EMERGING TECHNOLOGIES & THEIR ADOPTION ACROSS US DOTS: A PURSUIT TO OPTIMIZE PERFORMANCE IN HIGHWAY INFRASTRUCTURE PROJECT DELIVERY

By

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ABSTRACT

In the transportation construction industry, emerging technologies have changed how state departments of transportation (DOTs) deliver highway construction projects. New and innovative technologies continue to be introduced, improved, and implemented for highway construction and their use has resulted in faster, more accurate, and more efficient planning, design, and construction. As the highway construction industry infuses more technologies into the process of project delivery, state DOTs have an opportunity to realize improved project performance regarding cost, schedule, and quality. The Federal Highway Administration (FHWA) Every Day Counts (EDC) initiatives promote the use of various advanced and emerging technologies (e.g., automated machine guidance, unmanned aircraft systems, building information modeling, handheld instruments and devices, and work zone intrusion detection systems).

The use and implementation of emerging technologies vary significantly across the United States. The variety of use and experience is attributed to challenges and barriers that DOT face to investigate, test, and implement a specific technology. The implementation of emerging technologies also depends on the support received from internal management, the state legislation, as well as the ability of the technology to solve a problem within the specific processes of a state DOT. As technologies continue to be introduced and improve, state DOTs continue to consider and explore various technologies for construction.

The main objective of this thesis is to identify and document the state of practice, typical benefits and challenges, and trends in the use of select emerging technologies for highway construction delivery. This thesis utilized survey questionnaire, interviews and case study as research tools to fulfill the objective of the research. This five technology areas are: 1) visualization and modeling; 2) interconnected technologies; 3) safety technologies; 4) instrumentation and sensors; and 5) unmanned aircraft systems. Visualization and modeling technologies include building information modeling, virtual and augmented reality, light detection and ranging (LiDAR), and 3D printing. Interconnected technologies for construction vehicles, equipment, and tools are used for delivery and haul vehicles, pavement and earthwork equipment, and handheld tools. The results show that each DOT uses a definitive approach from initiation to implementation of technology. Some technologies like visualization and modelling have matured more than others and hence are exploited to full potential. The major challenges faced by DOTs in technology implementation are lack of availability of standard documents and the reluctance from senior management towards change. Case study results showed that general contractors are more active in implementing the technologies and reaping the benefits from these technologies, have in house staff that is experienced on its use, and exploit the possible outputs. The results of this study will provide practitioners and professionals with proactive measures and guidance on successfully implementing technology at agency (DOT) and project level.

DEDICATION

I dedicate this thesis to my parents and family. Their support from my first days of college to the capstone of a thesis has been both unquestioning and essential. Love you all.

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I would first like to thank my Advisor and committee chair, Dr. Daniel Tran for his continuous guidance and support during my thesis for its successful completion. The door to Prof. Tran's office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it. He helped me in every possible way during these two years of my stay in the United States and I will be forever grateful to him.

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CHAPTER 1 – INTRODUCTION

1.1 Introduction

State departments of transportation (DOTs) across the United States continually seek solutions to improve their managerial, organizational, and operational effectiveness and project delivery for much-needed transportation projects (Keck et al., 2010). The use of technologies for highway construction delivery has helped DOT agencies realize faster results which are more accurate, more efficient planning, design, and construction. For example, the FHWA Every Day Counts-2 (EDC2) has shown that the combination of 3D modeling and a GPS for machine control helps state DOTs complete highway projects faster with improved quality and safety. This combination can increase productivity by up to 50% for some operations and cut survey costs by up to 75% (FHWA, 2016). Similarly, EDC-3 promoted e-construction technologies as an effective tool to (1) decrease the delays inherent in paper-based project administration; (2) support secure, expedited, and transparent document transmission, distribution, and storage; and (3) enhance real-time management of all documents (FHWA, 2017; Landers, 2015). Research showed that e-construction time savings average around 1.78 hours per day per inspector and inspectors collect 2.75 times more data than ever before. Cost savings of using e-construction have been reported at approximately $40,000 per construction project per year (Weisner et al., 2017).

Some technologies, which include digital, visualization, and modeling technologies, safety technologies for workers and motorists, and construction automation and material technologies, are currently being used in the construction industry. Many of the technologies included in these categories are new and innovative to the transportation construction industry, and their use and implementation vary significantly across the United States. The variety of use and experience with emerging technologies is attributed to various challenges and barriers that DOT face to investigate, test, and implement a specific technology for construction delivery. Further development of innovative technologies for construction depends on the support a State DOT received from internal management and the state legislation as well as the ability of the technology to solve a problem within the specific processes of a state DOT. As technologies continue to be introduced and improve, state DOTs continue to consider and explore various technologies for construction. The purpose of this thesis is to shed some light on the current state in the use of emerging technologies by state DOTs for highway construction delivery.

1.2 Research Goals

This thesis intends to investigate the state-of-practice related to emerging technologies to understand how DOTs apply technologies to deliver highway construction projects. The study also examines the existing barriers that limit the implementation or further application of new technologies. The thesis focuses on the technologies shown in Table 1.1.

Table 1.1 Emerging technologies investigated in this thesis and examples of each.

Emerging Technology	**Examples**
Visualization and modeling technologies for constructability, communication, and documentation during construction	• 3D and 4D modeling • Virtual and augmented reality • Virtual design and construction • Building and Bridge information modeling • Civil integrated management

Interconnected construction vehicles, equipment, and tools at construction project sites	• Haul vehicles • Delivery vehicles • Machine guidance controls for equipment • e-Ticketing
Safety technologies used during construction for DOT and contractor workers, and traveling motorists	• Variable speed zones • Proximity and intrusion warning alarms • Queue detection systems • Communication systems for motorists
Instrumentation during construction to evaluate short-term or locked-in boundary conditions or member forces for specialty projects	• Stress and strain gauges • Sensors to measure environmental conditions • Sensors to measure specifications • Ground penetrating radar
Uses of unmanned aerial systems for construction monitoring, documentation, surveying, and inventory	• Construction surveys • Inspections • Site mapping • Asset management/Inventory
Any other promising technologies currently in use by DOTs	• Remote controlled trench compactors • Intelligent compaction and thermal profiling • Portable rumble strips • Non-destructive testing devices

Explicitly, the thesis (1) identifies technologies currently in use by DOTs to deliver construction projects; (2) determines the strengths and weaknesses of emerging technologies; (3) recognizes unique opportunities to improve construction delivery; (4) identifies barriers that DOTs have experienced in applying specific technologies to construction delivery; and (5) documents how DOTs are using specific emerging technologies. Finally, the thesis documents lessons learned in the application of specific emerging technologies and their use by DOTs for highway construction.

The findings from this study provide highway agencies with knowledge and recommendations for technology implementation on infrastructure projects. The aim of these recommendations is to provide guidance to highway agencies that are willing to use technologies for the first time or have a very little experience using them or have not realized the benefits of technology due to lack of standardized documentation or the agency being of risk averse nature as implementation of any technology.

1.3 Thesis Organization

The thesis is divided into six chapters:

Chapter 1, this chapter, introduces the subject area and covers the scope, objectives, and study methodology.

Chapter 2 provides the background and literature of the five technologies and the various types and uses of each technology as applied to construction delivery.

Chapter 3 provides an overall framework of the research methodology employed in the study. A discussion is made on the point of departure, research questions, and methodology including the content analysis, a national survey, a case study.

Chapter 4 provides the details of survey results in detail.

Chapter 5 summarizes the results of the project case study on how the technology is being used at the project level and discusses the deviation of implementing technologies from the agency level.

Chapter 6 provides the conclusion for the thesis and recommendations for future research.

CHAPTER 2 – LITERATURE REVIEW

2.1 Introduction

This chapter of the thesis discusses the literature review on the implementation of emerging technologies for construction delivery of highway transportation projects. The objective of this chapter is to establish the background and context for the findings from the survey and case examples presented in Chapters 3 and 4 respectively. A range of emerging technologies that are in use by various stakeholders in the construction industry are discussed at length. It is noted that the term "technology" has broad representation and the same technology can underpin a number of different products, offered by the same or different vendors. This chapter focuses on discussion of three main types of technologies used in construction: (1) digital, visualization, and modeling technologies; (2) construction automation technologies; (3) work zone safety-related technologies. The chapter concludes with a detailed discussion on the influence of emerging technologies for highway construction.

2.2 Digital, Visualization, and Modeling Technologies

The construction industry is one of the least digitized sectors. A recent report shows that the construction sector is relatively less digitized in business transactions, interactions, and processes because of geographical dispersion and technical challenges (Mckinsey&Company 2016). Digital solutions for construction delivery focus on online real time sharing of information that helps to achieve transparency and collaboration, improved quality control, and timely risk assessment, and cost effective outcomes (Avsatthi 2017). The construction sector has exhibited very little productivity growth during the last two decades. There is a direct correlation between the extent to which an industry is digitalized and productivity growth (McKinsey Global Institute, 2018).

For example, the adoption of best practices with regard to the infusion of digital technology, new materials and advanced automation, can contribute 6-10% to productivity increases and 4-5% to cost savings in the industry (McKinsey Global Institute, 2018). Continued reliance on paper-based processes during project development and delivery (e.g., design, procurement, and construction progress reports) is a contributing factor to the poor productivity in the construction sector and impeding innovation (Pistorius, 2017). A lack of digitalization causes delays in information sharing that may lead to challenges in data analysis, progress reports, and other issues. Figure 2.1 summarizes digital solutions for delivering construction projects.

State DOTs have traditionally administered contracts and managed construction of highway projects using paper-based documentation systems, digital technologies are increasingly being used in highways recently. In 2015, the Federal Highway Administration (FHWA) Every Day Counts (EDC-3) initiated e-Construction technologies including digital electronic signatures, electronic communication, secure file sharing, version control, mobile devices, and web-hosted data archival and retrieval systems to improve construction documentation management. EDC-3 found that in addition to time and cost saving, the e-Construction process allows faster approvals, increased accuracy, and enhanced document tracking, all while increasing transparency (FHWA EDC-3, 2017). Building upon the success of EDC-3, FHWA-EDC4 promotes *e-Construction* as practices that can be used in concert to help deliver transportation improvements smarter and faster. The FHWA EDC-4 highlights that "*paperless technologies enhance partnering among stakeholders on construction projects, improving communication and workflows while streamlining project delivery*."

Design management	Scheduling	Materials management	Crew tracking
• Visualize drawings and 3-D models on-site, using mobile platforms • Update blueprints in the field with markups, annotations, and hyperlinks	• Create, assign, and prioritize tasks in real time • Track progress online • Immediately push work plan and schedule to all workers • Issue mobile notifications to all subcontractors	• Identify, track, and locate materials, spools, and equipment across the entire supply chain, stores, and work front	• Provide real-time status updates on total crew deployed across work fronts, number of active working hours, entry into unauthorized areas, and so on
Quality control	**Contract management**	**Performance management**	**Document management**
• Offer remote site inspection using pictures and tags shared through app • Update and track live punch lists across projects to expedite project closure	• Update and track contract-compli-ance checklists • Maintain standardized communication checklists • Provide updated record of all client and contractor communications	• Monitor progress and performance across teams and work areas • Provide automated dashboards created from field data • Offer staffing updates and past reports generated on handheld devices	• Upload and distribute documents for reviewing, editing, and recording all decisions • Allow universal project search across any phase

FIGURE 2.1 Digital solutions for construction needs (Mckinsey&Company 2016)

There is a wide range of technologies directly linked to digitalization and visualization. This section discusses the following common digital, visualization, and modeling technologies and applications:

- Light Detection and Ranging (LiDAR);
- Building Information Modelling (BIM); and
- Virtual reality (VR) and augmented reality (AR)

Light Detection and Ranging (LiDAR)

LiDAR is an optical remote sensing technology typically used for measuring the distance and direction between a surface and its sensing units. LiDAR is becoming increasingly popular as a means to create accurate three-dimensional models of any surface within visual sight of the sensing unit. Almost all state DOTs across the U.S. have been adopting practical use of the LiDAR technology for transportation related applications. Typically, there are three main LiDAR types: (1) static LiDAR (i.e., a system is mounted to a single location), (2) mobile LiDAR (a system can be attached to a vehicle), and (3) airborne LiDAR (a system is attached an aircraft). The static LiDAR, collects highly accurate data, but is comparatively much slower than mobile and aerial LiDAR and exposes DOT personnel to more traffic risk. Both aerial and mobile LiDAR provide mapping-grade accuracy at high rates of travel. The mobile LiDAR application involves digital highway measurement vehicles, typically including LiDAR, inertial navigation systems, and GPS, can be used to measure pavement markings and pavement cross sections, including shoulders and curbs (NCHRP Synthesis 367). The aerial LiDAR system can collect data when traveling at 115 miles per hours at an elevation of approximately 1,640 feet (Michigan DOT 2014). Figure 2.2 shows an overview of common technologies used in site surveys.

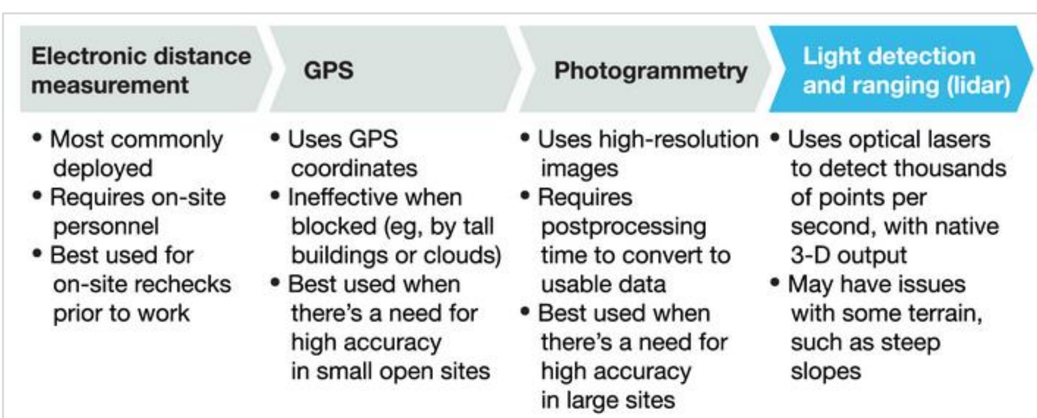

FIGURE 2.2 Common technology evolution in site surveys (Mckinsey&Company 2016)

One of the key benefits of LiDAR technology is that its acquired data can be used 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 "*Guidelines for the Use of Mobile LIDAR in Transportation Applications*" shows various applications of using mobile LiDAR related to construction delivery, including:

- *As-build and repaired documentation*—the data is integrated into a centralized database that is continuously updated for future planning and construction.
- *Pavement smoothness and quality determination*—data collected at higher resolutions can be used to evaluate pavement smoothness and quality.
- *Construction automation, machine, quality control*—Change detection and deviation analysis software uses design models to identify deviations from LiDAR point clouds for construction quality control.
- *Building information modeling (BIM)/Bridge Information modeling (BrIM)*—LiDAR provides an abundance of sample points and models extracted from point cloud data will generally be geometric primitives.
- *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 (checking for intersections of proposed objects with existing objects modeled in the point cloud
- *Inspections*—MLS can provide overall geometric information and a gross condition assessment.

