdouzis, D., Kumar, B., & Anumba, C. (2007). Radio-frequency identification (RFID) applications: A brief introduction. *Advanced Engineering Informatics*, 21, 350-355.
- Dorafshan, S., Maguire, M., Hoffer, N. V., Coopmans, C., & Thomas, R. J. (2017). *Unmanned aerial vehicle augmented bridge inspection feasibility study (Report No. CAIT-UTC-NC31)*. U.S. Department of Transportation.
- Dorafshan, S., & Maguire, M. (2018). Bridge inspection: human performance, unmanned aerial systems and automation. *Journal of Civil Structural Health Monitoring*, 8, 443-476.

- Duque, L., Seo, J., & Wacker, J. (2018). Synthesis of unmanned aerial vehicle applications for infrastructures. *Journal of Performance of Constructed Facilities*, 32(4), 04018046.
- El-Gohary, N., El-Rayes, K., Liu, L.Y., Golparvar-Fard, M., & Zhang, R. (2017). *ICT Project R27-163: Adapting Construction Staking to Modern Technology (Report No. FHWA-ICT-17-015)*. Illinois Department of Transportation.
- Federal Highway Administration (FHWA). (2020). *Nondestructive Evaluation Program Strategic Plan for FY 2019-2020, Publication Number: FHWA-HRT-20-045*. U.S. Department of Transportation.
- FHWA. (2019). *Every Day Counts: An Innovation Partnership With States —EDC-4 Final Report*. U.S. Department of Transportation.
- FHWA. (2018). *e-Construction and partnering: A vision for the future -- Peer-to-peer exchange. Indiana, Oregon, Pennsylvania, Utah, and Wisconsin Departments of Transportation (Report No. FHWA-HIF-19-004)*. U.S. Department of Transportation.
- FHWA. (2017a). *Specification for intelligent compaction: A review on national and state specifications (Technical Brief No. FHWA-HIF-17-037)*. U.S. Department of Transportation.
- FHWA. (2017b). *Utilizing 3D digital design data in highway construction: Case studies*. U.S. Department of Transportation.
- FHWA. (2014). *Automated machine guidance with use of 3D models: The use of automated machine guidance on the Florida SR 417 lane widening project (Tech Brief No. FHWA-HIF-13-055)*. U.S. Department of Transportation.
- FHWA. (2013a). *Automated machine guidance with use of 3D Models: Executive summary (Tech Brief No. FHWA-HIF-13-054)*. U.S. Department of Transportation.

- FHWA. (2013b), *Intelligent compaction: Executive summary*. U.S. Department of Transportation.
- FHWA. (2011). *Accelerated implementation of intelligent compaction technology for embankment sub grade soils, aggregate base, and asphalt pavement materials (FHWA-IF-12-002)*. U.S. Department of Transportation.
- Gautreau, G. P., Abu-Farsakh, M., & Cooper, S., III, (2016). *Field evaluation of roller integrated intelligent compaction monitoring (Report No. FHWA/LA.15/555)*. Louisiana Department of Transportation and Development.
- Gillins, D. T., Parrish, C. E., & Gillins, M. N. (2016). *Cost-effective bridge safety inspections using unmanned aerial vehicles (UAVs)*. U.S. Department of Transportation.
- Gillins, D. T., Parrish, C., Gillins, M. N., & Simpson, C. (2018). *Eyes in the sky: Bridge inspections with unmanned aerial vehicles (Report No. FHWA-OR-RD-18-11)*. Oregon Department of Transportation.
- Goulias, D., & Scott, M. (2015). *Effective implementation of ground penetrating radar (GPR) for condition assessment & monitoring of critical infrastructure components of bridges and highways*. Maryland State Highway Administration.
- Ham, Y., Han, K. K., Lin, J. J., & Golpavar-Fard, M. (2016). Visual monitoring of civil infrastructures via camera-equipped unmanned aerial vehicles (UAVs): A review of related works. *Visualization in Engineering*, 4(1), 1.
- Holsti, O. R. (1969). *Content Analysis for the Social Sciences and Humanities*. Addison-Wesley Publishing.
- Hubbard, B., & Hubbard, S. (2020a). Opportunities for transportation departments to leverage construction UAS data. Proceedings of the Creative Construction e-Conference, 20-26.

- Hubbard, B., & Hubbard, S. (2020b). Unmanned aircraft systems (UAS) for bridge inspection safety. *Drones*, 4, 40.
- Iacovidou, E., Purnell, P., & Lim, M. K. (2017). The use of smart technologies in enabling construction components reuse: A viable method or a problem creating a solution? *Journal of Environmental Management*, 216, 214-223.
- Icenogle, P. J., Kabir, S. M., King, W. Jr., & Abadie, C. D. (2013). Automation of asphalt truck delivery ticket using barcode technology. Transportation Research Board 92nd Annual Meeting. Washington, D.C., 13-17 January 2013.
- IP-S3. Topcon Positioning Systems, Inc. (2021, October 20). Retrieved February 21, 2022, from <https://www.topconpositioning.com/scanning/mobile-mapping/ip-s3>
- Irizarry, J., & Johnson, E. N. (2019). *Field-test-based guideline development for the integration of unmanned aerial systems (UASs) in GDOT operations*. Georgia Department of Transportation.
- Jackson, J., Saborio, R., Ghazanfar, S.A., Gebre-Egziabher, D., & Davis, B. (2018). *Evaluation of low-cost, centimeter-level accuracy OEM GNSS receivers (Report No. MN/RC 2018-10)*. Minnesota Department of Transportation.
- Jaselskis, E. J., Anderson, M. R., Jahren, C. T., Rodriguez, Y., & Njos, S. (1995). Radio-frequency identification applications in construction industry. *Journal of Construction Engineering and Management*, 121(2), 189-196.
- Jirik, T., & Harrington-Hughes, K. (2007). *Research opportunities in radio frequency identification transportation applications*. Transportation Research Board.
- Korzilius, J., Symanietz, G., Malsczycki, M., & Kuehl, R. (2019). *Validation of electronic truck delivery ticketing of HMA material*. National Road Research Alliance.

- Lee, H. W., Harapanahalli, B. A., Nnaji, C., Kim, J., & Gambatese, J. (2018). Feasibility of using QR codes in highway construction document management. *Transportation Research Record*, 2672(26), 114-123
- Lee, H.W., Harapanahalli, B. A. (2015). *Investigating the feasibility of using quick response codes in highway construction for document control (Report No. 2013-S-OSU-37)*. Pacific Northwest Transportation Consortium.
- Lee, J. H., & McCullouch, B. (2008). *Automating material delivery records (Report No. FHWA/IN/JTRP-2007/26)*. Purdue University.
- Leica Geosystems. (n.d.). Leica Pegasus: Two mobile sensor platform. Retrieved February 21, 2022, from https://leica-geosystems.com/en-us/products/mobile-mapping-systems/capture-platforms/leica-pegasus_two .
- Lercel, D., Steckel, R., & Pestka, J. (2018). *Unmanned aircraft systems: An overview of strategies and opportunities for Missouri (Report Nol. cmr 18-009)*. Missouri Department of Transportation.
- Li, N., Becerik-Gerber, B. 2011. Life-cycle approach for implementing RFID technology in construction: learning from academic and industry use cases. *Journal of Construction Engineering and Management*, 137(12), 1089-1098.
- Lin, Z., Pan, H., Wang, X., & Li, M. (2019). *Improved element-level bridge inspection criteria for better bridge management and preservation (Report No. MPC 19-403)*. U.S. Department of Transportation.
- Lodgher, A., Perkins, J. A., Yang, Y., Jones, E., & Hawkins, H. G., Jr. (2010). *Feasibility and applications of RFID technologies to support right-of-way functions: Technical report (Report No. FHWA/TX-10/0-6142-1)*. Texas Department of Transportation.

- Maier, F., Mallela, J., Torres, H. N., Ruiz, J. M., & Chang, G. K. (2018). *Automation in highway construction part II: Design guidance and guide specification manual (Report No. FHWA-HRT-16-031)*. Federal Highway Administration.
- Maier, F., Chummers, L. E., Pulikanti, S., Struthers, J. Q., Mallela, J., Morgan, R. H. (2017). *Utilizing 3D digital design data in highway construction: Case studies (Report No. FHWA-HIF-17-027)*. Federal Highway Administration.
- Mallela, J., Mitchell, A., Gustafson, J., Olsen, M., Parrish, C., Gillins, D., Kumpula, M., & Roe, G. (2018). *Effective use of geospatial tools in highway construction (Report No. FHWA-HIF-19-089)*. Federal Highway Administration.
- Mardapour, P., & Mehrabi, A. (2019). *Principal and considerations for design of small unmanned aerial vehicles for inspection and survey (Report No. ABC-UTC-2013-C3-FIU05)*. Accelerated Bridge Construction University Transportation Center.
- McCloud, D. (2020). E-ticketing accelerates on road projects as DOTs ban paper; app services offered at no cost. *Equipment World's Better Roads*. Retrieved from <https://www.equipmentworld.com/coronavirus-e-ticketing-road-projects-dots/>. Accessed 13 October 2020.
- McGuire, M., Rys, M., & Rys, A. (2016). *A study of how unmanned aircraft systems can support the Kansas Department of Transportation's efforts to improve efficiency, safety, and cost reduction (Report No. K-TRAN: KSU-15-3)*. Kansas Department of Transportation.
- Minnesota Department of Employee Relations (n.d.). *Strategic Staffing Guidebook*.
- Moreu, F., Injante, M., Maharjan, D., Shelton, P., Glisic, G., & Mascarenas, D. (2018). *TRB straight to recording for all: Augmented reality for structural inspections*. Transportation Research Board.

- Moselhi, O., & El-Omari, S. (2006.) Integrating bar coding and RFID to automate data collection from construction sites. *Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, 1734-1741.
- National Asphalt Pavement Association (2020). *E-ticketing synopsis*.
- Neuendorf, K. A. (2002). *The Content Analysis Guidebook*. SAGE Publications.
- Nikolow, P. (2012). "1D, 2D, & 3D Barcodes." Retrieved from <http://www.mobiliodevelopment.com/1d-2d-3d-barcodes/>. Accessed 31 May 2021.
- Otero, L. D., Gagliardo, N., Dalli, D., Huang, W. H., & Cosentino, P. (2015). *Proof of concept for using unmanned aerial vehicles for high mast pole and bridge inspections*. Florida Department of Transportation.
- Peoples, C. A. (2018). RFID asset tracking: Materials & tests unit. Annual Virginia Concrete Conference. Richmond, Virginia, 1-2 March 2018.
- Perez, M. A., Zech, W. C., & Donald, W.N. (2015). Using unmanned aerial vehicles to conduct site inspections of erosion and sediment control practices and track project progression. *Transportation Research Record*, 2528(1), 38-48.
- Qiao, F., Yu, L., Zhang, R., Chen, Z., & Fatholahzadeh, R. (2009). *RFID applications in transportation operation and intelligent transportation systems (Report No. SWUTC/09/476660-00044-1)*. Southwest Region University Transportation Center.
- Reeder G. D. & Nelson G. A. (2015). Implementation manual 3D engineered models for highway construction: The Iowa Experience.
- Resh, M. (2020). Asphalt delivery tracking goes digital with some 2020 construction projects. *Crossroads: Minnesota's transportation research blog*. Retrieved from

<https://mntransportationresearch.org/2020/06/11/asphalt-delivery-tracking-goes-digital-with-some-2020-construction-projects/>.

Scherer, S. (2019). *Aerial contact sensing for improved inspection of transportation infrastructure*. U.S. Department of Transportation.

Shehab, T., Moselhi, O., & Nasr, E. (2009). Barcode-assisted system for document management of construction projects. *International Journal of Construction Education and Research*, 5(1), 45-60.

Shepard, L. (2017). *e-Ticketing in Iowa* [PowerPoint Slides]. Retrieved from https://www.fhwa.dot.gov/construction/econstruction/peer_exchange/edc3peer.cfm. Accessed 18 May 2019.

SHRP2. (2009). Nondestructive testing technologies for concrete bridge decks (R06A) Presentation.

SHRP2 R06C. (2018). Technology to enhance quality control on asphalt pavements: Paver mounted thermal profiler, FHWA webinar slides, http://shrp2.transportation.org/Pages/R06C_RapidTechnologiestoEnhanceQualityControl.aspx, accessed on June 10, 2021.

Sicaras, V. K. (2020). Producer, state DOT embrace e-ticketing pilot for paving project. *Concrete Products*, July 2020, 10-11.

Sillars, D. N., Ng, E. H., Calvo-Amodio, J., Capalbo, S., Martin, M. A., Jahanger, Q. K., Zimmerman, G., Hadziomerspahic, A., Wang, S., & Elatlassi, R. (2017). Advanced technology: Return on investment at the Oregon Department of Transportation, PROJECT 30530-16-14.

- Snyder, K., & Zajowski, T. (2016). *Unmanned aircraft systems: A new tool for DOT Inspections (Report No. 2016-2)*. North Carolina Department of Transportation.
- Sreenath, S., Malik, H., Husnu, N., & Kalaichelavan, K. Assessment and use of unmanned aerial vehicle for civil structural health monitoring. *Procedia Computer Science*, 170, 656-663.
- Sturgill, R. E., Dadi, G. B., Van Dyke, C., Patel, D., Withrow, J., & Newcomer, C. (2019). *E-ticketing and advanced technologies for efficient construction inspections (Report No. KTC-19-14/SPR18-554-1F)*. Kentucky Transportation Cabinet.
- Sullivan, J. L., O'Neill-Dunne, J., & McFaden, S. (2016). *Using remote collection to identify bridges and culverts susceptible to blockage during flooding events (Report No. TRC Report 16-003)*. Vermont Transportation Research Center.
- Tomiczek, A. P., Whitley, T. J., Bridge, J. A., & Ifju, P. G. (2019). Bridge inspections with small unmanned aircraft systems: case studies. *Journal of Bridge Engineering*, 24(4) 05019003.
- Torres, H. N., Ruiz, J. M., Chang, G. K., Anderson, J. L., & Garber, S. I. (2018). *Automation in highway construction part I: Implementation challenges at state transportation departments and success stories* (No. FHWA-HRT-16-030). United States Federal Highway Administration Office of Infrastructure Research and Development.
- Trimble MX9. Trimble MX9 | Mobile Mapping | Trimble Geospatial. (n.d.). Retrieved February 21, 2022, from <https://www.geospatial.trimble.com/products-and-solutions/trimble-mx9>
- Tsai, Y., & Wang, Z. (2016). *A remote sensing and GIS-enabled highway asset management system (Report No. GA-15-1008)*. Georgia Department of Transportation.
- United States Department of Transportation (2018). *Roadside Safety Hardware Identification Methods*.
- Utah Department of Transportation. (2019). *Innovation & efficiencies report*.

- Valdes & Perdomo (2013). *Using mobile computers to automate the inspection process for highway construction projects*. University Transportation Research Center - Region 2.
- Valero, E., Adán, A., & Cerrada, C. (2014). Evolution of RFID applications in construction: A literature review. *Sensors, 15*, 15988-16008.
- Valero, E., & Adán, A. (2016). Integration of RFID with other technologies in construction. *Measurement, 94*, 614-620.
- Vennapusa, P. K. R., White, D. J., & Jahren, C. T. (2015). Impacts of automated machine guidance on earthwork operations. *Civil, Construction and Environmental Engineering Conference Presentations and Proceedings, 34*.
- Vonderohe, A., & Hintz, C. (2010). *3D design terrain models for construction plans and GPS control of highway construction equipment (Report No. CFIRE 02-05)*. U.S. Department of Transportation.
- von Ellenrieder, K., & Wampler, J. (2016). *Unmanned surface vessel (USV) systems for bridge inspection*. Florida Department of Transportation.
- Wells, J., & Lovelace, B. (2018). *Improving the quality of bridge inspections using unmanned aircraft systems (UAS) (Report No. MN/RC 2018-26)*. Minnesota Department of Transportation.
- Wells, J., & Lovelace, B. (2017). *Unmanned aircraft system bridge inspection demonstration project phase II final report (Report No. MN/RC 2017-18)*. Minnesota Department of Transportation.
- White, D., Jahren, C., Vennapusa, P., Westort, C., Alhasan, A., Turkan, Y., Guo, F., Hannon, J., Dubree, A., & Sulbaran, T. (2018). *Use of automated machine guidance within the*

transportation industry (NCHRP Web-Only Document 250). Transportation Research Board.

Yin, R. K. (2009). *Case study research: Design and methods*. SAGE Publications.

Yu, T. (2016). *Quantitative sensing of bridges, railways, and tunnels with autonomous unmanned aerial vehicles*. U.S. Department of Transportation.

Zhou, S., & Gheisari, M. (2018). Unmanned aerial system applications in construction: A systematic review. *Construction Innovation*, 18(4), 453-468.

Zink, J., & Lovelace, B. (2015). *Unmanned aerial vehicle bridge inspection demonstration project (Report No. MN/RC 2015-40)*. Minnesota Department of Transportation.

APPENDIX A : SURVEY QUESTIONNAIRE

GENERAL INFORMATION

1. Please provide the following contact information:

First Name:

Last Name:

Phone Number:

E-mail:

Agency/State in which
you are employed:

2. What group/division do you primarily work in? (Please check all that apply)

Construction

Materials

Asset Management

Contracts/procurement

Engineering Design

Maintenance/Operations

Research

Other: _____

3. Which of the following technologies has been used by your agency to inspect highway infrastructure during construction or maintenance of assets? (Please check all that apply).

- Geospatial Technologies
- Remote sensing & Monitoring Technologies
- Mobile Devices & Software Applications
- Nondestructive Evaluation Methods
- None of the above

GEOSPATIAL TECHNOLOGIES

4. Approximately, how many years has your agency been using *Geospatial Technologies* to inspect highway infrastructure **during construction or maintenance** of assets?