NCHRP Report 748 indicates that transportation agencies use a cost/benefit analysis as a main indicator to determine if MLS is the optimal technological approach for a specific project. Comparing to other potential technologies, the typical steps to perform the cost/benefit analysis for mobile LiDAR are as follows:

- Including all potential uses of the data;
- Estimating the workload needed;
- Deciding how the data will integrate into existing workflows;
- Determining what workflows would need to be improved and/or updated;
- Understanding the ability to data sharing;
- Incorporating both resolution and accuracy needs; and
- Considering additional data acquired from the same platform (Olsen, et al. 2013).

Building Information Modelling (BIM)

Computer-aided design was first used for aircraft in the 1970s to transform the design and manufacturing. A similar approach to the construction industry was introduced in the mid-1980s (Aish 1986 and Ruffle 1986). However, the concept of using computer-aided design was not popular until the early 2000s when Autodesk published a white paper entitled "Building Information Modeling" (Autodesk 2002). Since BIM has evolved big time it finds several applications in construction. BIM is the extensive process of developing and using a computer-generated model to simulate the phases of a construction project digitally. Consequently, this includes simulation of planning, design, construction and operation of buildings and structures. BIM models have many applications and purposes like visualizations through 3D rendering can be generated, drawings and shop drawings can be extracted and building codes can be reviewed through analysis of object parameters. Figure 2. 3 shows BIM functionalities to integrate design, cost, and schedule with a 3D output.

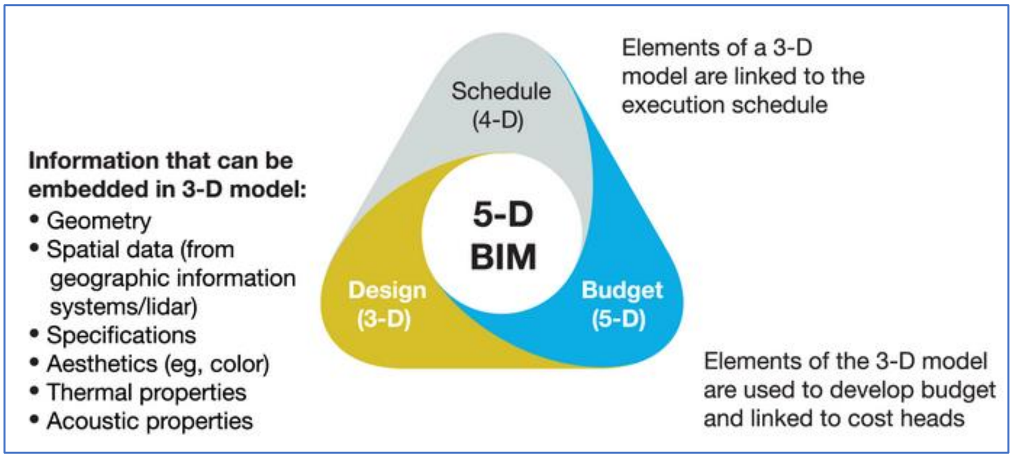

FIGURE 2.3 BIM functionality (Mckinsey&Company 2016)

Based on the report from Dodge Data, Figure 2.4 shows the level of adoption of BIM in infrastructure projects in different sectors from 2009 to 2013. Specifically, the level of using BIM increased more than double from the years of 2009 to 2013 for the road and bridge projects.

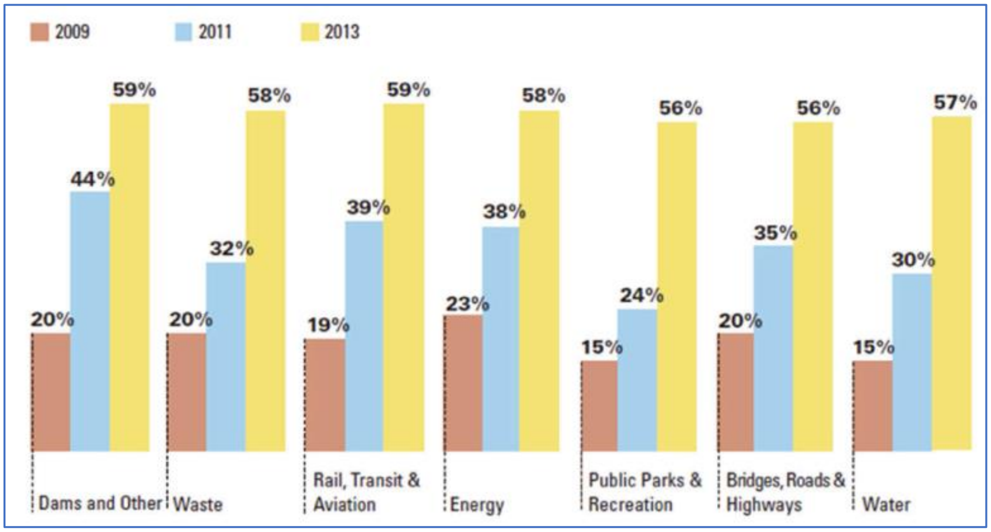

FIGURE 2.4 Level of adoption of BIM in infrastructure projects (Dodge Data & Analytics 2014)

Figure 2. 5 shows agencies promoting application of BIM associated with A/E firms, contractors, and owners. Figure 2.5 indicates that as of 2012 more than 51% of projects represent a "high/very high" utilization rate of BIM technologies.

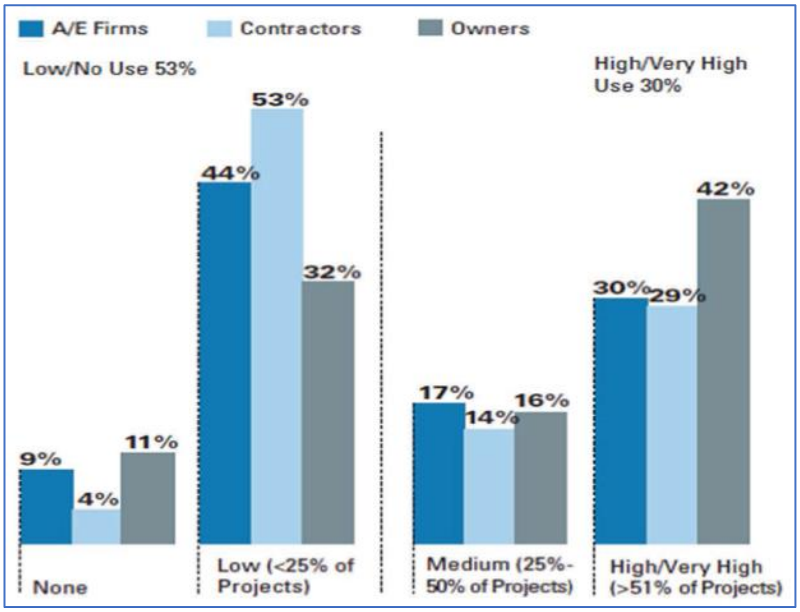

FIGURE 2.5 Agencies promoting application of BIM (Dodge Data & Analytics 2012)

FHWA emphasized 3D engineered models for design and construction starting in EDC-2 and was continuing this support under EDC-3. These initiatives found that the 4D and 5D modeling efforts

> Some key benefits realized from use of 3D models include:
> - Improved project delivery by accelerating construction progress, making construction more accurate and cost effective, and increasing safety on the job site.
> - Improved communication between key stakeholder communities (e.g., owner, public, consultants, contractor, utility companies, prefabricators, and material suppliers).
> - Enhanced clash detection and identification of possible errors and inconsistencies in design before construction.
> - Improved visualization of subgrade features and potential utility conflicts.
>
> FHWA (2013)

facilitate communication between multiple stakeholders and allow contractors to streamline construction schedules, which can produce major cost and schedule advantages (FHWA 2013).

Recently, NCHRP Report 831, *Civil Integrated Management (CIM) for Departments of Transportation*, provides guidance for state DOTs and other agencies for adopting and applying practices and tools entailing collection, organization, and management of information in digital formats about a highway or other transportation construction project. The term "CIM" derives from BIM practices, but focuses on horizontal construction. CIM is defined as a technology that encompasses the set of foundational and emerging technologies that assist in digital workflow that includes data collection, design, construction, and asset management activities (NCHRP Report 831). The study classifies CIM into two categories: CIM tools and CIM functions. Figure X.6 graphically illustrates the list of CIM tools under three main groups of technologies: modeling, data management, and sensing. It is noted that there are various technologies used in CIM tools, including LiDAR, Unmanned Aerial Vehicles (UAVs), or n-D modeling tools (Figure 2.6).

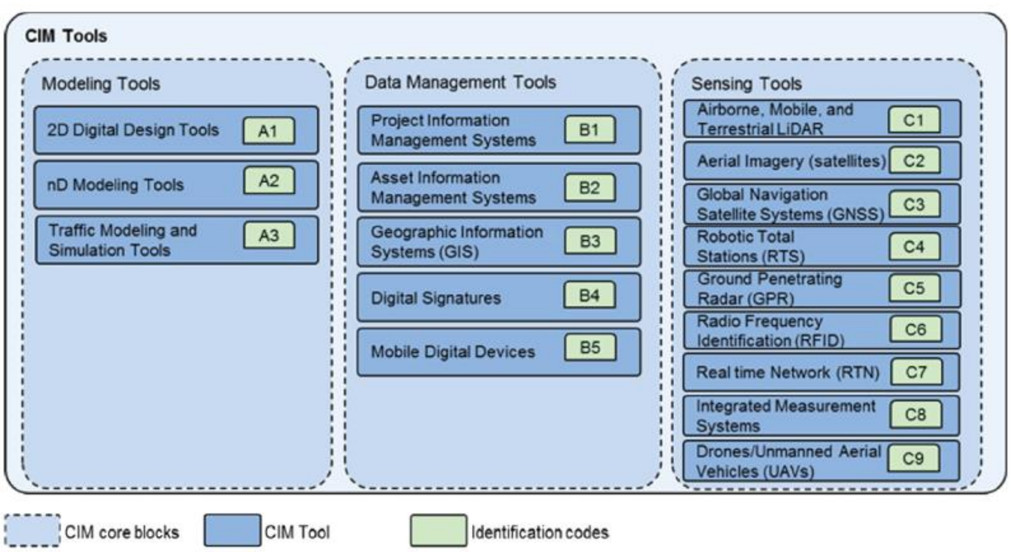

FIGURE 2.6 CIM tools (NCHR Report 831)

Figure 2.7 shows the CIM functions along with different project activities in surveying, design, construction, and project management. It is noted that project activities do not correspond to project phases of the project development process, but relate to a group of similar CIM functions.

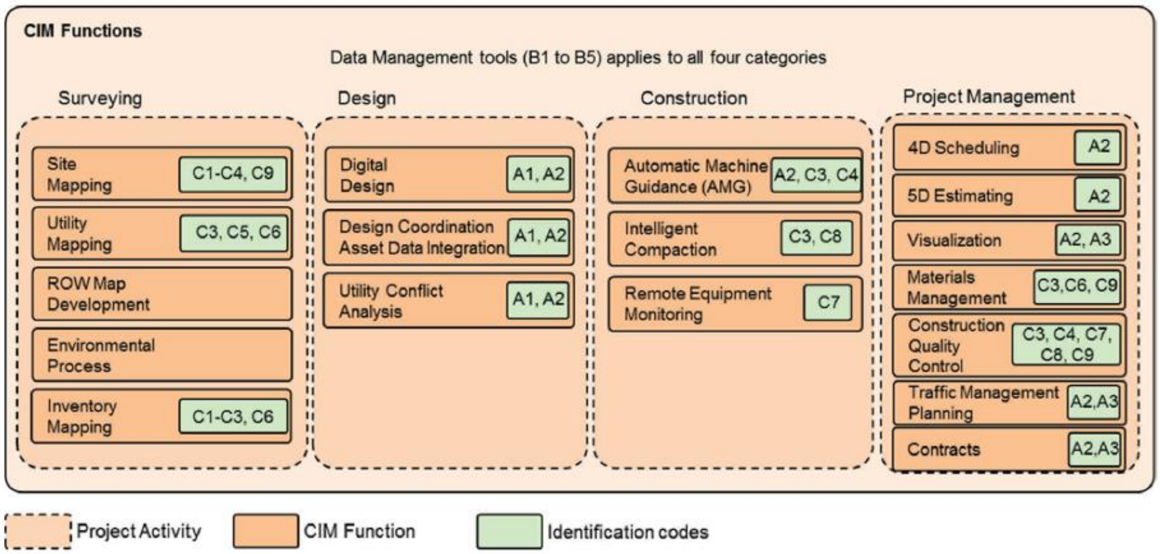

FIGURE 2.7 CIM functions (NCHR Report 831)

NCHRP Report 831 also cited the perceived benefits and challenges of BIM based on the study from OPEN BIM network (building SMART UK User Group 2014). Figures 2.8 and 2.9 show the perceived benefits and challenges of BIM.

FIGURE 2.8 Perceived benefits of BIM (NCHR Report 831)

FIGURE 2.9 Perceived challenges of BIM (NCHR Report 831)

NCHRP Report 831 concluded that although BIM/CIM practices have been successfully used in a number of projects, but they are not widely adopted in transportation projects of all scales. The BIM/CIM benefits and challenges are often based on a case-by-case analysis.

Virtual reality (VR) and augmented reality (AR)

VR technology superimposes a computer-generated image on a user's view of the real world, thus providing a composite view that isolates the user's sensory receptors (eyes and ears) from the real physical world (Behzadan et al., 2015). VR has been used within the construction industry for many different applications such as design, collaborative visualization, and as a tool to improve construction processes. VR forms a good route for building design as it provides 3D visualization that can be manipulated in real-time and be used collaboratively to explore different stages of the construction process (Whyte, 2007). In contrast to VR, AR creates an environment where computer generated information is superimposed onto the user's view of a real-world scene. AR consists of a live, imitative version of the real world – with the capacity to add certain elements to the simulated landscape. AR preserves the user's awareness of the real environment by compositing the real world and the virtual contents (Azuma et al. 2001).