- < 2 years
- 2 – 5 years
- 5-10 years
- > 10 years

5. Which of the following *geospatial technologies* has been used by your agency to inspect highway infrastructure **during construction or maintenance** of assets? (Please check all that apply)

Geospatial Technologies	Construction	Maintenance	Not Sure
Global Navigation Satellite Systems (GNSS)/ Global Positioning System (GPS)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Geographic Information Systems (GIS)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Unmanned Aircraft Systems (UAS) (<i>Note: UAS is also a remote sensing technology</i>)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Robotic Total Stations (RTS)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Terrestrial Photogrammetry (TP)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
e-Ticketing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other, please specify: _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

6. How are *geospatial technologies* used to inspect highway infrastructure **during construction** in your agency? (Please only respond to the technologies used in your agency and check all that apply)

Geospatial Technologies	GPS/ GNSS	GIS	UAS	RTS	TP	e- Ticket	Not Sure
Tracking position of bulk material (concrete, asphalt, aggregate loads)	<input type="checkbox"/>						
Tracking of finished materials and inventory (pipe, rebar, etc.)	<input type="checkbox"/>						
Measurement of material strength and temperature (concrete, base course, etc.)	<input type="checkbox"/>						
Measurement of pavement thickness	<input type="checkbox"/>						
Earthwork inspection and quantities	<input type="checkbox"/>						
Structural inspection and quantities	<input type="checkbox"/>						

Monitoring construction progress	<input type="checkbox"/>						
Verification and documentation of work completed for payment	<input type="checkbox"/>						
Locating underground utilities and underground assets	<input type="checkbox"/>						
Collecting as-built information/Developing 3D as-built models	<input type="checkbox"/>						
Quality control/Quality assurance	<input type="checkbox"/>						
Erosion control inspection	<input type="checkbox"/>						
Site photos & videos	<input type="checkbox"/>						
Other (please specify): _____	<input type="checkbox"/>						

7. How are *geospatial technologies* used to inspect highway infrastructure **during maintenance** of assets in your agency? (Please only respond to the technologies used in your agency and check all that apply)

Geospatial Technologies	GPS/ GNSS	GIS	UAS	RTS	TP	e- Ticket	Not Sure
Location of pavement/ material placement for performance tracking	<input type="checkbox"/>						
Signage, culvert, guardrail& other asset inventories and inspection	<input type="checkbox"/>						

Sharing asset information between different functional units	<input type="checkbox"/>						
Pavement crack and defect detection	<input type="checkbox"/>						
Structural inspection	<input type="checkbox"/>						
Slope stability & landslide assessment	<input type="checkbox"/>						
Location of voids/ buried assets	<input type="checkbox"/>						
Other (please specify): _____	<input type="checkbox"/>						

8. What are the **main factors** holding back the use of *geospatial technologies* for inspection **during construction or maintenance** of assets in your agency? (Please check all that apply).

- Cost issues
- Insufficient agency network levels, IT infrastructure/cellular service
- Access, privacy, or security concerns
- Lack of standard contract specifications
- Incompatibility with (or restricted by) legal, regulatory, or policy requirements
- Lack of reliable internet connection in remote locations
- Incompatibility with existing hardware
- Lack of training, knowledge, and skills to use technologies
- Lack of technical results/case studies demonstrating accuracy
- Quality of data collected
- Device maintenance and user support

Resistance to change

Other (please specify): _____

REMOTE SENSING & MONITORING TECHNOLOGIES

9. Approximately, how many years has your agency been using *Remote Sensing and Monitoring Technologies* to inspect highway infrastructure **during construction or maintenance** of assets?

< 2 years

2 – 5 years

5-10 years

> 10 years

10. Which of the following *remote sensing and monitoring technologies* has been used to inspect highway infrastructure **during construction and maintenance** of assets? (Please check all that apply)

Remote Sensing & Monitoring Technologies	Construction	Maintenance	Not Sure
Light Detection and Ranging (LIDAR)/ 3D laser scanning	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Radio-frequency identification (RFID)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Intelligent Compaction (IC)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Remote Sensors (e.g., accelerometers, maturity meter sensors, strain gauges, etc.) (RS)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Infrared sensors (e.g., thermal, motion detectors, object detection, thermal profiling) (IS)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Remote Cameras (RC)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Barcodes & Readers (B&R)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (please specify): _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

11. How are *remote sensing and monitoring technologies* used to inspect highway infrastructure **during construction** in your agency? (Please only respond to the technologies used in your agency and check all that apply)

Remote sensing & Monitoring Technologies	LiDAR	RFID	IC	RS	IS	RC	B&R	Not Sure
Tracking position of bulk material (concrete, asphalt, aggregate loads)	<input type="checkbox"/>							
Tracking of finished materials and inventory (pipe, rebar, etc.)	<input type="checkbox"/>							
Measurement of material strength and temperature (concrete, base course, etc.)	<input type="checkbox"/>							
Measurement of pavement thickness	<input type="checkbox"/>							
Earthwork inspection and quantities	<input type="checkbox"/>							
Structural inspection and quantities	<input type="checkbox"/>							
Monitoring construction progress	<input type="checkbox"/>							
Verification and documentation of work completed for payment	<input type="checkbox"/>							

Remote sensing & Monitoring Technologies	LiDAR	RFID	IC	RS	IS	RC	B&R	Not Sure
Locating underground utilities and underground assets	<input type="checkbox"/>							
Collecting as-built information/Developing 3D as-built models	<input type="checkbox"/>							
Quality control/Quality assurance	<input type="checkbox"/>							
Erosion control inspection	<input type="checkbox"/>							
Site photos & videos	<input type="checkbox"/>							
Other (please specify): _____	<input type="checkbox"/>							

12. How are *remote sensing and monitoring technologies* used to inspect highway infrastructure **during maintenance** of assets in your agency? (Please only respond to the technologies used in your agency and check all that apply)

Remote sensing & Monitoring Technologies	LiDAR	RFID	IC	RS	IS	RC	B&R	Not Sure
Location of pavement/ material placement for performance tracking	<input type="checkbox"/>							
Signage, culvert, guardrail& other asset inventories and inspection	<input type="checkbox"/>							
Sharing asset information between different functional units	<input type="checkbox"/>							
Pavement crack and defect detection	<input type="checkbox"/>							

Structural inspection	<input type="checkbox"/>							
Slope stability & landslide assessment	<input type="checkbox"/>							
Location of voids/ buried assets	<input type="checkbox"/>							
Other (please specify): _____	<input type="checkbox"/>							

13. What are the **main factors** holding back the use of *remote sensing and monitoring technologies* for inspection **during construction and maintenance** of assets in your agency? (Please check all that apply).

- Cost issues
- Insufficient agency network levels, IT infrastructure/cellular service
- Access, privacy, or security concerns
- Lack of standard contract specifications
- Incompatibility with (or restricted by) legal, regulatory, or policy requirements
- Lack of reliable internet connection in remote locations
- Incompatibility with existing hardware
- Lack of training, knowledge, and skills to use technologies
- Lack of technical results/case studies demonstrating accuracy
- Quality of data collected
- Device maintenance and user support
- Resistance to change
- Other (please specify): _____

MOBILE DEVICES & SOFTWARE APPLICATIONS

14. Approximately, how many years has your agency been using *mobile devices and software applications* to inspect highway infrastructure **during construction or maintenance** of assets?

- < 2 years
- 2 – 5 years
- 5-10 years
- > 10 years

15. Which of the following *mobile devices and software applications* has been used to inspect highway infrastructure **during construction and maintenance** of assets? (Please check all that apply).

Mobile Devices & Software Applications	Construction	Maintenance	Not Sure
3D Engineered Models/BIM (3D)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Automated Machine Guidance (AMG)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Tablet computers/smart phones (TS)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Handheld data collectors (e.g., Real-time Kinematics (RTK), Trimble Yuma) (HDC)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Virtual Reality/Augmented Reality (VR/AR)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (please specify): _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

16. How are *mobile devices and software applications* used to inspect highway infrastructure **during construction** in your agency? (Please only respond to the technologies used in your agency and check all that apply).

Mobile Devices & Software Applications	3D	AMG	TS	HDC	VR/AR	Not Sure
Tracking position of bulk material (concrete, asphalt, aggregate loads)	<input type="checkbox"/>					
Tracking of finished materials and inventory (pipe, rebar, etc.)	<input type="checkbox"/>					
Measurement of material strength and temperature (concrete, base course, etc.)	<input type="checkbox"/>					
Measurement of pavement thickness	<input type="checkbox"/>					
Earthwork inspection and quantities	<input type="checkbox"/>					
Structural inspection and quantities	<input type="checkbox"/>					
Monitoring construction progress	<input type="checkbox"/>					
Verification and documentation of work completed for payment	<input type="checkbox"/>					
Locating underground utilities and underground assets	<input type="checkbox"/>					
Collecting as-built information/Developing 3D as-built models	<input type="checkbox"/>					
Quality control/Quality assurance	<input type="checkbox"/>					
Erosion control inspection	<input type="checkbox"/>					
Site photos & videos	<input type="checkbox"/>					

Mobile Devices & Software Applications	3D	AMG	TS	HDC	VR/AR	Not Sure
Other (please specify): _____	<input type="checkbox"/>					

17. How are *mobile devices and software applications* used to inspect highway infrastructure **during maintenance** of assets in your agency? (Please only respond to the technologies used in your agency and check all that apply)

Mobile Devices & Software Applications	3D	AMG	TS	HDC	VR/AR	Not Sure
Location of pavement/ material placement for performance tracking	<input type="checkbox"/>	<input checked="" type="checkbox"/>				
Signage, culvert, guardrail& other asset inventories and inspection	<input type="checkbox"/>					
Sharing asset information between different functional units	<input type="checkbox"/>					
Pavement crack and defect detection	<input type="checkbox"/>					
Structural inspection	<input type="checkbox"/>					
Slope stability & landslide assessment	<input type="checkbox"/>					
Location of voids/ buried assets	<input type="checkbox"/>					
Other (please specify): _____	<input type="checkbox"/>					

18. What are the **main factors** holding back the use of *mobile devices and software applications* for inspection **during construction and maintenance** of assets in your agency? (Please check all that apply).

- Cost issues
- Insufficient agency network levels, IT infrastructure/cellular service
- Access, privacy, or security concerns
- Lack of standard contract specifications
- Incompatibility with (or restricted by) legal, regulatory, or policy requirements
- Lack of reliable internet connection in remote locations
- Incompatibility with existing hardware
- Lack of training, knowledge, and skills to use technologies
- Lack of technical results/case studies demonstrating accuracy
- Quality of data collected
- Device maintenance and user support
- Resistance to change
- Other (please specify): _____

SUMMARY & FINAL THOUGHTS

19. For each type of highway infrastructure listed below, which technologies does your agency use for inspection during **construction or maintenance** of assets? (Please check all that apply)

Highway Infrastructure	Geospatial technologies	Remote sensing & monitoring	Nondestructive evaluation methods	Mobile devices & Software Applications	Other, _____
Roadways	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bridges	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Non-bridge structures	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Drainage systems	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Earthwork/grading	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Signage/Roadside	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (Please specify): _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

20. Does your agency provide training in the use of technologies for highway inspection? (Please check all that apply)

- Hands on/field-based training
- Classroom based training
- Online training
- Workshop
- Vendor demonstration
- Only provided reference materials (hardcopy or electronic)
- Peer training
- No training provided
- Other (please specify): _____

21. When evaluating performance of the use of the technologies for highway infrastructure inspection, what metrics does your agency consider? (Please check all that apply)

- Cost-benefit analysis
- Efficiencies gained
- Agility/flexibility for desired tasks
- Increase in quality
- End user approval
- Durability and maintenance of devices/technology
- Enhancing limited inspection resources
- Advancement in technology
- Other (please specify): _____

22. Does your agency track the cost-effectiveness of implementing technologies for highway inspection?

- Yes No Not sure

If "Yes", please explain: _____

23. Approximately, what is the overall return on investment (ROI) from using the following technologies for highway infrastructure inspection in your agency?

$$(\text{ROI} = [\text{benefit (estimated in \$)} - \text{cost}] / \text{cost} * 100\%)$$

Type of Technologies	ROI						
	Negative	0-10%	10-20%	20-50%	50-100%	>100%	Unsure/Info. not available
Geospatial Technologies	<input type="checkbox"/>						
Remote sensing & Monitoring Technologies	<input type="checkbox"/>						
Mobile Devices & Software Applications	<input type="checkbox"/>						
Other (please specify): _____	<input type="checkbox"/>						

24. What are the primary drivers for selecting the technologies for highway inspection in your agency?

(Please check all that apply.)

Type of Technologies	Enhance Staffing	Improve Efficiency (e.g., Cost, Schedule, Quality)	Promote E-Construction	Enhance Safety of Inspectors	Other, _____
Geospatial Technologies	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Remote sensing & Monitoring Technologies	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Mobile Devices & Software Applications	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (please specify): _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

APPENDIX B: WORKING PAPER

Assessing the Impacts of Geospatial Technologies on Highway Infrastructure Construction Inspection

ABSTRACT

Geospatial technologies have the ability to improve various construction tasks while making the construction process more efficient and productive. As a result, state departments of transportation (DOTs) increasingly use geospatial technologies for inspecting highway construction projects. Yet, the current state of practice in the use of these technologies widely varies among state DOTs. This study intends to (1) investigate the use of geospatial technologies for highway construction inspection and (2) identify the current methods used to assess the viability and efficiencies of inspection technologies and implementation challenges. The geospatial technologies examined in this study include global navigation satellite system (GNSS)/global positioning system (GPS); geographic information systems (GIS); unmanned aircraft systems (UAS); robotic total stations (RTS); photogrammetry technology (PT); and e-ticketing. A triangulation research methodology including an extensive literature review, survey questionnaire of state DOTs, and eight case studies was employed. Results of the study show that GNSS/GPS is the most dominant technology used by state DOTs for the inspection of highways. The top inspection activities involving geospatial technologies include earthwork inspection and quantities, verification and documentation of work completed, monitoring construction progress, tracking construction materials, and collection of as-built information. The primary drivers for selecting technologies for highway inspection are improving efficiency, promoting e-construction, and enhancing the safety of inspectors. The main challenges with the implementation of geospatial technologies are compatibility issues, staff

training and technology adoption, and procurement costs. The findings from this study provide valuable information for state DOTs in implementing geospatial technologies effectively for highway construction inspection.

INTRODUCTION

The quality of highway construction projects has been a major concern of transportation agencies and contractors. Quality assurance (QA) in the inspection of construction projects is defined as a tool or means by which the owner and contractors ensure that the project is constructed in accordance with approved plans and specifications by the most economical, efficient, and safe methods (1). Typically, inspection staff, such as construction inspectors and technicians, are responsible for conducting and verifying the results of the inspection processes (2, 3). These processes may be onsite (e.g., visual field inspection), off-site (e.g., shop and source inspection), or laboratory testing (4). It is important to note that the project inspection staff is in charge of gathering massive amounts of data and information from the field. Obtaining timely and accurate inspection data improves project quality by minimizing nonconformance issues that may result in penalties, or cost and schedule burdens associated with rework (5). Valdes and Perdomo (6) and Snow et al. (7) mentioned that, due to a staff shortage, construction inspectors cannot check all aspects of the project, which may affect the project's progress, quality, and cost. This situation motivated several state departments of transportation (DOTs) to adopt emerging technologies, including geospatial technologies, in their construction inspections.

Emerging technologies have been widely used in the building construction sector, manufacturing, or industrial projects and services to improve quality concerns. Researchers indicated that the implementation of technologies in these sectors showed substantial improvements in quality

performance (8). Emerging technologies enable accurate data collection, easier access to real-time information, and information sharing among project inspection and management staff (e.g., geospatial, mobile technologies, sensors, and others). These technologies give inspectors access to a vast range of options that can help them in conducting field inspections. For instance, technologies are commonly used to enter and track inspection data, record field activities in the construction management system, access plan sets and manuals, and communicate with office staff (9).

With the latest technological advancements, the inspection landscape has been rapidly changing by incorporating technologies. For example, a wide range of technologies is available to support construction inspection activities and collect digital data to estimate quantities, verify and accept work, and create as-built records. These technologies potentially offer benefits, including improved data quality and consistency, enhanced communication, transparency, and safety of field personnel. Geospatial technology is one of the most common sets of tools used for the inspection of highway construction projects. In fact, geospatial technologies have proven to be an effective tool for collecting accurate data in near real-time (10, 11). However, little research has been conducted to examine the state of practice in field applications of geospatial technologies. There is a need to identify construction work inspected by geospatial technologies, the applicability, benefits, and barriers of adopting such technologies, and motivations for transportation agencies to adopt these technologies.

BACKGROUND

Geospatial technologies have rapidly evolved over the past decade. There is a wide range of geospatial technologies, and their applications provide numerous benefits to highway construction projects and programs. This study focused on the following six geospatial technologies: (1) global navigation satellite systems /global positioning system (GNSS/GPS), (2) geographic information systems (GIS), (3) unmanned aircraft systems (UASs), (4) robotic total stations (RTS), (5) photogrammetry technology (PT), and (6) e-ticketing. The following sections briefly discuss these technologies.

Global Navigation Satellite Systems and Global Positioning System

GNSS is the standard term for satellite navigation systems (i.e., constellation) that provide autonomous geospatial positioning anywhere on earth. The main GNSS constellations include GPS, GLONASS, Galileo, and BeiDou. These satellites provide signals from space and transmit positioning and timing data to GNSS receivers. Using multiple satellites reduces delays in finding adequate ranges and maintains the accuracy, redundancy, and availability at all times for collecting location data (10). If one satellite does not provide a quality position or fails to operate, GNSS receivers can pick up signals from other systems. GPS has been fully operational for over two decades and has become a vital tool in the construction industry (10, 11, 12). GPS consists of up to 32 medium Earth orbit satellites in six different orbital planes. The exact number of satellites in GPS varies because older satellites are retired and replaced.

A number of GPS-based systems have been proposed or implemented to facilitate highway infrastructure inspection through the identification and tracking of materials on construction sites. Typically, GPS and GNSS technologies include three main segments as follows:

- *Space segment*—This segment consists of satellites that continuously broadcast position and time data to GNSS receivers.
- *Control segment*—This segment consists of ground stations that monitor, track, and collect the satellite broadcast signals.
- *User segment*—This segment consists of receivers, processors, and antennas allowing operators to determine the position, velocity, and time of the operator’s location.