A VR/AR system, typically referred to hardware components, software, and algorithms, has various applications in the construction industry. Rankohi and Waugh (2013) showed that field workers and project managers have high interest in using VR/AR technologies during project construction phase mainly to monitor progress and detect defective work. Shin and Dunston (2008) discussed the potential of AR applications in eight work tasks of a construction project, including: layout, excavation, positioning, inspection, coordination, supervision, commenting, and strategizing. A VR/AR technology can also be integrated with BIM to create a seamless interaction between offices and work site (Pistorius, 2017). Researchers show that VR/AR allows users to find difference between an as-design 3D model and an as-built facility (Georgel et al. 2007). Other researchers implemented a system for visualizing performance metrics to represent progress deviations through the superimposition of 4D as-planned models over time-lapsed real jobsite photographs [Golparvar-Fard et al. 2009].

Many VR/AR applications focus on construction safety including safety planning (e.g., hazard identification), safety training and education, and safety inspection and instruction. For example, Albert et al. (2014) developed a System for Augmented Virtuality Environments (SAVEs) to more effectively detect hazard stimuli in dynamic construction environments. SAVES was designed to immerse trainees in a hyper-realistic, 3D environment including functionality to assess worker hazard recognition performance, provide feedback, and equip workers with a holistic approach for hazard stimuli detection using retrieval mnemonics. Figure 2. 10 shows an overviews of SAVEs.

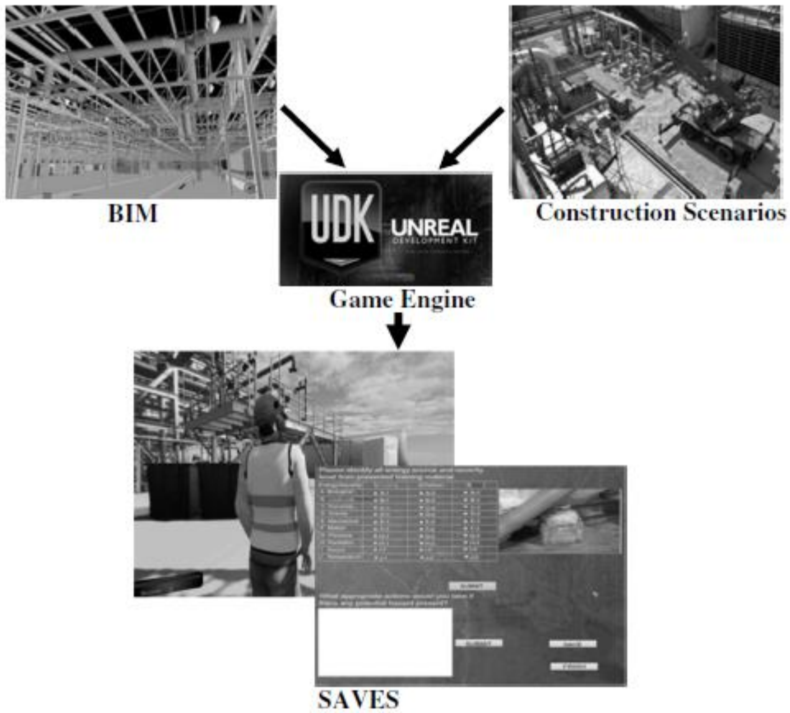

FIGURE 2.10 System for Augmented Virtuality Environments (Albert et al. 2014)

It is important to note that although VR/AR technologies have a number of applications to improve construction performance and received considerable attention within research communities, they are still relative new in the transportation construction industry. In fact, Pistorius (2017) indicated that the construction industry has so far only "dabbed in the use of VR/AR to aid construction

> **Safety enhancement applications of VR/AR**
>
> - Virtual and augmented reality allows costly mistakes to identified and rectified before they occur by being able to visualize how something will work, without the costs and hazards of physical trial and error.
> - Field conditions can be communicated in real-time to people who are not physically present on site.
> - Possible dangerous situations can be explored without subjecting people to dangerous environments.
> - Aid in safety training for new employees. Dangerous and hazardous situations can be simulated, and employees trained to deal with them, without having to do the training in a real environment.
>
> Pistorius (2017)

projects." However, because cheaper and higher quality 3D options come to market, it is expected that VR/AR technologies are rapidly used in construction project in the future (Pistorius 2017).

2.3 Construction Automation Technologies

Construction automation is capital intensive and machine centered to necessitate disruptive changes in products, processes, organization, management, stakeholders, and business models (Bock 2015). Implementation of automation on construction sites is a mechanism to enhance construction productivity (McKinsey Global Institute, 2017). A number of emerging technologies are contributing to automation in the construction industry. For example, 3D printing is finding increasingly use in construction, including the printing of parts and models but also modular panels and even entire buildings. Large 3D printers specifically designed for construction use a technique known as 'contour crafting', with cement as the 'ink'. Robotics is set to impact on construction, ranging from robots involved in site preparation and waste clearance to brick laying and welding. Unmanned aircraft vehicles have many construction applications. They can be fitted with a range of image, video and related sensors. This enables them to conduct aerial mappings and surveys, safety inspections as well as recordings of project progress. Although approaches of construction automation are still in a seed phase, it can be expected that construction automation may soon enter into the growth phase and encounter adoption on a larger scale (Bock 2015). While many technologies contribute to construction automation, this section discusses three main following technologies:

- Construction robotics
- 3D printing
- Unmanned aircraft systems

Construction Robotics

Robotic technology provides the construction industry with numerous advantages, including improved productivity, reduced construction cost, and higher quality. Robots perform work with precision and accuracy throughout all construction processes leading major time and financial savings (Pistorius 2017). Using robotics in construction has a substantial effect on the construction workforce and labor market. The World Economic Forum predicts that the increasing use of machines allows construction companies to employ fewer staff who become responsible for a variety of activities with different core skill sets (Construction Word 2017).

One of the earliest uses of robotics in construction has been in demolition, including breaking down walls, crushing concrete and gathering debris. Currently, robotics in construction is being used for self-operating machinery, including bulldozers, excavators, and cranes, but the implications for such technology are important. Using robotic systems allows for greater automation in various construction processes. It is expected that the traditional construction activities such as bricklaying, tiling, spool fabrication, welding, material handling, packing, dispensing, concrete recycling, cutting, or packing can be automated (partially or fully) using robots to improve precision and accuracy throughout construction processes (Pistorius 2017). For example, a Semi-Automated Mason (SAM) bricklaying robot, created by New York-based Construction Robotic Company, can lay 3,000 bricks per day, compared with the average construction worker who can lay 400-500 per day (Construction Robotics 2018). Figure 2. 11 shows an example of a SAM bricklaying robot. It is noted that SAM is not completely automated – a human needs to follow it and tidy up after it or carry out more intricate tasks such as laying corner bricks. SAM can save a great deal of lifting. It is also able to perform a wide array of functions due to computer algorithms, sensors that measure velocity, orientation and angles, and a laser that acts as the robot's eyes to sense depths and distance (Construction Robotics 2018).

FIGURE 2.11 SAM bricklaying robot (Construction Robotics 2018)

Bock (2015) categorized construction robotic technology into five categories: (1) robot-oriented design, (2) robotic industrialization, (3) construction robots, (4) site automation, and (5) ambient robotics. The robot-oriented design is concerned with the co-adaptation of construction products, processes, organization and management, and technology and innovation methodologies. The robotic industrialization involves technologies to transform parts and low-level components into higher level components by highly mechanized, automated, or robot supported industrial settings. The high level components include building modules (prefabricated bath modules or building subsystems) and building units (prefabrication of fully finished building). The construction robots initially focus on simple systems in the form of single-task construction robots (STCR) that can execute a single, specific construction task in repetitive manner. In most case, the construction robots were not integrated with upstream and downstream construction processes because of demanded safety measurements and hindered parallel execution of work tasks by human workers (Bock 2015). The site automation involves setting up controlled, factory-like environments on the construction site in the form of automated/robotic on-site factories. The site automation is considered as a logical step forward to integrate stand alone or STCR technology into controlled on-site environments to networked machine systems and to improve organization, integration, and material flow on the construction site. Finally, the ambient robotics involves merging construction automation technology, STCR approaches, service robot systems, and other microsystems technology to advance human–machine communication in the built environment.

In the highway construction sector, the FHWA published Automated Machine Guidance (AMG) in 2013 to explore the use of automated machine for highway projects. AMG involves using construction equipment (e.g., bulldozers, blades, scrapers, and paving machines) mounted with onboard computers to provide horizontal and vertical guidance in real time to construction equipment operators (FHWA 2013b). AMG uses positioning devices, singly or in combination, such as Global Positioning Systems (GPS), total stations, or rotating laser levels to determine and control the real time position of construction equipment. The onboard computer combines input data with engineered digital terrain and design models to provide output to video screens and hydraulic systems, all to assist the equipment operator in constructing the project more efficiently (Caltrans 2013). Figure 2.12 shows an example of AMG systems used in Caltrans.

FIGURE 2.12 AMG system (Caltrans 2013)

FHWA notes that the use of AMG improves construction efficiency, quality, and safety while reducing schedule, cost, and the environmental impacts. Specifically, the typical benefits of AMG are:

- Reduced construction costs by
    - Decreased costs of maintenance and fuel
    - Decreased agency support costs
    - Improved machine productivity
    - Lowered operating costs (wages, overtime)
    - Increased potential for electronic "as-built"
- Reduced project schedules by
    - Increased equipment productivity
    - Reduced time for survey and staking
    - Improved equipment logistics arising from less rework

- Increased quality by
    - Increased levels of accuracy with greater precision over conventional construction methods
    - Increased control of elevation and cross-slope for asphalt paving
    - Fewer errors requiring rework
    - Decreased margin of error
    - Increased calculation accuracy for quality assurance and quantity calculations
    - Increased efficiency in calibration and control of paving equipment by total station compared with string line and level
- Improved safety by
    - Reduced need for elimination of string lines for improved worker safety
    - Fewer field personnel exposed to heavy equipment and potential back-over/run-over incidents (FHWA 2013b).

3D printing

3D printing is a process to create 3D objects from a digital file. The process includes laying down successive layers of thin horizontal cross-sections until the entire object is completed. Current materials in use for 3D printing technology include plastics, glass, ceramics, liquids, organic materials, cement, bituminous concrete, metal powders, and others. There are several applications from using 3D printing technology. For example, models of buildings, prototypes and smaller parts can be 3D printed (Pistorius 2017). Using 3D printers can also create construction modules to be shipped to the construction site from off-site factories. Further, large construction structures such as buildings or bridges can be 3D printed with super-size printers and specialized materials. Figures 2.13 shows an example of using 3D printers for a wall structure.

FIGURE 2.13 3D printed walls (3D Printhuset, 2018)

Among a number of using 3D printing technology in the construction industry, the typical benefits include:

- Increased speed, accuracy and efficiency;
- Lowering labor costs and cost savings on supplies;
- Reduced the amount of waste; and
- Creating safer work environments and reducing health and safety risks (Pistorius 2017).

However, 3-D printing is still in the early stages of its development and cannot yet be deployed at the scale and speed required for large projects (Mckinsey&Company 2016)

> There is tremendous potential for 3D printing to revolutionize the way our infrastructure is built in the future. But in order to achieve this potential, there must be collaboration and further innovation of the engineering, construction, materials, technology and financial industries — in addition to leadership of federal, provincial and local governments.
>
> Harrington (2016), Chairman and CEO of Parsons

Unmanned Aerial Systems

Unmanned aerial systems (UASs) are an emerging technology that has a wide range of applications in construction, ranging from monitoring tasks to simple item manipulation or cargo delivery scenarios. The definition of UASs or unmanned aerial vehicles (UAVs) is broad. In practice, any aerial vehicle that does not rely on an on-board human operator for flight, either autonomously or remotely operated, is considered a UAV. UASs are often consisted one or more UAVs. Typically, UAVs can be equipped with various sensors, such as video or still cameras, including far and near infrared, radar or laser based range finders, or specialized communication devices (GDOT 2014). Figure 2.14 shows a fixed and rotary wing UAV.

FIGURE 2.14 Fixed wing (left) (ADS 2016) and rotary wing UAV (right) (DJI, 2016)

Pistorius (2017) summarizes a number of applications of UAVs in the construction follows:

- *Pre-project assessments and project survey data*—UAVs can offer unprecedented aerial images of a project site much more accurately and realistically than aerial photographs.
- *Conducting aerial surveys*—UAVs can provide real-time aerial views of key project areas, allowing management and construction staff to monitor operations and performance, which

in turn supports decision-making.

- *Site mapping*—UAVs can be used to document project evaluation and progress for costing, remote project management and related applications.
- *Building surveillance and inspections*—UAVs can be used for inspection, including of roofs, high tension electric wires, remote sites and other areas which are difficult to access.
- *Asset tracking*—UAV can be used to keep track of movement of machines and equipment, tools, vehicles and people. UAV can monitor workers on site and is a convenient tool to keep track of how many employees are working in sensitive or hazardous areas.
- *Monitoring the movement of materials, stockpile reporting and inventory management*—UAVs can be used to keep record of linear metres of material being installed, for example
- *Enhanced safety*—UAVs can provide real-time data of safety violations or situations which might have a negative safety impact during the construction process.
- *Enhanced 3D modeling*—UAV data can be acquired instantly and integrated with mapping and BIM models.

Several state DOTs have used UASs for different purposes such as tracking construction progress, monitoring roadside environmental conditions, or traffic management and safety improvement. For example, Virginia DOT demonstrates the feasibility of UAS for real-time traffic surveillance, monitoring traffic incidents and signals, and environmental condition assessment of roadside areas (Carroll and Rathbone 2002). Ohio DOT uses UAVs to collect data about freeway conditions, intersection movement, network paths, and parking lot monitoring (Coifman et al. 2004). Utah DOT, in collaboration with Utah State University Hydraulic Lab, used UAV systems to take high-resolution pictures of highways to inventory their features and conditions at a very low cost and in short time TRB (2012). The North Carolina DOT uses UAS to support construction inspections and perform accident scene reconstructions to open travel lanes more quickly (FHWA 2018). New Jersey DOT is currently using UAS to support structural inspections, real-time construction project monitoring, traffic incident management, aerial 3D corridor mapping, emergency response assessments, and traffic congestion assessments (FHWA 2018). Recently, Kansas DOT is beginning a pilot project to determine how UAV could be used in future road design work, employing UAV technology in conjunction with a road project for the first time in May 2018. Figure 2.15 shows an example of using UAV for highway construction.

FIGURE 2.15 UAV application for highway construction (FHWA 2018)

One of the selected FHWA/EDC-5 innovations is the implementation of UAVs for highway construction. The FHWA/EDC-5 (2018) highlights that "UAS improve operations, construction, inspection, and safety by collecting data needed to design, build, and operate the highway system."