Geographic Information Systems (GIS)

GIS is a computer-based system that provides tools for creating, managing, analyzing, and displaying spatial data. The deployment of computer-based GIS for transportation (GIS-T) was initiated in the 1980s. In its early days, the application of computer-based GIS-T was for the 2D cartographic display of roadway data. Since then, GIS has evolved along with applications used by federal, state, and local agencies for infrastructure planning and management, routing and scheduling, and others (13). GIS was initially deployed as a means of demonstrating the content of text-based inventory database systems. With substantial deployment in many areas of the transportation industry, GIS is increasingly becoming a common roadway inventory database (13). As a result, GIS serves as a data management tool integrated into civil infrastructure management, which is an “asset management system that starts with planning the construction or modification of a transportation asset, moves through design and construction, and, once built, transitions to deployment, operations, maintenance, and performance evaluation system” (14). GIS enhances the field of transportation asset management. GIS maps help project managers see the extent of problems, understand the geographic impact of their decisions, and make more

informed decisions. GIS also enables state DOTs to show information about their assets on maps that both technical and non-technical audiences can understand (15).

Unmanned Aircraft Systems (UAS)

Over the past decade, there has been increasing attention and resources dedicated to the application and operation of UASs. In 2016, the Federal Aviation Administration (FAA) published the final rule for civil operations of UASs. In 2017, the USS DOT and FAA established the UAS Integration Pilot Program to (1) accelerate the safe integration of UAS into the national airspace system, (2) address ongoing concerns regarding the potential security and safety risks, (3) promote innovation, and (4) identify the most effective models of UAS integration (16). UASs have been investigated for various highway infrastructure applications. Pistorius (17) and Pecoraro et al. (18) summarize applications for using UASs in construction:

- *Pre-project assessments and project survey data*—UASs can offer aerial images of a project site much more accurately, realistically, and timely than traditional aircraft photographs.
- *Conducting aircraft surveys and site mapping*—UASs can provide real-time aerial views of key project areas, allowing management and construction staff to monitor operations and performance, supporting decision-making.
- *Site inspections and surveillance*—UASs can be used for inspection, including bridges, high-tension electric wires, remote sites, and other areas which are difficult to access. UASs equipped with a camera and video equipment provide site security.
- *Asset tracking and management*—UASs can be used to keep track of the movements of machines and equipment, tools, vehicles, and people. UASs can monitor workers on site

and is a convenient tool to track how many employees are working in sensitive or hazardous areas.

- *Monitoring the movement of materials, stockpile reporting, and inventory management*—UASs are used to record materials being delivered, stored, and installed.
- *Enhanced safety*—UASs can provide real-time data on safety violations or situations that might have an adverse safety impact during the construction process.
- *Enhanced 3D modeling*—UAS data is acquired in real-time and integrated with mapping and BIM models.

Additionally, researchers have applied UASs for monitoring traffic; inspecting structures; assisting with construction safety inspections; inventorying roadside conditions; surveying and topographic mapping features; monitoring construction progress; estimating earthwork volumes; identifying potential avalanches near roadways; monitoring unstable slopes and mapping landslides; and reconstructing and documenting crash scenes (10, 11, 19, 20).

Robotic Total Stations (RTSs)

RTSs allow for more technological convenience by offering remote control abilities to perform more calculations and inspections in less time and with less staff than a traditional total station. RTSs allow for increased safety in challenging terrain because of their unique ability to operate at a distance. RTSs are a well-established technology and one of the most common geospatial tools used by state DOTs for construction inspection (10, 11). Total stations typically include the following capabilities:

- *Prism measurement*—The ability to measure angles and distances between points and

coordinates;

- Reflectorless measurement—The ability to collect features not accessible with a prism (e.g., obtaining measurements on the sides of bridges or steep slopes);
- Imaging—The ability to collect 360-degree digital images;
- Integrated GNSS—The ability to record the instrument location, providing added flexibility in georeferencing total station data; and
- Integrated lidar scanning—Multi-function systems to acquire small point clouds (10, 11).

Photogrammetry Technology (PT)

Photogrammetry is the process of extracting geometric measurements from photographs. A wide range of studies discuss the application of photogrammetry on highway construction. The two main types of photogrammetry include aerial photogrammetry and photogrammetry. While conventional aerial photogrammetry is suitable for acquiring data over large areas, it often involves the expense of mobilizing an aircraft to the project site. Because UASs are relatively inexpensive and their ability to perform data collection, using the combination of UASs with photogrammetry can be a viable tool to reduce the costs of conventional aerial photogrammetry (10, 11). Photogrammetry requires less investment and is suitable for mapping movement-related issues such as monitoring highway construction progress.

While photogrammetry is a mature discipline, structure from motion (SfM) is a relatively new application in the construction industry. SfM is a photogrammetric approach developed based on the advanced image matching algorithms originating from computer vision (10, 11). SfM typically involves high-resolution, close-range images. As a result, SfM is an effective tool for

extracting detailed 3D spatial information of individual objects on a construction site (10, 11). Researchers have applied photogrammetry and SfM for several areas related to highway infrastructure inspection, including as-built data; real-time 3D construction field data; asset condition evaluation; bridge inspection; construction project progress tracking; and construction quality control (10, 11).

E-Ticketing

E-ticketing technology allows users to collect, document and share bulk material load delivery data electronically. E-ticketing allows for safer and more efficient construction inspection and management. The FHWA promoted e-Ticketing as an e-Construction technology that can be collaborative and mutually beneficial to both state DOTs and their contractors. Several state DOTs (e.g., Florida, Ohio, Alabama, Iowa, and Minnesota) have experience in the use of e-Ticketing for their highway construction projects and indicated the benefits of e-Ticketing implementation are improved safety, enhanced efficiency, and an offset to staff reductions (21). E-ticketing has gained substantial momentum over the last five years. Additionally, due to the impact of the COVID-19 pandemic, many state DOTs are increasingly using or implementing e-Ticketing technologies to improve the safety of inspectors and onsite personnel by reducing the risk of virus transmission. Current e-ticketing practices typically involve a third-party provider connecting to the loadout system of a material producer (most often asphalt or concrete) to collect material and load information. In some cases, GPS units are installed on mobile equipment such as haulers and pavers, and a web-based interface can then allow for real-time tracking of deliveries and reporting of electronic load information (22). The three main types of e-ticketing projects include (1) hot mix asphalt (HMA), (2) Portland cement concrete (PCC), and

(3) aggregates. Other types of projects that are less common for e-Tickets include structural steel, rebar, guardrails, signs, and millings. E-Ticking provides all stakeholders with an electronic means to produce, transmit, and share materials data and to track and verify material deliveries with enhanced safety, streamlined inspections, and improved contract administration processing. Electronic ticket exchanges enable access via mobile devices and simplify the handling and integration of material data into construction management systems for acceptance, payment, and source documentation (18).

METHODOLOGY

Figure 1 shows the three-phase research methodology employed to achieve the study’s goal. Phase 1 involved conducting a comprehensive literature review of geospatial technologies for highway construction inspection. Phase 2 included a survey of state DOTs and conducting eight case studies. Finally, Phase 3 included an analysis of the results. The key findings related to the use of geospatial technologies and challenges in adopting these technologies for highway construction inspection are discussed in detail.

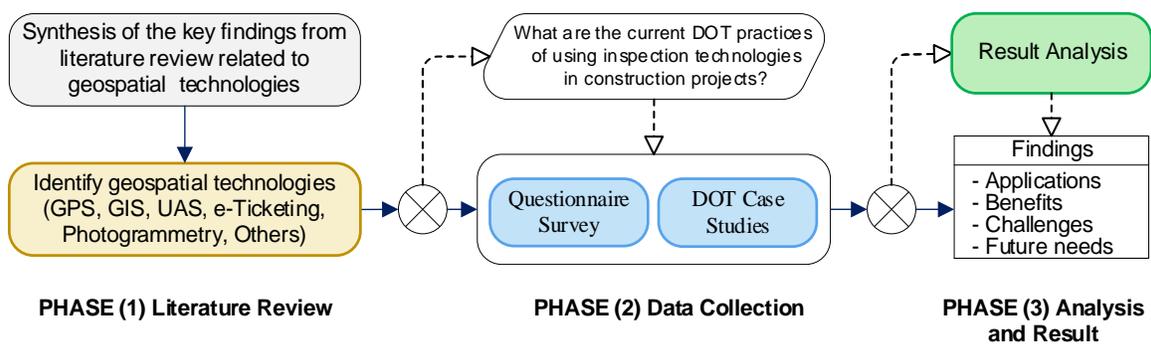


Figure 1 Research methodology

Literature Review

In this phase, the authors conducted a comprehensive literature review of GNSS/GPS, GIS, UASs, TRS, P.T., and e-ticketing technologies and their applications in the area of highway construction inspection. The authors searched academic literature, industry publications, state DOT websites, and government reports to find the most current trends and practices in these inspection technologies. The literature review was conducted using TRB Transportation Research Information Systems, general internet search engines, academic databases, ASCE civil engineering database, and the Federal Highway Administration (FHWA) research library. The result of searching these sources is presented in the background section.

Survey of DOTs

A national survey of state DOTs was conducted to better understand geospatial technologies state-of-the-practice in highway construction inspection. The survey questionnaire was developed based on the finding from the literature review and was distributed in a web-based form to the American Association of State Highway and Transportation Officials (AASHTO) Committee on Construction members, representing all 50 states. The respondents were asked to forward the survey questionnaire to the best-qualified person in their organization. After two follow-up requests, responses from 42 state DOTs were received (84% response rate). The respondents on average had more than ten years of experience in highway construction and maintenance projects. The respondents also had knowledge of inspection methods and are involved in inspection activities for highway construction. The survey questionnaire asked the participants to describe not only their state of practice related to inspection technologies but their perception regarding the challenges in adopting these technologies. A sample of the survey questions are:

1. Approximately how many years has an agency been using geospatial technologies and applications to inspect highway infrastructure during construction?
2. How are geospatial technologies and applications used to inspect highway infrastructure during construction in the agency?
3. What are the main factors holding back the use of geospatial technologies and applications for inspection during construction?