> The benefits of unmanned aerial systems (UAS) are wide ranging and impact nearly all aspects of highway transportation. UAS provide high-quality survey and data mapping that can be collected automatically or remotely. Large areas can be mapped relatively quickly in comparison to traditional survey and mapping practices. UAS are also used for survey and imagery as part of emergency response events where traditional surveying and mapping practices are inadequate or impossible.
>
> FHWA/EDC-5 (2018)

Three main benefits from UAVs include improved construction safety, accelerated construction, and enhanced asset maintenance.

2.4 Safety Technologies

State DOTs are implementing different safety technologies to protect construction workers and traveling motorists from incidents. Some of the commonly used safety technologies are work zone intrusion alarms, wearables, proximity warnings system, amongst others. While many technologies contribute to highway construction safety, this section discusses three main following technologies:

- Work zone intrusion alarm systems
- Wearable technologies
- Variable speed limits and dynamic message signs

Work zone intrusion alarm systems

A work zone intrusion alert technology is a type of safety system that is used in a roadway work zone to alert field workers and secure time for them to escape when errant vehicles intrude into the work zone (ODOT 2017). Work zone intrusion alarm systems (WZIAs) are installed upstream of a work zone to address drivers not complying with the work zone and roadway messaging and entering an active work area where workers are located (MnDOT 2015). These systems improve upon existing work zone signage which intends to provide safety to workers, allow sufficient space for roadway work, and provide signs and/or messaging systems that improve roadway safety and inform motorists. WZIA offers an alert to roadway workers when a non- authorized vehicle enters the work zone and typically consists of static signing, detection devices, dynamic message signs, and an alarm or other notification device. Figure 2.16 shows a typical work zone intrusion alarm system.

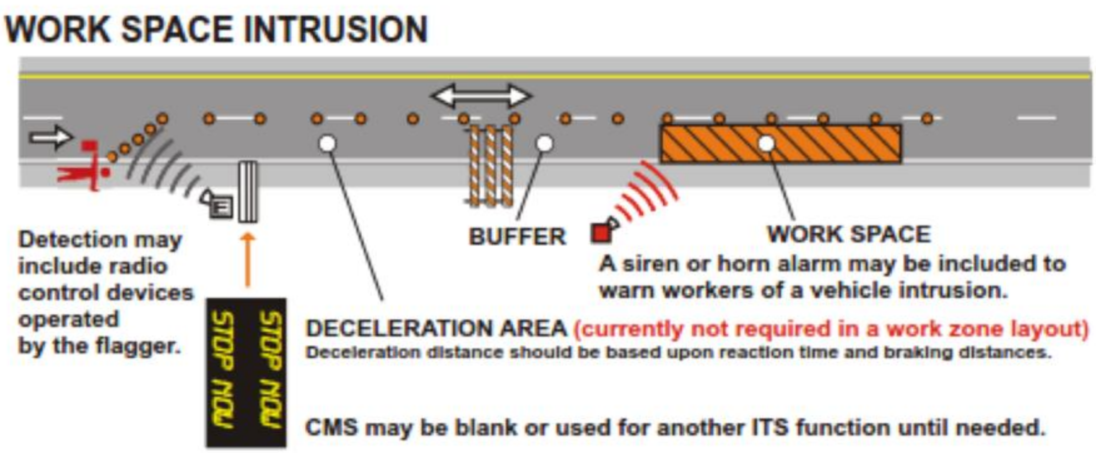

FIGURE 2.16 A typical work zone intrusion alarm system

The main benefit of WZIA system includes reducing the risk of injury or death by providing advance warning to workers and equipment operator. Additionally, it is relatively easy to deploy and retrieve thereby creating minimal exposure of workers to roadway hazards and causing minimal interruption to construction operations. However, the technology has several limitations. For example, WZIA sometime provides sound signals that are not always effective on a construction site where many equipment are working together at same time (ODOT 2017).

Wearable technologies in construction

Wearable technologies refer to textiles and other devices worn by a person. The information collected from wearable technologies reflect the person's physical and emotional state, movement or position as well as other environmental variables. Wearable technologies are used for the identification, tracking and geo-location of people as well as the monitoring of their health status. Some of the benefits of wearable technologies in construction include improving safety, real time streamlined data collection process and enhancing communication. Not only is there a more robust and accurate data set to analyze and utilize on current or future projects, but it also frees up the project manager's time which was spent walking the site conducting headcounts or safety checks.

The common wearable technologies used at construction jobsites are:

- *Smart Cap***:** This device uses brain waves to monitor fatigue and send alerts through vibrations and noise to the wearer when a hazard is identified.
- *Smart Vests*: With GPS capabilities, vital monitoring, emergency buttons and built-in alert systems, smart vests offer enormous benefits for all construction workers.
- *Smart Helmet*: This device includes features such as fall impact detection, emergency alerts and video recording. Using RFID technology, the device warns the worker with an alarm if it enters an unsafe zone in proximity to a heavy equipment.
- *Smart Glasses*: The device provides workers with the ability to record videos and receive instructions from more skilled workers or managers off-site in real-time.

Variable Speed Limits and Dynamic Message Signs

Dynamic message signs (DMSs), also known as changeable message signs (CMSs), are traffic control devices used for traffic warning, regulation, routing and management. DMSs are intended to affect the behavior of drivers by providing real-time traffic- related information (Dudek 2004). As a critical component in intelligent transportation systems (ITS) of modern traffic management, DMSs are widely used as an effective means to provide motorists with up to date information regarding accidents, congestion, road conditions and travel time. Variable speed limit (VSL) systems are used to provide speed variation through work zones. VSL helps to reduce speeds when workers are present, work activity near travel lanes, or unfavorable weather conditions. The systems detect traffic volumes and/or speeds at various locations using sensors and send the data to a computer that can use the data to determine the most appropriate message to display. Figure 2.17 shows a dynamic message sign.

FIGURE 2.17 Example of Dynamic Message sign

2.5 Alternative Construction Materials

Construction materials play an essential role in any highway projects. Materials usually account for more than half the total cost of projects (Agarwal et al., 2016). The traditional materials such as concrete, steel, and asphalt remain widely used with continuous improvements to these materials through extensive research efforts. Recent advances in technologies have led to many new materials. This section discusses briefly the improvements in traditional construction materials and newly developed materials.

Improvements in pavement materials

Concrete is the most widely used material in the construction industry. It is estimated the annual direct cost for maintenance and repair of concrete highway bridges in the U.S. due to reinforcement corrosion amounts to 4 billion dollars (FHWA, 2001). Researchers have developed a range of microcapsule-based, self-healing systems in recent years. Jonkers et al. (2010) developed an innovative plan to increase the lifespan of concrete by embedding self-activating limestone-producing bacteria within the building material itself. Several direct benefits of concrete self-healing are: (1) the reduction of the rate of deterioration, (2) extension of service life, and (3) reduction of repair frequency and cost over the life cycle of a concrete infrastructure (Li and Herbert, 2012). These direct benefits lead to indirect advantages including enhanced environmental sustainability, reduction in energy consumption and pollutant emission in material production and transport, and improved traffic and construction safety during repair/reconstruction events. Self-healing approaches may be broadly grouped into five categories: (a) chemical encapsulation, (b) bacterial encapsulation, (c) mineral admixtures, (d) chemical in glass tubing, and (e) intrinsic self-healing with a self-controlled tight crack width (Li and Herbert 2012). Figure 2.18 illustrates these five phases of self-healing concrete.

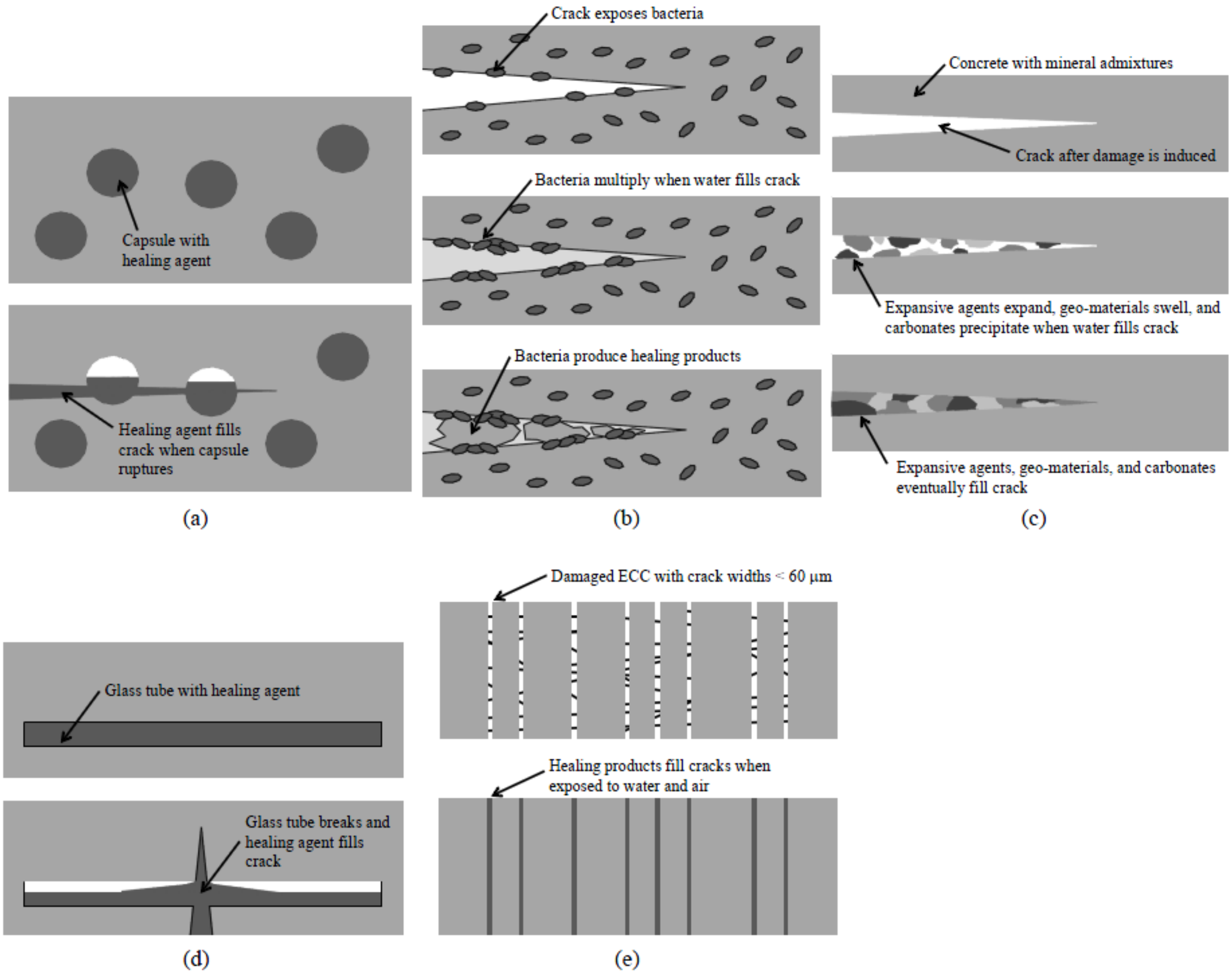

Figure 2.18 Five phases of self-healing concrete (Li and Herbert, 2012)

Similarly, current research in bituminous asphalt materials is investigating the use of adding micro- and nano-capsules and hollow fibers that include an asphalt rejuvenator to an asphalt mixture. This emerging technology would enhance an asphalt mixture's resistance to cracking damage caused by vehicle and environmental loads on the roadway. Accordingly, the maintenance of a deteriorated asphalt pavement can cost up to four times the amount needed to maintain asphalt pavement in excellent condition (Sahin, 2005). Therefore, since roughly 93% of the 2.6 million miles of United States paved roads are paved with asphalt, determining innovative ways to pave with asphalt using emerging technologies and research can substantially help reduce maintenance to DOTs for asphalt roadways (Clines, 2015).

With the use of asphalt rejuvenators, which emerged as an innovative product that helps improve aged asphalt binder characteristics found in the use of recycled asphalt material, roadways could "repair" themselves, which reduces the maintenance efforts needed by the state DOT. Asphalt rejuvenators work by softening the asphalt material and restoring the asphalt to maltenes ratio (Karlsson and Isacsson, 2006). However, the research found that surface treatments of asphalt rejuvenators typically only penetrate to a maximum depth of three-quarters of an inch, which does not penetrate deep enough into the used pavement (Chiu and Lee, 2006). Therefore, infusing novel micro and nano-technologies into the asphalt mixture will allow for the asphalt rejuvenator to penetrate the entire depth of the asphalt pavement (Garcia et al., 2010). Figure 2.19 illustrates the self-healing process of microcapsules with asphalt rejuvenator in an asphalt pavement.

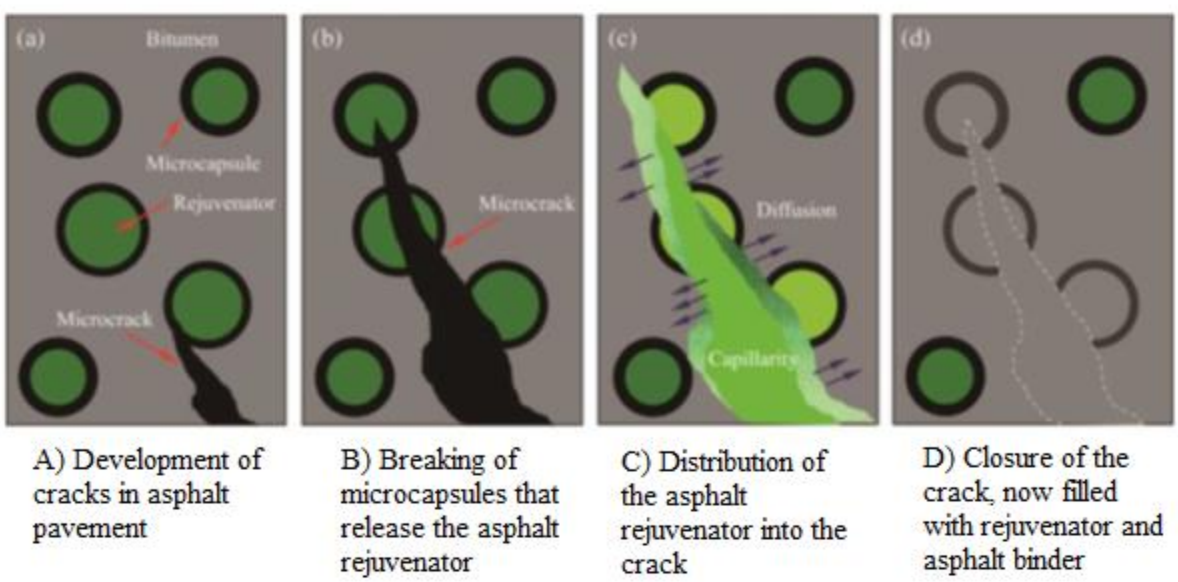

Figure 2.19 Asphalt pavement self-healing process using microcapsules (Su et al., 2016)

Other alternative construction materials

There have been several innovation and trends in developing new construction materials over the past decade. Some typical trends of new construction materials include:

- *Green construction materials.* Refers to the use of sustainable materials that provides environment-friendly and energy efficiency throughout the project lifecycle;
- *Top mix permeable.* A fast-draining concrete pavement solution absorbs 4,000 liters of water a minute. This innovative new material offers the potential for the design of sustainable urban drainage systems and can help urbanized areas to deal with surface flooding by allowing water to drain and dissipate through the pavement naturally. Top mix permeable is in the early-adoption stage;
- *Aerogel.* This material is a synthetic, porous, and ultra-lightweight insulation material in which the liquid component of the gel is replaced with a gas. The resulting super-transparent and super-insulating material consists of 99.98% air/gas that has an extremely low density and low thermal conductivity;
- *Nanomaterials.* These materials are super-strong, ultra-lightweight materials that can eventually be a substitute for steel reinforcement in structures and foundations, though they are still in the research stage (Pistorius, 2017).

2.5 Summary

The literature review results presented in this chapter document the most relevant topics to innovative and emerging technologies for construction. Chapter 2 provides vital information for understanding the state of practice in the use of specific emerging technologies in the delivery of highway construction projects. The key concepts of the four main types of technologies used in construction; digital, visualization, and modeling technologies; construction automation technologies; work zone safety-related technologies; and alternative construction materials were discussed in detail. The concepts in this chapter set the basis for the survey questionnaire and case example protocols applied in this synthesis. The next two chapters summarize the findings from the distributed survey questionnaire and seven case examples conducted.

CHAPTER 3 – RESEARCH METHODOLOGY

3.1 Introduction

This chapter discusses the research methodology for this thesis. The chapter starts by discussing the theoretical point of departure for research thesis and then states the research questions that are investigated in Chapters 4 and 5. A research framework is introduced which describes the work conducted in each step of the proposed research framework. A detailed explanation of individual research task is provided.

3.2 Theoretical Point of Departure

The thesis starts from the fact that there is a lack of research specifically focused on use and implementation of emerging technologies in the construction industry. There is a lack of documentation, implementation strategies, or the driving forces that state DOTs should consider for implementation of emerging technologies to deliver their highway construction projects. Hannon (2007) investigated the use of five technologies: (1) Global positioning systems (GPS), (2) Handled computers for construction records; (3) Automated temperature tracking; (4) 4D modeling; and (5) remote project monitoring with web-based video cameras. The study found that the application of these technologies promises time and cost savings. The study also identified typical barriers to transportation agencies to implement these five technologies, including: budget restraints, lack of standardization and specification, ignorance of the technology's potential benefits, lack of end-user technical skills, and agency.

However, many new technologies have been introduced in the construction industry that are being used extensively by DOTs across 50 states in the US in last decade. Additionally, general contractors and subcontractors realize benefits such as increased productivity, overcome labor shortage or improved communication and relations between various stakeholders through using technologies. Further, the Federal Highway Administration (FHWA) initiative studies have shown that the combination of 3D modeling and a global positioning system (GPS) helps state DOTs complete highway projects faster with improved quality and safety (FHWA, 2015). This combination can increase productivity by up to 50% for some operations and cut survey costs by up to 75%. Similarly, FHWA promoted e-Construction technologies as an effective tool to (1) decrease the delays inherent in paper-based project administration, (2) support secure, expedited, and transparent document transmission, distribution, and storage; and (3) enhance real-time management of all documents. Research showed that e-Construction time savings have averaged 1.78 hours per day per inspector (FHWA, 2015). Cost savings of using e-Construction have been reported at approximately $40,000 per construction project per year (FHWA, 2015).

Building upon from the literature, this research utilizes survey questionnaire and case studies as a tool to provide a more comprehensive view of the current state-of-practice of using emerging technologies for highway construction. It would specifically discuss factors influencing the decision to select what technologies will be used, how the implementation will happen, and then what are the lessons learned from the experience.

3.3 Research Questions

To investigate the aforementioned research objectives, this study aimed at investigating the following research questions:

1. How does a state DOT decide which technology will be used for a project? What are the factors influencing such decision?

2. Does the agency have standardized documents for each technology?
3. What are the benefits, limitations, and lessons learned on implementation of emerging technologies?

3.4 Research Approach

According to Yin (1994), there are five different types of research approaches including: experiment, survey, archival analysis, and a case study. To address the aforementioned research questions, the methods adopted for conducting this research include four main steps: (1) content analysis of the literature, (2) survey questionnaire (3) case study, and (4) analysis of survey data and discussion of findings. Literature review was undertaken to help establish the research questions and to ascertain the extent and depth of existing knowledge on the use of five emerging technologies under discussion. Based on the literature available, a formal conventional content analysis was conducted to identify the approaches implementation of technologies.

3.4.1 Literature Review

Conference papers, web publications, journal articles, technology vendor websites and other published material was used to carry out literature review. Data collected was used deductively to identify the questions that need be answered to achieve the goals of this research. The key findings from the literature were summarized in Chapter 2.

3.4.2 Survey Questionnaire

The second step was to conduct a national survey questionnaire to identify the current state-of-practice, determine factors considered in decision, benefits and challenges in the use and implementation of emerging technologies. A survey questionnaire was developed based on the literature review and was distributed in web-based forms to the representatives from 50 state

DOTs. Response was received from 41 state DOTs. The overall response rate was 82%. The responses received have been discussed in detail in Chapter 4. Appendices A and B present the questionnaire and the associated responses.

3.4.3 Case-Study

The primary purpose of the case study was to gather data on how the contractors are making use of emerging technologies on their project.

Case study was conducted in accordance with the following protocol.

1. Identification of Project(s) or the General Contractor that have been using the five technologies as discussed earlier on their projects and have gained good amount of experience with the same, and are open to sharing information with the research team.
2. Conduct a brief interview with the Project representative/ Project Manager to orient the research team and obtain relevant documentation viz. project goals, standardized implementation manuals;
3. Collect examples of key success factors, effective practices, and challenges faced at project level and the type of support received from the Client (DOTs)
4. Verify the results obtained against the data collected from survey questionnaire from various DOTs.

A structured interview protocol was used during discussion and data collection. The Project Manager was interviewed using a list of questions focusing on the following points.

- Decision making protocol for specific technology use;
- Use of the technology;

- Level of investment Vs benefits realized;
- Barriers/Roadblocks in implementation & Driving forces; and
- Lessons learned.

3.5 Summary

Chapter 3 provided the theoretical point of departure for the research thesis. Also, this chapter provided the research questions that are investigated and serve as a basis of this research. The proposed research features three major sections which include literature review, conducting national survey and conducting case study. The results from the survey serve as a basis to validate the findings of content analysis and supplement towards conducting case study. The survey and case study results are discussed in detail in the following chapters.

CHAPTER 4 – SURVEY RESULTS AND DISCUSSION

4.1 Introduction

This chapter would discuss the findings from survey and content analysis. This chapter presents the current practices in the use of the five emerging technologies for delivering highway construction projects, including

(1) visualization and modeling technologies;

(2) interconnected vehicles, equipment, and handheld tools;

(3) safety technologies;

(4) instrumentation technologies; and

(5) unmanned aerial systems.

To collect the most updated information of these five technologies for use on transportation projects, a web-based survey was developed from the extensive literature review and distributed to members of the AASHTO Committee on Construction (CoC), which includes representatives from all 50 state DOTs. The findings presented in this chapter include reviewing 41 state DOT responses (82% response rate). In addition, the content analysis results of DOT's manuals, guidelines, and relevant documents obtained from the survey on each of the technologies investigated are also included to support the findings. The chapter begins by reporting the general findings on the use of the five technologies. It then discusses the current practices that DOTs are experiencing regarding each of the five technologies. It is important to note that the 41 state DOT respondents were not required to respond to all questions in the survey. As a result, the sample size (n) of each question varies. The following sections discuss the key findings from the survey in detail. The survey questionnaire used is shown in Appendix B, while additional details of the survey data analysis are found in Appendix C.

4.2 General information of technologies in transportation

The use of emerging technologies for highway construction projects varies among state DOTs. Figure 4.1 shows a map indicating state DOTs have implemented five emerging technologies for delivering highway construction projects, including (1) visualization and modeling technologies; (2) interconnected vehicles and equipment; (3) safety technologies; (4) instrumentation technologies; and (5) unmanned aerial systems. Out of 40 respondents, most of state DOTs have implemented at least two of these five technologies. Only Louisiana DOT reported that it has not used any of these technologies (Figure 4.1). More than10 state DOTs have implemented all five technologies to deliver their highway construction projects.

Figure 4.2 presents a detailed result of emerging technology implementation in highway. Out of the 40 respondents, more than 20 states DOTs (50%) reported that they implement at least four out of five emerging technologies. Specifically, 25 state DOTs (62.5%), 24 state DOTs (60%), 29 state DOTs (72.5%) and 23 state DOTs (57.5%) reported that they have implemented visualization and modeling technologies, safety technologies, instrumentation, and UAV technologies, respectively. Figure 4.1 summarizes the current state of practices in the use of five emerging technologies. The survey results reflect state DOTs have more experience using instrumentation technology than any other technologies. Interconnected vehicle technologies seem relatively news to state DOTs. In fact, 17 state DOTs out of 40 respondents reported they implement the interconnected vehicle technology, but in the form of automated machine guidance.

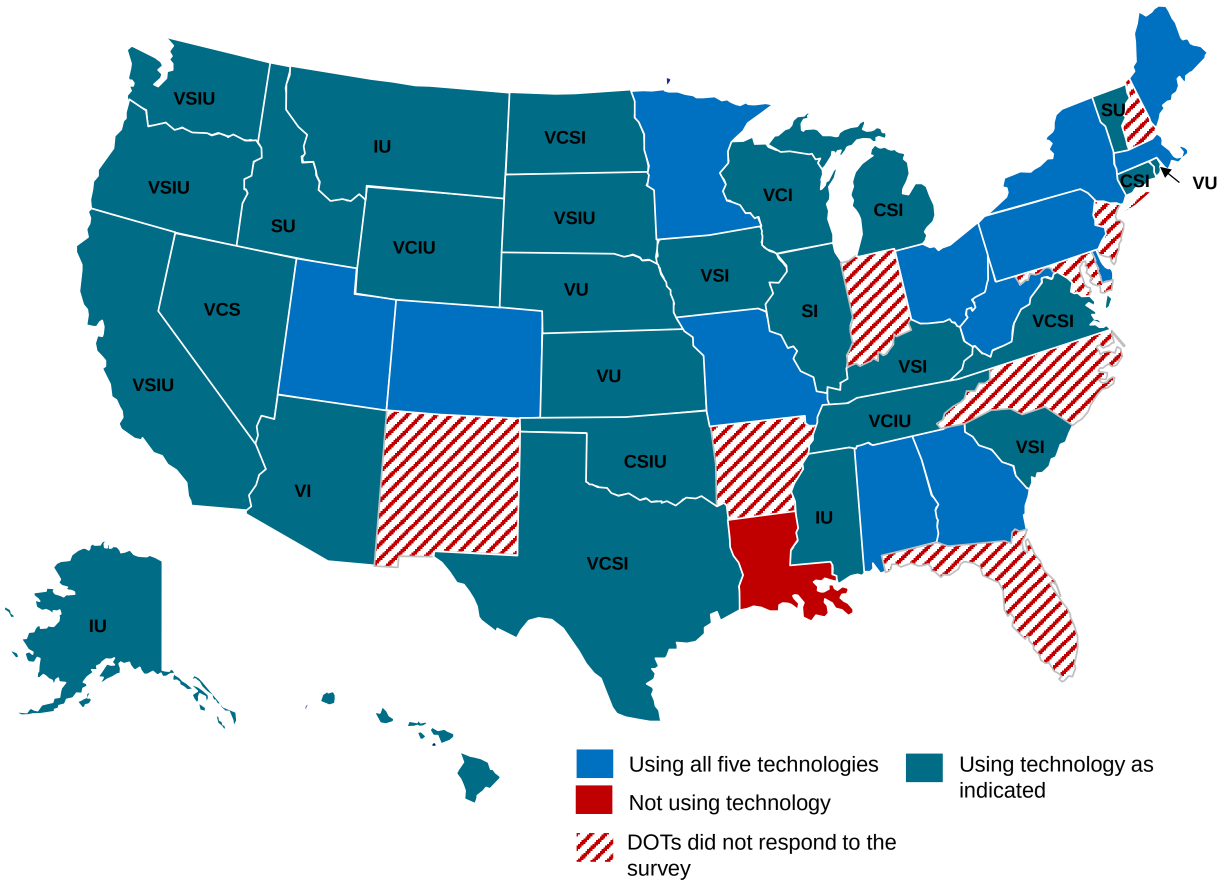

FIGURE 4.1. Current state of practice in five emerging technologies (n = 40)

(Notes: V = Visualization & Modeling technologies; C = Interconnected Vehicles & Equipment; S = Safety technologies; I = Instrumentation technologies; U = Unmanned Aerial Systems)

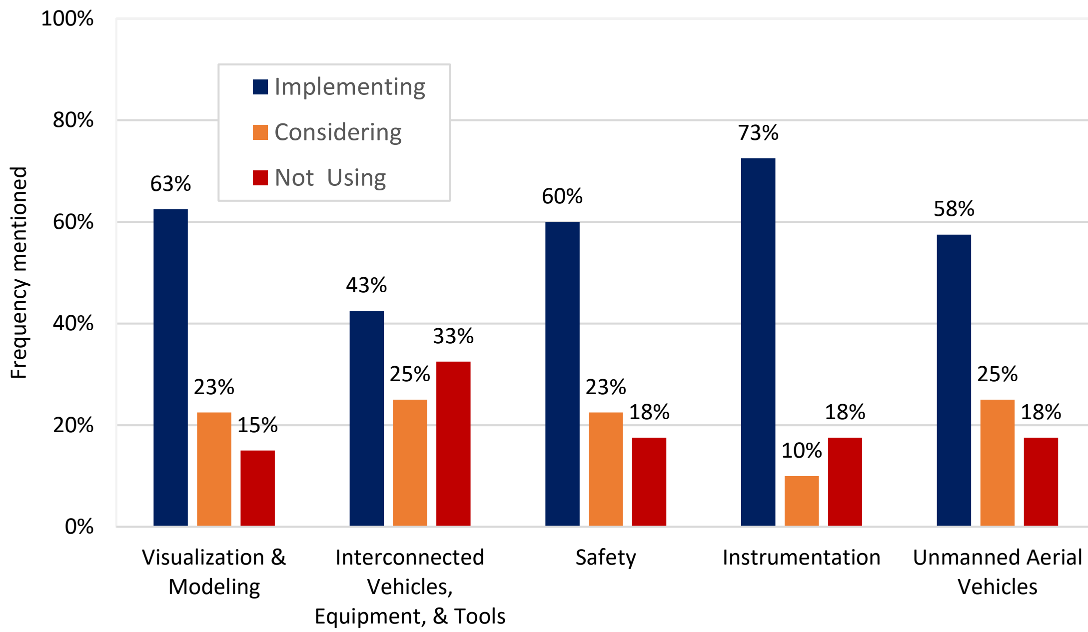

FIGURE 4.2. Use of emerging technologies in highway construction (n = 40)

Emerging Technologies versus Project Types

This section presents the results from the national survey with regard to the current use of five emerging technologies associated with different types of transportation projects, including: bridges, drainage, paving, utilities, non-bridge structures, and others (e.g., grading, traffic management, and signaling projects). Figure 4.3 shows the use of visualization and modeling technologies associated with different project types. Out of 25 state DOTs implementing visualization and modeling technologies, 20 state DOTs (80%) use this technology for their bridge projects. Only 10 state DOTs use this technologies for non-bridge structures. Two state DOTs also use visualization and modeling technologies for grading and traffic management projects.