The survey questionnaire helped to draw conclusions on the use of geospatial technologies in highway construction. Additionally, the survey responses identified suitable DOTs for the case studies.

Case Studies

The authors conducted eight in-depth case studies to gather specific information on using geospatial technologies for inspections of highway construction projects. Data from the survey and literature review were used to select the DOTs for further study. The authors used the following selection criteria:

- Experience with the use of geospatial technologies for highway construction;
- Comprehensiveness and availability of geospatial technology documents and data; and
- The willingness of DOT personnel to participate in the study.

Participation involved conducting interviews with DOT staff that use geospatial technologies, collecting related documents and reports, and reviewing the findings for accuracy.

The following protocol was used for each case study:

1. The authors contacted the agency representatives to orient the research team to the DOT and request participation and access to staff knowledgeable about geospatial technologies for highway construction inspection.
2. The authors interviewed agency staff to identify the uses, benefits, challenges, and lessons learned from using geospatial technologies for highway construction.
3. The agency staff provided the research team with geospatial technology documents and reports.
4. The authors conducted follow-up interviews with agency representatives to verify the findings.

The authors used Oppenheim's (23) approach for questionnaire design, interviewing and attitude measurement as a research guide to develop the case study questions. Using the protocol outlined above, structured interviews were conducted in accordance with the Government Accountability Office procedures (24). The eight DOTs that agreed to participate in this study are Florida, Illinois, Iowa, Minnesota, New York, Oregon, Pennsylvania, and South Dakota.

Florida DOT

The Florida DOT (FDOT) uses GPS, UASs, photogrammetry, and e-ticketing. First, GPS rovers are used by consultant construction inspectors, which involves a range pole with a GPS unit attached to it along with a tablet that allows the inspector to measure aspects of a project and collect location data in three-dimensional space. In addition, the GPS rovers were able to communicate with contractor base stations on one pilot project, which helped ensure accuracy when using the technology. GPS is also used for locating soil borings. UASs, along with

photogrammetry, are used by consultant inspectors, primarily for taking aerial photographs to track progress, albeit in an informal approach. The UAS flies the project at specific times, such as monthly, and the photos taken are compared with one another to visually see the progress of the work and if it appears correct based on the plans and specifications. Furthermore, FDOT is currently exploring using UASs and photogrammetry to take actual measurements and quantify materials. Finally, UASs have been used in a limited capacity for official surveys to check the work put in place. E-ticketing is used by FDOT, primarily for asphalt material deliveries to construction sites. FDOT has been moving toward the use of e-ticketing for a few years, but the COVID-19 pandemic accelerated its implementation and use.

Illinois DOT (IDOT)

IDOT's use of geospatial technologies has been to improve efficiency in different highway construction areas. For construction inspection, IDOT crews use GPS rovers and RTS to perform project layouts and check alignments and grades as construction is performed. While not programmatically implemented, UASs have been used to collect photos and videos of project sites. While the contractor in most instances performs this UAS use, IDOT does have a Division of Aeronautics with UASs capable of performing these activities. IDOT's investigation into e-ticketing has been according to the reception of their contractors. IDOT indicated that e-ticketing will become the industry standard based on the benefits it provides to the contractor and agency.

Iowa DOT

The Iowa DOT uses GPS and GNSS, UAS, GIS and e-ticketing. Iowa DOT has a limited number of survey-grade GPS units that provide accuracy through RTK (real-time kinematic) corrections using Iowa's Real-Time Network. These GPS devices are used for checking quantities, measuring items and distances, referencing project stations and offsets, measuring cuts and fills, and more. These devices may also be used to complement mobile devices in the collection of asset-grade data for entry into GIS systems. As part of Iowa DOT's as-built process, data is processed in the inventory and asset management system as collected for signs, culverts, roadway tiles, and other features. Iowa DOT contractors also use RTS for machine-controlled paving. Iowa DOT inspection staff are provided access to these stations and GPS rovers to check measurements and quantities. Iowa has been a leader and pioneer in the use of e-ticketing. Iowa DOT piloted this technology heavily, conducting 94 projects in 2020, using several different vendors.

Minnesota DOT (MnDOT)

MnDOT uses geospatial technologies for construction inspection, including GPS and handheld devices for measuring quantities and assisting with developing as-builts, UASs for bridge inspections, RTS for inspections and verification, photogrammetry for measuring quantities and progress, and e-ticketing for digitally tracking materials. Pavement work at MnDOT includes profile milling. To implement this, MnDOT provides the digital model to contractors to mill according to this model rather than telling them to mill one or two inches. To inspect the profile milling, inspectors use RTS to verify the milling. Further, MnDOT invested time and resources into its e-ticketing initiative. Using e-ticketing removes individuals from harm's way in that a

person does not have to navigate through heavy machinery to collect tickets as materials are brought to the site and placed, and the information is transferred digitally to MnDOT.

New York State DOT (NYSDOT)

NYSDOT uses RTS and digital levels to check specifications on a project. GPS is used along with these tools to accurately locate specific aspects of a construction project. Along with the use of GPS, GIS is gaining traction on the construction site, as using this technology helps to distribute information easier to different department units and contractors. GIS is more robust, allows for adding more attributes, and is easier to use without converting files, as GIS files are more compatible than other file types. Photogrammetry is conducted by the NYSDOT photogrammetry department and is used for monitoring the progress of construction work using UASs.

Oregon DOT (ODOT)

The geospatial technologies used by ODOT for construction inspections include GNSS/GPS, UAS, and RTS. In addition, ODOT is starting to explore the use of e-ticketing to improve the tracking, exchange, and archiving of materials tickets. For GPS use, ODOT has a statewide GNSS network that is used for a variety of tasks, including construction inspections. As stated by ODOT staff, the software that ties with GNSS is easy to use, and ODOT trains all inspectors to use the software and associated field equipment. UASs used for construction inspections at ODOT include taking videos, checking elevation data, tracking progress, and verifying payment

quantities. In addition, UASs are used for geotechnical work to monitor slides near construction sites and to create surface models that are then used with ground-based radar to track the movement of slides. RTS are used for most surveying and inspection processes on ODOT projects, as well as for monitoring construction, staking the project, measuring quantities, and checking vertical clearances.

Pennsylvania DOT (PennDOT)

PennDOT employs GPS, UAS, photogrammetry, and e-ticketing. PennDOT uses mobile devices in the field, and tablets include a GPS antenna to record the location of inspections and work progress for a project. Specifically, for guiderails and light pole installations, GPS coordinates are determined during inspections that then feed into the maintenance GIS system to track the location of guiderails and light pole assets. The location of guiderails has been of particular importance as PennDOT was informed that some of their guiderails across the state were not manufactured correctly in accordance with specifications. Additionally, PennDOT used UASs to monitor the contractor's cut and fill tasks of a project to determine the amount of material removed or added. PennDOT noted that using UASs makes it easy to track the movement of material and the progress of the work. PennDOT also uses photogrammetry with UASs to fly and take site photos to monitor the work progress. For e-ticketing, PennDOT has been piloting its use with asphalt projects since 2017 and is one of the leading state DOTs in implementing e-ticketing.

South Dakota DOT (SDDOT)

SDDOT has used GPS and RTS for surveying of preliminary work, locating items of work, and recording quantities. The SDDOT staff noted that the data generated from these technologies is

manually entered into the construction management system for inspection purposes. The benefit of using geospatial technologies for highway construction inspection is the accuracy of data collected. In addition, the project team can check data at any time during construction. Using GPS and RTS helped SDDOT offset the lack of inspection staff and allowed for better allocation of inspection resources.

FINDINGS AND DISCUSSION

The literature review, survey questionnaire of DOTs, and case studies of select DOTs provided the data for this study. The authors analyzed the data collected to identify the uses and challenges of geospatial technologies that DOTs employ for delivering highway infrastructure construction projects. It is important to note that 42 state DOTs identified their experiences with different geospatial technologies used to inspect highway infrastructure during construction. About half of these state DOTs have used geospatial technologies for more than five years to inspect highway infrastructure during construction, less than half of the surveyed state DOTs have experience with these technologies for between two to five years, and only two state DOTs have used geospatial technologies for less than two years. The 42 state DOT respondents were not required to respond to all questions in the survey. As a result, the sample size (n) of each question varied. The following sections present the key findings from this study in detail.

Application Areas of Geospatial Technologies

Figure 2 shows the application areas of geospatial technologies. More than half of the surveyed state DOTs have used geospatial technologies for inspection of roadways, signage/roadside, and earthwork/grading. Likewise, less than half of the surveyed DOTs have used geospatial technologies for the inspection of non-bridge structures and drainage systems.