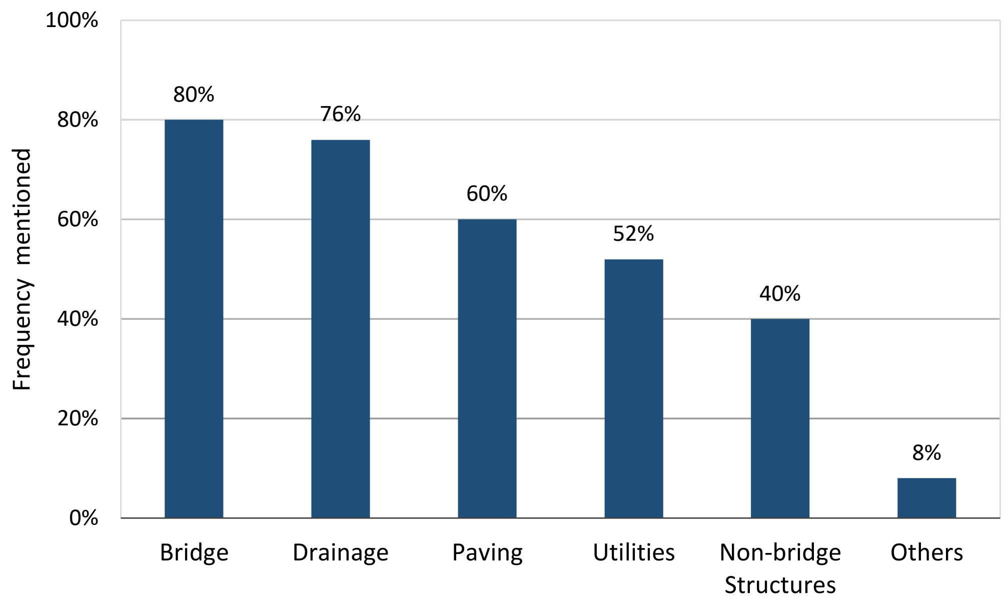

FIGURE 4.3. Visualization and modeling technologies vs. project types (n = 25)

Figure 4.4 summarizes the use of interconnected vehicle and equipment technologies associated with different project types. All of 17 state DOTs implementing the interconnected vehicle and equipment technology reported that they use this technology for paving projects. Five state DOTs (29%) use this technology for their bridge, non-bridge, or drainage projects.

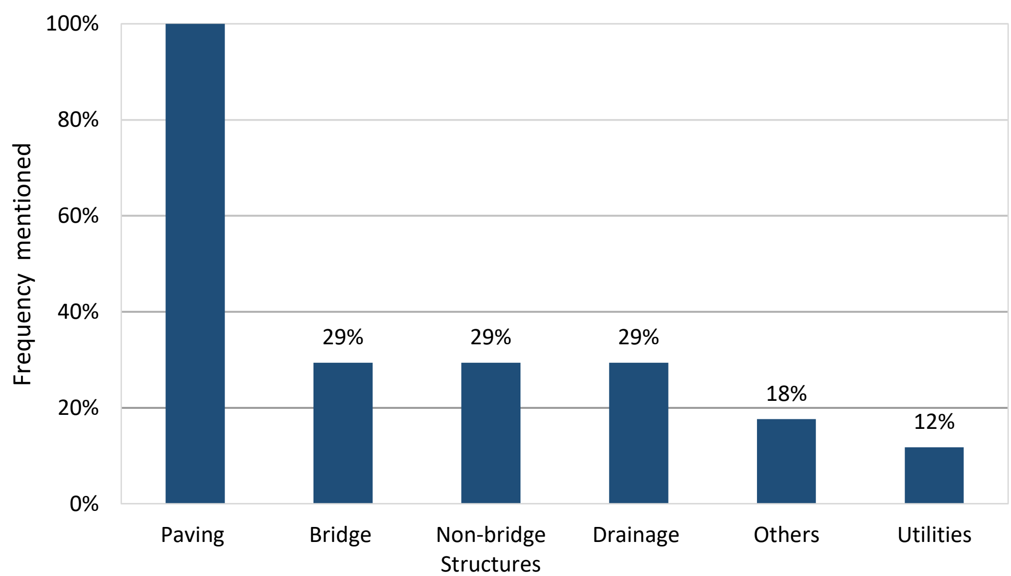

FIGURE 4.4. Interconnected vehicle and equipment technologies vs. project types (n = 17)

Figure 4.5 summarizes the use of safety technologies associated with different project types. Out of 24 state DOTs implementing the safety technology, 22 state DOTs (92%) reported that they use this technology for paving projects. More than 50% state DOTs also indicated that the safety technologies are typically used for bridge or non-bridge projects (Figure 4.5)

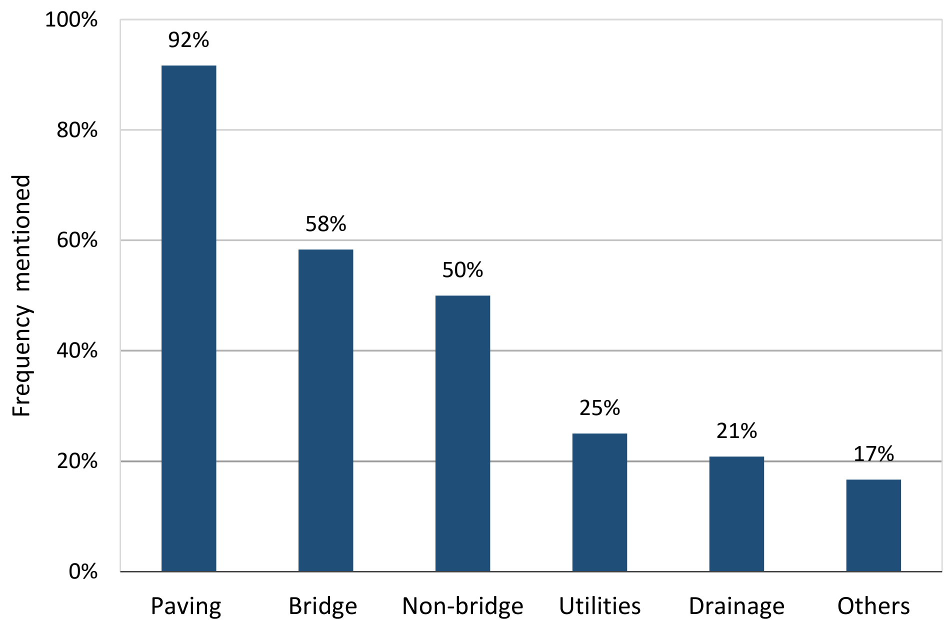

FIGURE 4.5. Safety technologies vs. project types (n = 24)

Figure 4.6 summarizes the use of instrumentation technologies associated with different project types. Out of 29 state DOTs implementing the instrumentation technology, 27 state DOTs (93%) reported that they use this technology for bridge projects. Further, 18 state DOTs (62%) also indicated that they often use the instrumentation technology for their bridge projects.

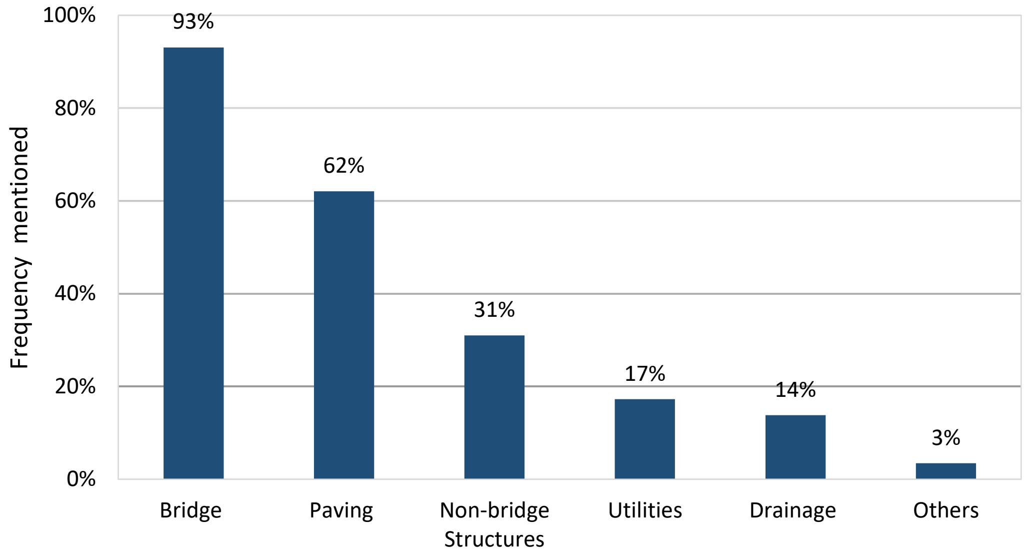

FIGURE 4.6. Instrumentation technologies vs. project types (n = 29)

Figure 4.7 summarizes the use of unmanned aerial systems associated with different project types. All of 23 state DOTs implementing UASs reported that they use this technology for bridge projects. Less than 50% state DOTs responded to this question use UASs for their bridge, non-bridge, paving, utilities, or other types of highway projects.

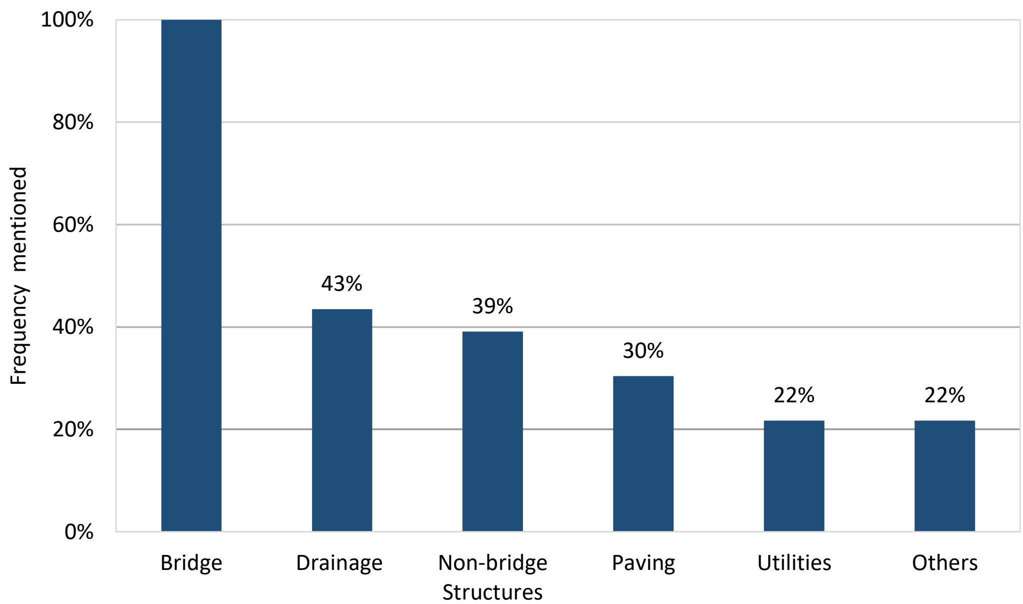

FIGURE 4.7. Use of unmanned aerial systems vs. project types (n = 23)

Emerging Technologies versus Construction Workforces

The construction industry largely depends on manpower to perform many tasks and employs close to 9% of total national workforce. Meeting workforce demands for the construction industry is a challenging. Some agencies leverage the use of specific construction technologies to offset a lack of human resources available. Respondents were asked to share views on technology use to help meet workforce needs during construction of highway projects. Figure 4.8 summarizes the result of this question. More than 50% respondents reported using one of these five emerging technologies (e.g. visualization and modeling technologies; interconnected vehicles and equipment; safety technologies; instrumentation technologies; and unmanned aerial systems) have no impacts on the construction workforces at their states.

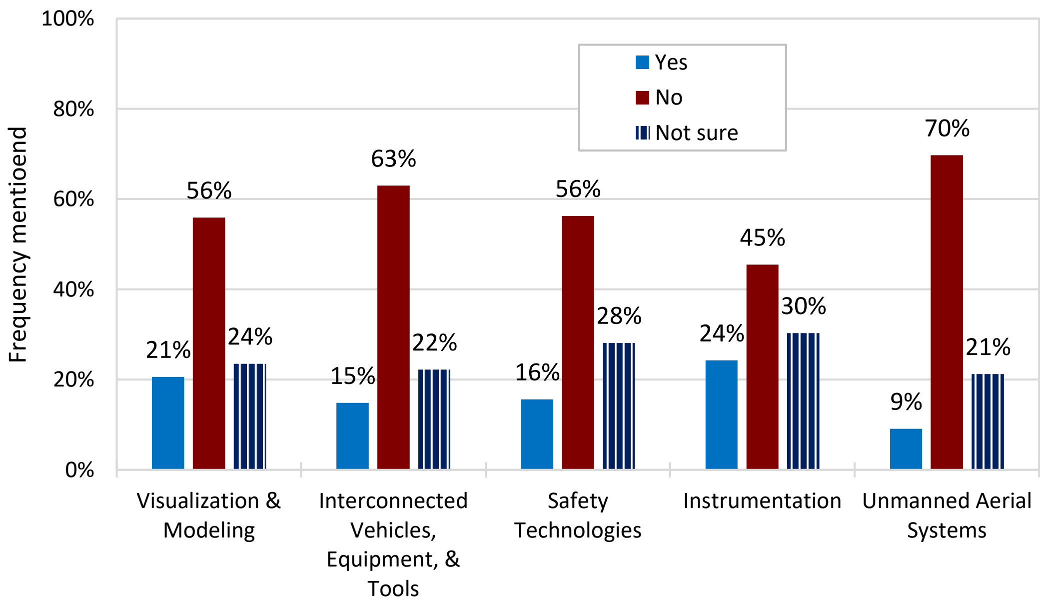

FIGURE 4.8 Impact of emerging technologies on construction workforces (n = 40)

The Use of Emerging Technology among Stakeholders

All state DOTs who mentioned using the emerging technology for their infrastructure projects were asked to provide information on the users of these technologies. Table 4.1 summarizes the result of this question. Table 4.1 indicates that state agencies are the most users (more than 72%) for visualization and modeling and instrumentation technologies; contractors are common users (approximately 60%) across all five emerging technologies; and subcontractors sometime (approximately 30%) involve using these technologies.