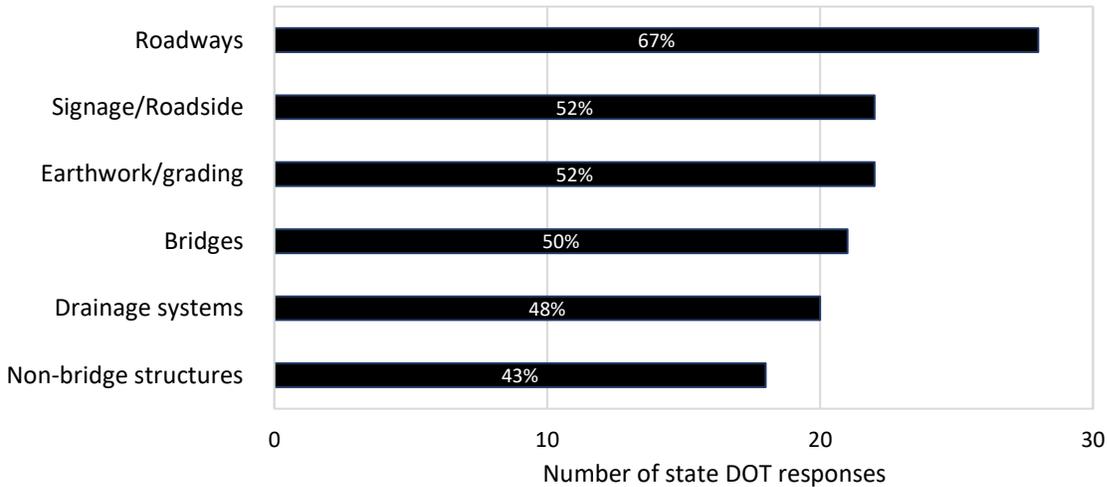


Figure 2 Use of technologies for highway infrastructure inspection (n=42)

Geospatial Technologies Used for Inspection

Table 1 shows the use of geospatial technologies by DOTs for highway construction inspection. Of the 41 DOT responses collected, 32 are implementing geospatial technologies. Of the 32 DOTs that implemented geospatial technologies, 26 (81%) responded that they implement GNSS/GPS while 19 (56%) have used e-ticketing technology. Then, 16 (50%) implemented UAS. 15 DOTs (47%) implemented RTS. Fifteen DOTs (47%) have almost the same implementation level for highway infrastructure inspection during construction using GIS. Only nine DOTs (28%) reported the use of PT. This result indicates that GNSS/GPS is the most commonly used technology by state DOTs, whereas PT is the lowest used geospatial technology.

Table 1 Types of geospatial technologies used for inspection (n=32)

State DOT	GNSS /GPS	GIS	UAS	RTS	PT	e-Ticketing
Alabama			✓			✓
Arkansas	✓					✓
California	✓		✓			✓
Colorado	✓	✓	✓			
Connecticut	✓	✓		✓	✓	✓
Delaware	✓	✓	✓			✓
Florida	✓	✓	✓	✓	✓	✓
Georgia						✓
Hawaii	✓	✓				
Illinois	✓			✓		✓
Indiana	✓					
Iowa	✓		✓			✓
Minnesota	✓	✓	✓	✓	✓	✓
Mississippi	✓			✓		✓
Missouri	✓			✓	✓	
Montana	✓	✓	✓	✓		
Nebraska	✓	✓	✓	✓	✓	✓
New Jersey		✓				
North Carolina	✓		✓	✓		✓
North Dakota	✓			✓		
Oregon	✓	✓	✓	✓	✓	
Pennsylvania	✓		✓		✓	✓
South Carolina	✓			✓		
South Dakota	✓			✓		
Tennessee	✓	✓	✓			✓
Texas	✓	✓		✓	✓	
Utah	✓	✓	✓			✓
Washington	✓	✓	✓			✓
West Virginia						✓
Wisconsin	✓	✓	✓	✓	✓	✓
TOTAL	26	15	16	15	9	19

Inspection Activities by Geospatial Technologies

Table 1 summarizes the application of each geospatial technology associated with common inspection activities during the construction of highway projects. Table 2 indicates that the GNSS/GPS technology is primarily used for earthwork inspection and quantities; UAS is dominantly used for monitoring construction and creating site photos and videos; and e-

Ticketing is dominantly used for tracking the position of bulk materials (e.g., concrete, asphalt, aggregate loads). For example, the top inspection activities using the GNSS/GPS technology during the construction of highway projects include earthwork inspection and quantities, collecting as-built information/Developing 3D as-built models, and verification and documentation of work completed for payment. Similarly, for the implementation of UAS, the top inspection activities during the construction of highway projects include monitoring construction progress, site photos and videos, and earthwork inspection and quantities.

TABLE 2 Geospatial technology applications for highway construction inspection

Typical Inspection Activities	GNSS/ GPS (n=26)	GIS (n=15)	UAS (n=16)	RTS (n=15)	PT (n=9)	e- Ticket (n=19)
Tracking position of bulk material (concrete, asphalt, aggregate)	23%	7%	6%	13%	0%	68%
Tracking finished materials and inventory (pipe, rebar, etc.)	19%	13%	0%	13%	0%	0%
Measurement of material strength and temperature (concrete, base course, etc.)	12%	13%	0%	0%	0%	0%
Measurement of pavement thickness	15%	7%	0%	13%	0%	5%
Earthwork inspection and quantities	65%	7%	50%	60%	44%	5%
Structural inspection and quantities	31%	20%	38%	13%	22%	5%
Monitoring construction progress	42%	27%	88%	40%	44%	5%
Verification and documentation of work completed for payment	50%	20%	13%	40%	11%	32%
Locating underground utilities and underground assets	27%	20%	0%	20%	0%	0%
Collecting as-built info/ 3D as-built models	50%	33%	19%	40%	33%	0%
Quality control/Quality assurance	38%	13%	13%	40%	11%	16%
Erosion control inspection	15%	13%	19%	0%	11%	5%
Site photos and videos	19%	27%	75%	0%	33%	0%

Drivers for Selecting Geospatial Technologies

Different methods are used to select and assess the viability and efficiencies of inspection technologies. As shown in Figure 3, examining the state of practice among DOTs revealed that

the primary drivers for selecting the technologies for high construction inspection are to (1) improve efficiency; (2) promote e-Construction; and (3) enhance the safety of inspectors.

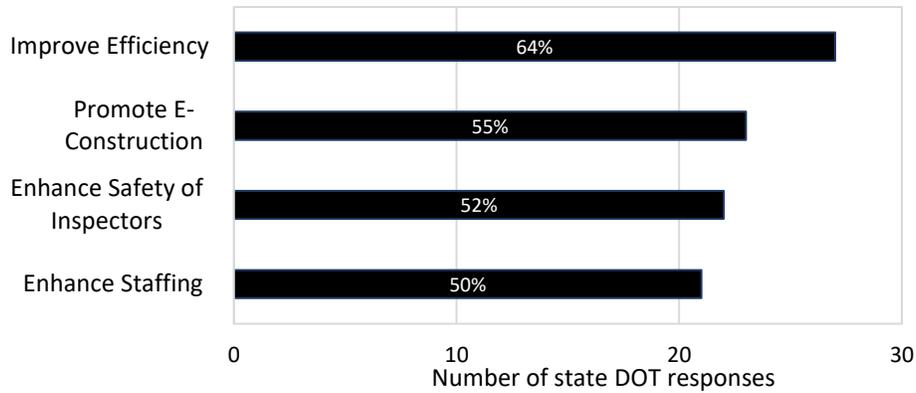


Figure 3 Primary drivers for selecting geospatial technologies for high construction inspection (n=42)

Challenges in Using Geospatial Technologies

Table 3 summarizes the main challenges in implementing geospatial technologies for highway infrastructure inspection. The top five challenges in the implementation of geospatial technologies for highway construction inspection include lack of training, knowledge, and skills to use technologies (74%); lack of reliable internet connection in remote locations (55%); cost issues (52%); lack of standard contract specifications (48%); and device maintenance and user support (45%). These results are supported by case study findings. The following section briefly discusses challenges in the implementation of geospatial technologies for highway construction inspection from case studies.

Table 3 Challenges in using geospatial technologies for highway construction inspection (n=32)

Challenge	State DOT
Cost issues	Alabama, Arkansas, Florida, Minnesota, Mississippi, Missouri, Nebraska, New Jersey, North Carolina, North Dakota, South Carolina, Tennessee, Texas, Texas, West Virginia, Wisconsin
Insufficient agency network	Arkansas, Connecticut, Iowa, Minnesota, Missouri, Montana, New Jersey, Utah, West Virginia

Challenge	State DOT
Access, privacy, or security concerns	New Jersey, Oregon, South Carolina
Lack of standard contract specifications	Alabama, Colorado, Connecticut, Florida, Georgia, Hawaii, Illinois, Iowa, Minnesota, New Jersey, North Carolina, Utah, Washington, West Virginia, Wisconsin
Incompatibility with legal, regulatory, or policy requirements	Alabama, Nebraska, New Jersey, South Carolina
Lack of reliable internet connection	Arkansas, Colorado, Hawaii, Iowa, Minnesota, Mississippi, Missouri, Montana, Nebraska, New Jersey, North Carolina, South Carolina, Texas, Utah, Vermont, West Virginia, Wisconsin
Incompatibility with existing hardware	New Jersey, Pennsylvania, Tennessee, Texas, Washington, West Virginia
Lack of training, knowledge	Alabama, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Hawaii, Illinois, Iowa, Minnesota, Mississippi, Missouri, Montana, New Jersey, North Carolina, Pennsylvania, South Carolina, South Dakota, Texas, Utah, Vermont, West Virginia
Lack of technical results	Colorado, Connecticut, Mississippi, Montana, New Jersey, Pennsylvania, South Carolina, Utah
Quality of data collected	Colorado, Missouri, Montana, Pennsylvania, South Carolina
Device maintenance and user support	Colorado, Connecticut, Hawaii, Iowa, Minnesota, Mississippi, Missouri, New Jersey, North Carolina, Pennsylvania, South Carolina, South Dakota, Texas, Vermont
Resistance to change	California, Colorado, Connecticut, Hawaii, Iowa, Minnesota, Nebraska, North Dakota, South Carolina, Texas, Utah, Vermont, Wisconsin

The FDOT representatives noted that they had experienced incompatibility issues, such as incompatible GPS rovers that cannot communicate with the contractor’s base station. This challenge has led FDOT toward a statewide network that broadcasts correction information for those devices instead of communicating with the base station. To overcome this incompatibility issue, FDOT has required specific technologies in the contracts so that consultant inspectors provide equipment compatible with the systems in place.