TABLE 4.1

Use of emerging technologies by project stakeholders (n = 33)

Stakeholders	Visualization & Modeling	IVET	Safety	Instrumentation	UAS
DOT Agency	74.3%	18.5%	54.5%	72.7%	57.6%
Contractor	60.0%	66.7%	63.6%	57.6%	57.6%
Construction Manager	34.3%	18.5%	24.2%	33.3%	21.2%
Subcontractor	25.7%	37.0%	36.4%	36.4%	24.2%
Vendor	17.1%	11.1%	12.1%	15.2%	21.2%
Program Manager	28.6%	3.7%	3.0%	9.1%	6.1%
Manufacturer	8.6%	7.4%	9.1%	9.1%	3.0%
Fabricator	11.4%	0.0%	12.1%	15.2%	0.0%

Transportation is evolving from a field focused on operational efficiency to one of the most innovative and rapidly changing areas of the economy. Emerging technology areas with the potential to significantly impact the transportation sector include unmanned aircraft systems, automated vehicles and other unmanned ground vehicles, the Internet of Things (IoT), and on-demand ride services. These, and other emerging technologies have the potential to advance the U.S. DOT's mission of providing safe, clean, accessible, and affordable transportation. (USDOT 2018).

4.3 Visualization and modelling Technologies

Of 40 respondents, 25 state DOTs mentioned they have implemented the visualization and modeling technology on their projects and nine state DOTs reported that they are considering this technology. When asked specific applications and technologies associated with visualization and modeling, most of state DOTs (85%) reported that they use LiDAR and 50% of state responded DOTs use 3D, 4D, and 5D BIM technologies. Figure 4.9 summarizes the result of this question. It is noted that only small number of state DOTs (less than 15%) use virtual reality, augmented reality, virtual prototyping, wearable visualization devices, and 3D printing to deliver their transportation projects.

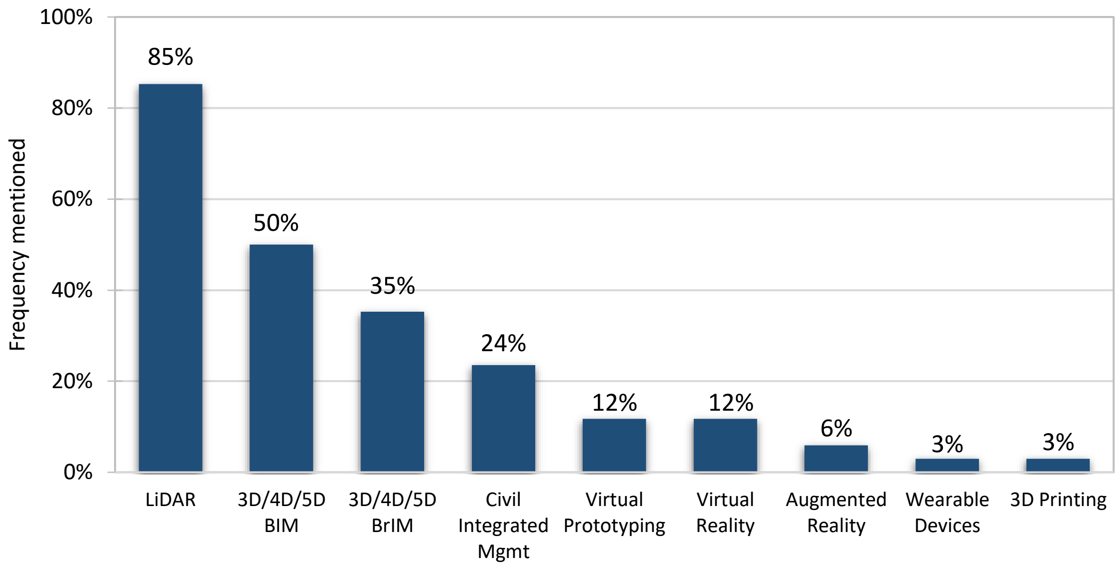

FIGURE 4.9 Specific visualization and modeling technologies and applications (n = 34)

(Note: including 25 implementing and 9 considering agencies)

Figure 4.10 summarizes the use of visualization and modeling technologies in different tasks of a highway construction project. One can observe that the most common task for using visualization and modeling technologies is conducting constructability reviews. Specifically, out of 25 valid responses, 21 state DOTs (84%) reported that they use visualization and modeling technologies for constructability. 44% of responded state DOTs indicated that they use visualization and modeling technologies for as-build planning and quality control/quality assurance (QA/QC) activities. Approximately one third (36%) state DOTs use visualization and modeling technologies for simulation of bridge or non-bridge construction, inspection, monitoring construction progress, and verification of work completed for payment. Interestingly, two state DOTs (4%) use visualization and modeling technologies for public outreach.

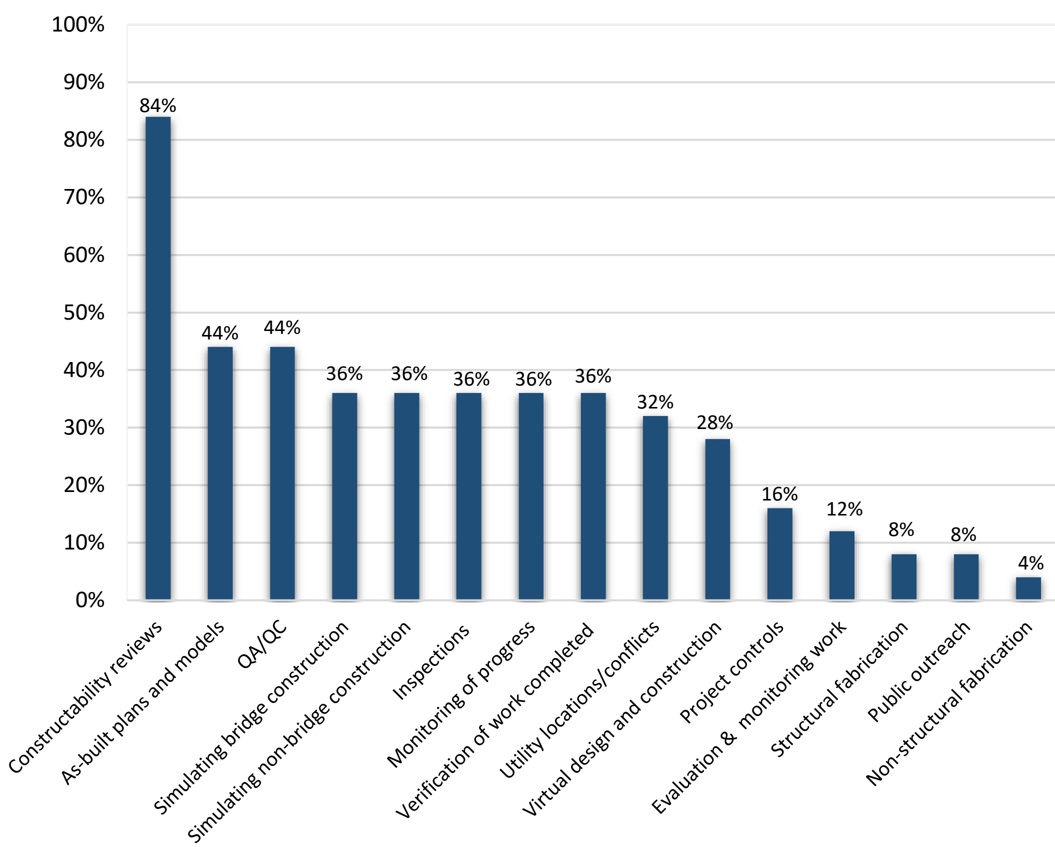

FIGURE 4.10 V&M technology uses for highway project delivery (n = 25)

Further, the DOTs were asked how frequently visualization and modeling technology is used for their highway construction projects. Most of state DOTs (23 out of 25) reported that they only use visualization and modelling technology for specific projects, especially for large complex projects.

Nevada DOT mentioned that:

> They are practicing 3D modeling in the design of projects and moving that information to the contractors for machine control construction. About 50% of their projects are being modeled now and the information is available to the contractors for use at their own risk. Additional interface development for ease of use by non-experts and training curriculum to educate project team on how to use existing and proposed data to create a realistic and optimized 3D model of any project are elements that can enable routine deployment of the technology.

4.4 Interconnected Vehicles & Equipment Technologies

Of 40 respondents, 17 state DOTs mentioned they have implemented the interconnected vehicle and equipment technology on their projects and 10 state DOTs reported that they are considering this technology. When asked specific vehicles used for this technology, most state DOTs use this technology for paving and earthwork equipment. Specifically, 19 state DOTs (70%) reported that they use this technology for their paving equipment such as compactors, asphalt pavers, concrete pavers, or planner. 17 state DOTs (63%) reported that they use this technology for their earthwork equipment including dozers, backhoes, graders, scrapers, and excavators. Figure 4.11 summarizes the result of this question. Some state DOTs also use this technology for their specific purpose. For example, Alabama DOT uses this technology to monitor agency vehicles for maintenance, tracking, and asset management purposes. New York, Wisconsin, and Oregon DOTs use automated machine guidance (AMG) to perform paving operations.

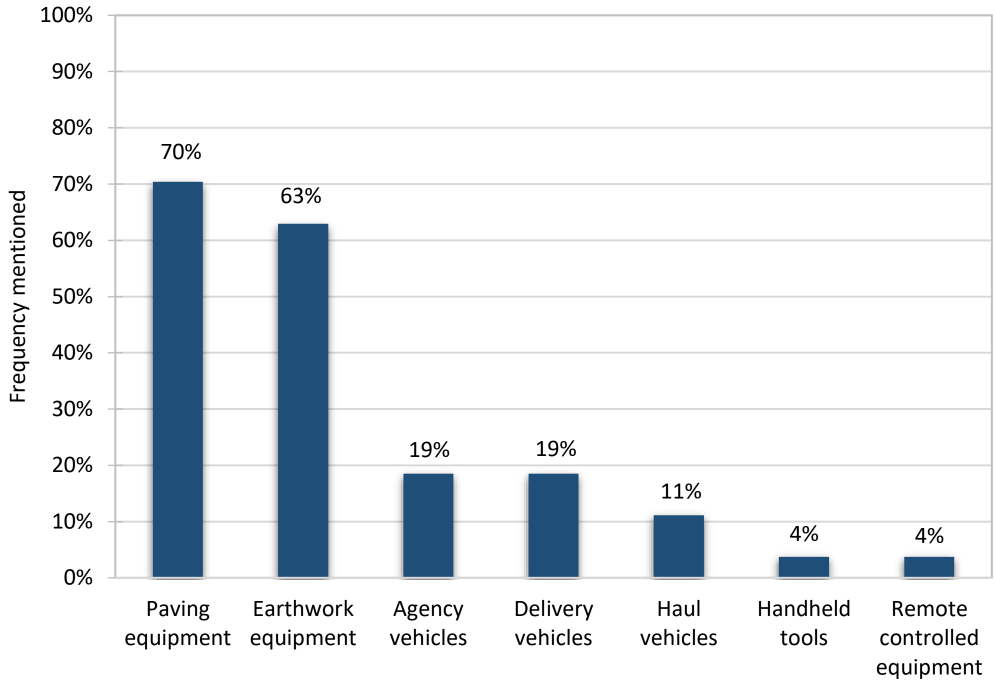

FIGURE 4.11 Specific IVET technologies in use (n = 27)

Figure 4.12 summarizes the use of interconnected construction vehicles and equipment in different tasks of a highway construction project. Figure 4.12 indicates that state DOTs typically use interconnected construction vehicles and equipment for machine control systems. Specifically, out of 17 valid responses, 13 state DOTs (76%) reported that they use interconnected construction vehicles and equipment for monitoring of vehicle performance. Additionally, this technology also can be used for identifying locations of vehicles (35%), inventory management (29%), and asset management (18%), vehicle maintenance (18%), accident avoidance (18%), or mobility tracking (18%). Some state DOTs also use this technology for e-ticketing or string-less paving. Similar to the visualization and modeling technology, most of state DOTs (13 out of 17) reported that they only use interconnected construction vehicles and equipment for specific projects.

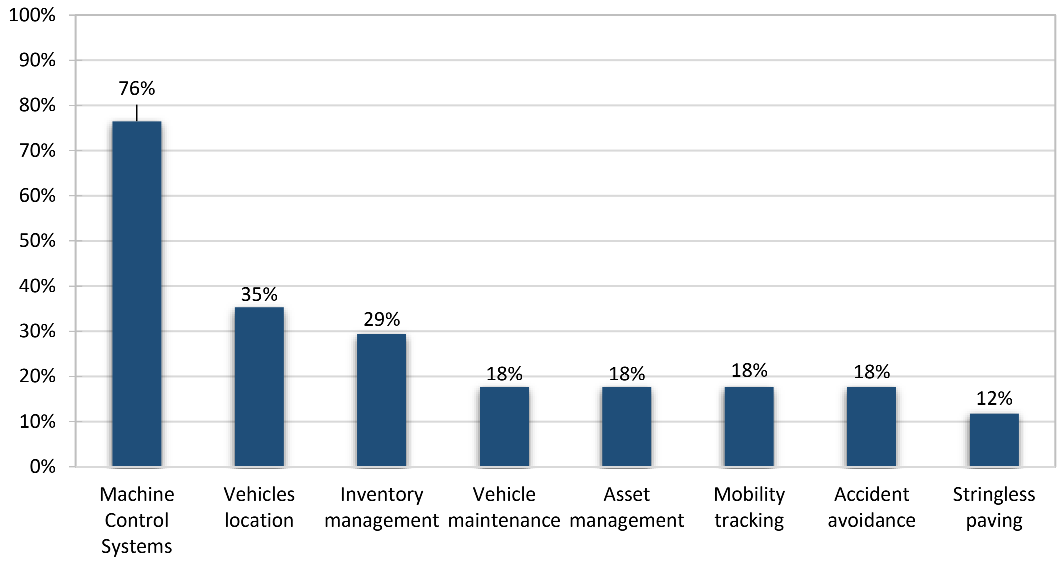

FIGURE 4.12 IVET technology uses for highway project delivery (n = 17)

Connected vehicle technology promises to exhibit profound effects on driver, passenger, and pedestrian safety…. Over 80 percent of non-impaired incidents could be mitigated by the implementation of connected vehicle technology. The groundbreaking communications technology utilized by connected vehicle applications will provide drivers with advance warnings of turning and stopped vehicles and other situations, allowing time for reaction and avoidance. (USDOT 2017).