IDOT indicated that, in general, procuring technologies could be very difficult in a government agency. This issue typically involves the ownership of the specified technology between IDOT or their construction contractor. The IDOT representative indicated that the policies and

specifications controlling these procurements can be problematic when piloting technology on a project-by-project basis. Additionally, IDOT noted that staff training and use of the technology present challenges. In fact, learning new technologies is sometimes viewed as a distraction even if efficiencies are an expected outcome.

Iowa DOT noted challenges with geospatial technologies include the management of data and technology from multiple vendors, lapses in cellular coverage, duplicative efforts while piloting the technology, and simply keeping up with technology advances. Iowa DOT noted that cellular coverage could be challenging with geospatial technologies as some GPS receivers require connectivity for corrections.

ODOT mentioned that they get push back on the use of technology at first because inspectors perceive that the technology will complicate their tasks and take longer to complete their work. Proof of concepts must be conducted to show the value and efficiency of using these technologies. Cost is a concern, and ODOT continually looks for grants and other resources to help offset the costs of purchasing the required equipment and updating them as the technologies advance. Moving from a linear reference system for locations to GNSS and a correct coordinate system has been difficult. Still, ODOT mentioned that a benefit of the correct coordinate system is that the geospatial positions can be used on more than a static straight-line chart.

Finally, the SDDOT representatives noted that the main challenges of using geospatial technologies for highway construction inspection are keeping equipment and software updated and providing essential skill sets for inspectors to use these technologies. In addition,

compatibility issues sometimes create complications in that SDDOT uses specific software and file types that are not compatible with the programs used by contractors.

CONCLUSIONS

Highway infrastructure inspection is critical in any transportation system. With the latest technological advancements, the inspection landscape has been rapidly changing through the incorporation of technology. This study examined the use of geospatial technologies for highway construction inspection by conducting a national survey and eight case studies with state DOTs. The six common geospatial technologies included GNSS/GPS, GIS, UASs, RTS, photogrammetry technology, and e-ticketing for inspection of highway construction projects were discussed in detail. The study found that the typical applications of geospatial technologies related to highway infrastructure inspection include earthwork, paving, verification, as-built surveys, site/progress monitoring, quality assurance/quality control, and asset management. The top challenges in the implementation of geospatial technologies for highway infrastructure inspection during construction include (1) lack of training, knowledge, and skills to use technologies; (2) lack of reliable internet connection in remote locations; (3) cost issues; (4) lack of standard contract specifications; and (5) device maintenance and user support.

Finally, although geospatial technologies have found a place in highway construction inspection, further development and research are needed to make these technologies more effective and comprehensive for highway construction projects. First, it is essential to identify approaches that transfer data between the different inspection technologies to obtain compatibility and a seamless integration process among these technologies. Second, researchers and practitioners may further

investigate inspecting more construction elements and activities using geospatial technologies. Finally, conducting benefit-cost analysis and performing return on investment assessments are essential for evaluating the effectiveness of technology implementation.

REFERENCES

- [1] Von Quintus, H.L., Rao, C., Minchin, R., Nazarian, S., Maser, K. and Prowell, B. *NCHRP Report 626: NDT technology for quality assurance of HMA pavement construction*. Transportation Research Board of the National Academies, Washington, DC, 2009.
- [2] Li, Y., Al-Haddad, S., Taylor, T.R., Goodrum, P.M. and Sturgill, R.E., 2019. Impact of Utilizing Construction Engineering and Inspection Consultants on Highway Construction Project Cost and Schedule Performance. *Transportation Research Record*, 2673(11), pp.716-725.
- [3] Mohamed, M. and Tran, D., 2022. Approach to Determination of Risk-Based Inspection Workload for Highway Construction Projects. *Transportation Research Record*, p.03611981211069958.
- [4] Sillars, D.N., Scholz, T. and Hallowell, M., (2010). Analysis of QA procedures at the Oregon Department of Transportation. Oregon State University. Dept. of Civil, Construction, and Environmental Engineering. Available: <https://www.oregon.gov/ODOT/Programs/ResearchDocuments/QA-QC.pdf>.
- [5] Yamaura, J. and Muench, S.T., 2018. Assessing the impacts of mobile technology on public transportation project inspection. *Automation in construction*, 96, pp.55-64.

- [6] Valdes, D. and Perdomo, J.L., 2013. Using Mobile Computers to Automate the Inspection Process for Highway Construction Projects. Available:
<https://rosap.ntl.bts.gov/view/dot/29454>.
- [7] Snow, M., White, G., Katara, S., Willoughby, K. and Garcia, R., 2013. Project inspection using mobile technology-phase I: an investigation into existing business processes and areas for improvement using mobile technology (No. WA-RD 840.1). Washington (State). Dept. of Transportation. Research Office.
- [8] Ogunrinde, O., Nnaji, C. and Amirkhanian, A., 2021. Quality Management Technologies in Highway Construction: Stakeholders' Perception of Utility, Benefits, and Barriers. Practice Periodical on Structural Design and Construction, 26(1), p.04020043.
- [9] Shah, K., Mitchell, A., Doris Lee, and Mallela, J. 2017. Report No. FHWA-HIF-17-028: Addressing Challenges and Return on Investment (ROI) for Paperless Project Delivery (e-Construction). Retrieved from:
<https://www.fhwa.dot.gov/construction/econstruction/hif17028.pdf>
- [10] Mallela, J., Mitchell, A., Gustafson, J., Olsen, M. J., Parrish, C., Gillins, D. T.; Roe, G. FHWA (2018a) Effective use of geospatial tools in highway construction (No. FHWA-HIF-19-089). United States. Federal Highway Administration. Office of Research, Development, and Technology.
- [11] FHWA (2018c), FHWA-HRT-16-032 TechBief: Automation in Highway Construction.
- [12] Ogaja, C.A. 2011. Applied GPS for Engineers and Project Managers, ASCE Press, Reston, VA, 208 pp.
- [13] Federal Highway Administration (FHWA) 2019. EDC-4 Final Report (Report No. FHWA-19-CAI-013). Washington, DC: USS Department of Transportation

- [14] Federal Highway Administration (FHWA) 2019. EDC-5 Summit Summary and Baseline Report (Report No. FHWA-19-CAI-011). Washington, DC: USS Department of Transportation.
- [15] Hector-Hsu, J., Kniss, V., Cotton, B., Sarmiento, M., & Chang, C. (FHWA 2012). Best practices in geographic information systems-based transportation asset management. United States. Federal Highway Administration.
- [16] Banks, E., Cook, S. J., Fredrick, G., Gill, S., Gray, J. S., Larue, T., ... & Waller, Z. (2018). Successful Approaches for the Use of Unmanned Aerial System by Surface Transportation Agencies (No. NCHRP Project 20-68A, Scan 17-01).
- [17] Pistorius C (2017) “The impact of emerging technologies on the construction industry,” Innovation Insight, Vol. 4, No. 17.
- [18] Pecoraro, J., C. Harper, and C. Wang (2017). “Unmanned aircraft systems in construction and agriculture: Uses, benefits, challenges, and why companies choose to invest,” Journal of Construction Engineering and Project Management, Vol. 7, No. 2.
- [19] Wang X, Al-Shabbani Z, Sturgill R, Kirk A, Dadi GB. Estimating Earthwork Volumes Through Use of Unmanned Aerial Systems. Transportation Research Record. 2017;2630(1):1-8.
doi:10.3141/2630-01
- [20] Harper CM, Tran D, Jaselskis E. Exploring Instrumentation and Sensor Technologies for Highway Design and Construction Projects. Transportation Research Record. 2020;2674(9):593-604.
doi:10.1177/0361198120930718
- [21] Federal Highway Administration (FHWA) 2021 EDC-6. Available from https://www.fhwa.dot.gov/innovation/everydaycounts/edc_6/ [Accessed April 20, 2021].

- [22] Dadi, G. B., Sturgill, R., Patel, D., Van Dyke, C., & Mulder, G. (2020). NCHRP Synthesis 545: Electronic Ticketing of Materials for Construction Management. National Academies of Sciences, Engineering, Medicine, Transportation Research Board.
- [23] Oppenheim, A.N., *Questionnaire Design, Interviewing and Attitude Measurement*, Continuum, London, U.K., 2000.
- [24] Government Accounting Office, *Using Structured Interviewing Techniques*, GAO/PEMD-10.1.5. U. S., Washington, DC, 1991.