4.5 Safety Technologies

Of 40 respondents, 25 state DOTs mentioned they have implemented the safety technology on their projects and eight state DOTs reported that they are considering this technology. When asked specific applications associated with the safety technology, most of state DOTs (70%) reported that they use safety technology for mobile or stationary dynamic message signs. Additionally, 50% of state DOTs use safety technologies for their variable speed work zones. Figure 3.13 summarizes the result of this question. Only less than 20% state DOTs responded to this question use safety technology for their wearable technology-enhanced personal protection equipment, dynamic lane merging, queue detection system, and automated cone placement and retrieval.

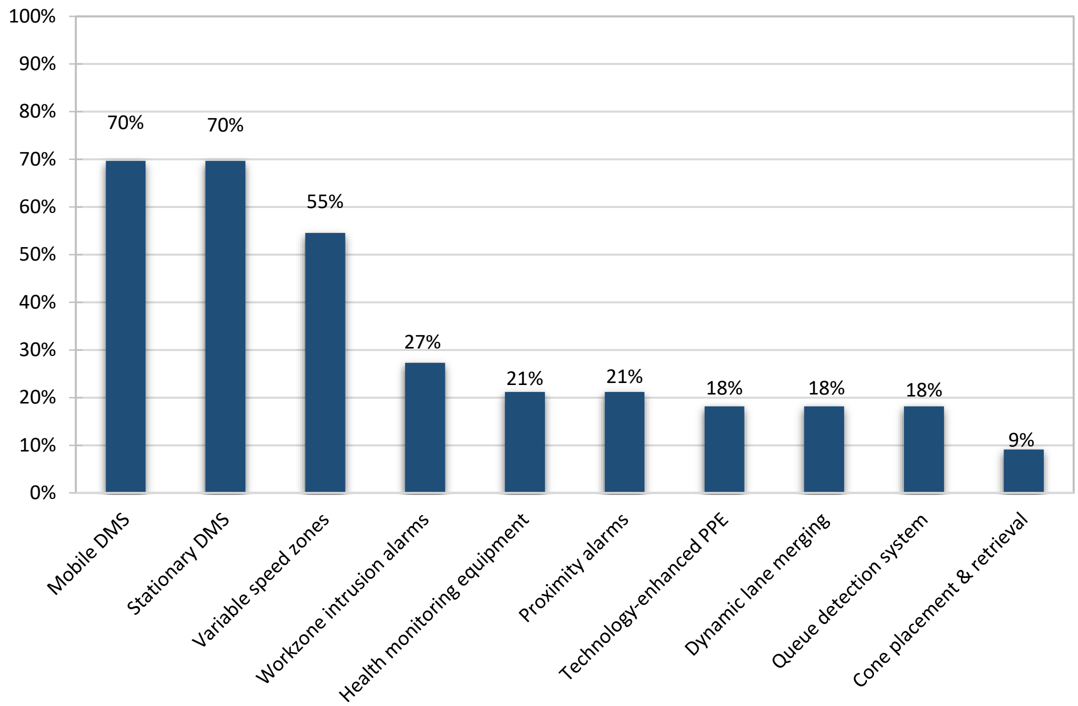

FIGURE 4.13 Specific safety technologies (n = 33)

The participants of the survey were asked to share information on how safety technologies help deliver their transportation projects. Figure 4.14 summarizes the use of safety technology for delivering a highway construction project. Figure 4.14 indicates that 20 out of 25 state DOTs (80%) use safety technology for work zone traffic management and information for motorists. Additionally, approximately 50% state DOTs use safety technology for accident avoidance and enhanced protection for workers. Interestingly, three state DOTs (12%) reported that they use safety technology for improving construction QA/QC. Most of state DOTs (22 out of 25) reported that they use safety technology based on a project-by-project basis.

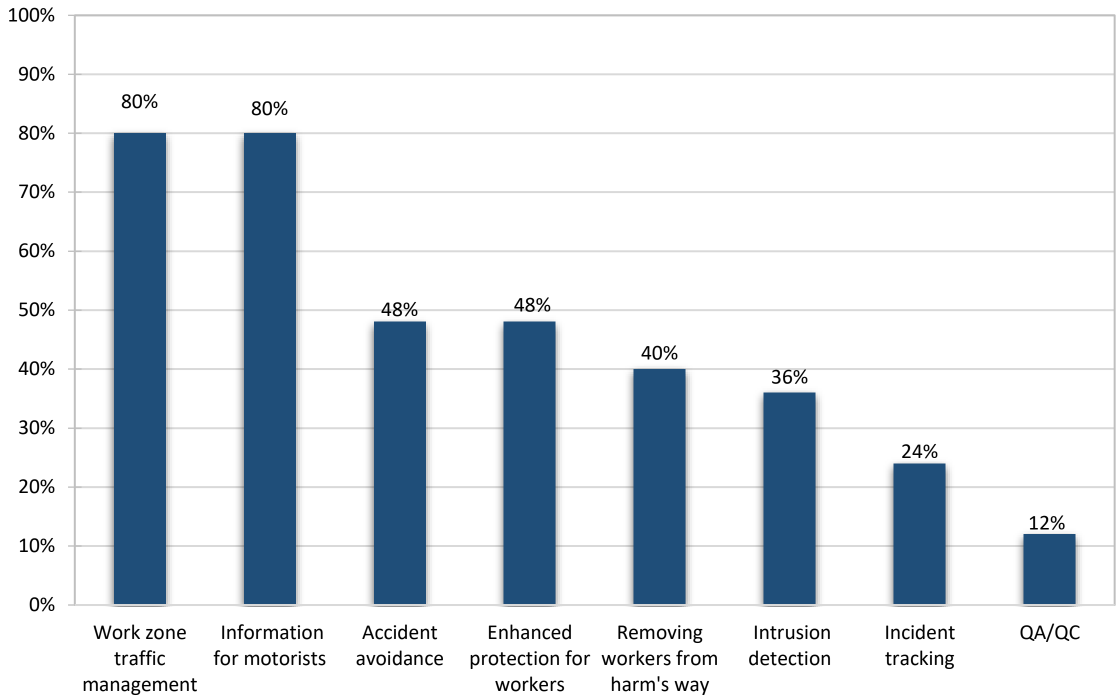

FIGURE 4.14 Safety technology uses for highway project delivery (n = 25)

4.6 Instrumentation Technologies

Of 40 respondents, 29 state DOTs mentioned they have implemented the instrumentation technology on their projects and four state DOTs reported that they are considering this technology. Figure 4.15 summarizes the result of this question. More than 50% state DOTs use the instrumentation technology associated with remote sensing, sensors for measuring/monitoring structural integrity (e.g., gauges for stress, strain, deformation, seismic/vibration, current/voltage), and Audio/Video/Closed Caption Television (A/V&CCTV). Further, 45% of state DOTs use the instrumentation technology as sensors for measuring specifications (e.g., compaction, depth, penetration) and 42% of state DOTs use the instrumentation technology as sensors for measuring/monitoring environmental conditions (e.g., heat, temperature, light, presence of toxins).

Other instrumentation technologies that find limited usage in the industry are infrared sensors and radio frequency identification (RFID).

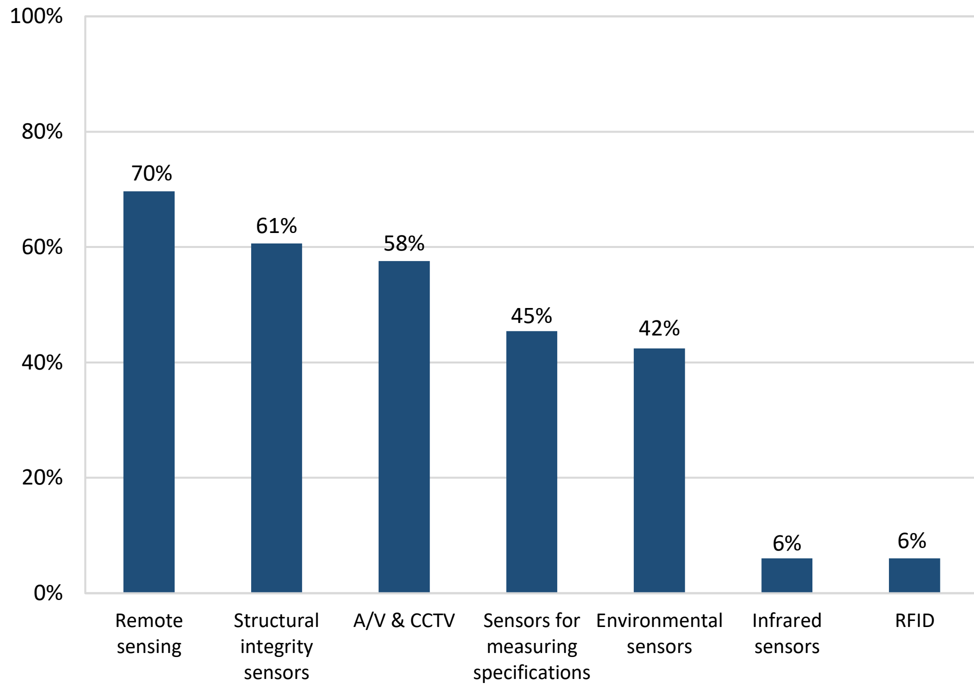

FIGURE 4.15 Specific instrumentation technologies (n=33)

Figure 4.16 summarizes the use of the instrumentation technology in different tasks of a highway construction project. Figure 3.16 indicates that more than 50% of agency respondents use the instrumentation technology for monitoring progress of work (e.g., time-lapse audio and video), QA/QC processes, and inspection. 45% of agency respondents use the instrumentation technology for evaluating forces of structural members. More than 30% of agency respondents use the instrumentation technology for identifying optimal conditions for placement of work (e.g., compaction, paving), recording placement of work for as-built purposes, verifying design during construction, and determining locations of utilities. 21% of agency respondents noted that they use the instrumentation technology for locating construction materials. Finally, less than 10% of state DOTs indicated that the instrumentation technology can be used for project control and evaluating boundary conditions of structural members. Most of state DOTs (25 out of 29) reported that they only use instrumentation technology based on specific project requirements.

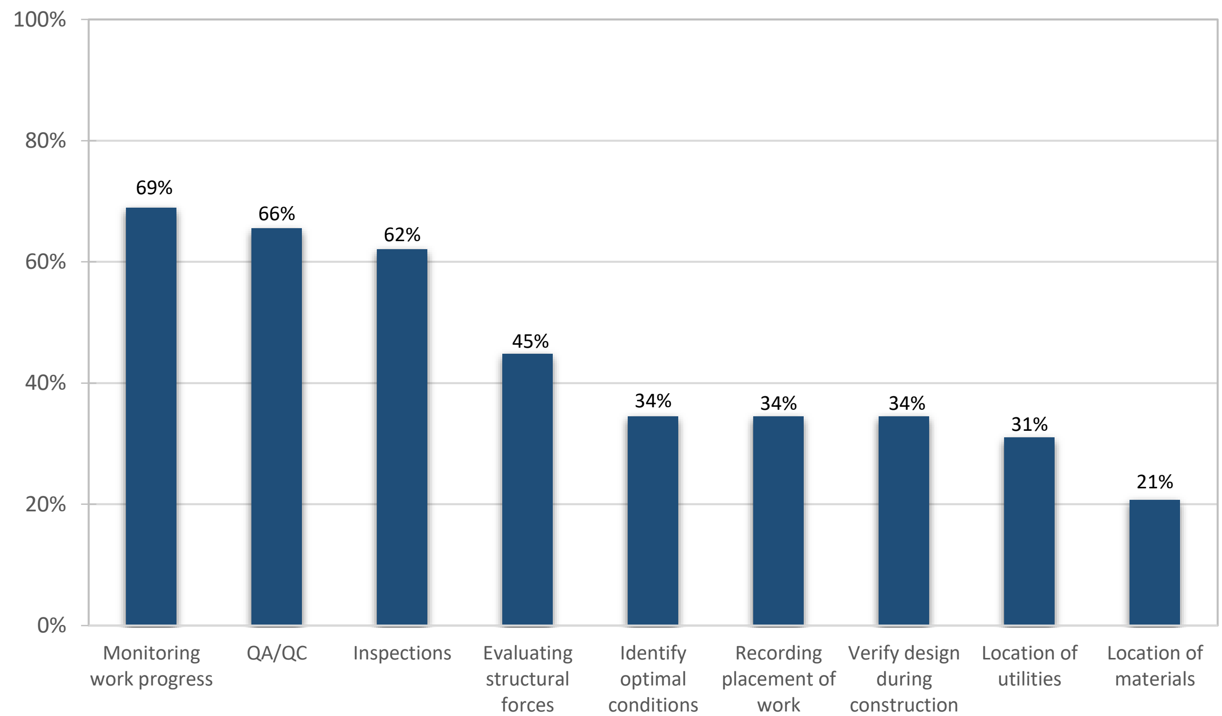

FIGURE 4.16 Instrumentation technology uses for highway project delivery (n = 29)

4.7 Unmanned Aerial System Technologies

The participants of the survey were asked to share information on how UASs help deliver their transportation projects. Figure 4.17 summarizes the result of this question. Specifically, approximately 50% of agency respondents reported that they use UASs for monitoring construction progress. Nearly 40% of agency respondents noted that they use UASs for site mapping. More than 30% of agency respondents indicated that they use UASs for construction documentation and surveying. Nearly 20% of agency respondents also noted that they use UASs for inspection and materials/equipment inventory. Less than 10% of agency respondents pointed out that they use UASs for geographic information systems. Similar to other four emerging technologies, most of state DOTs (19 out of 23) reported that they only use UASs based on specific project requirements.

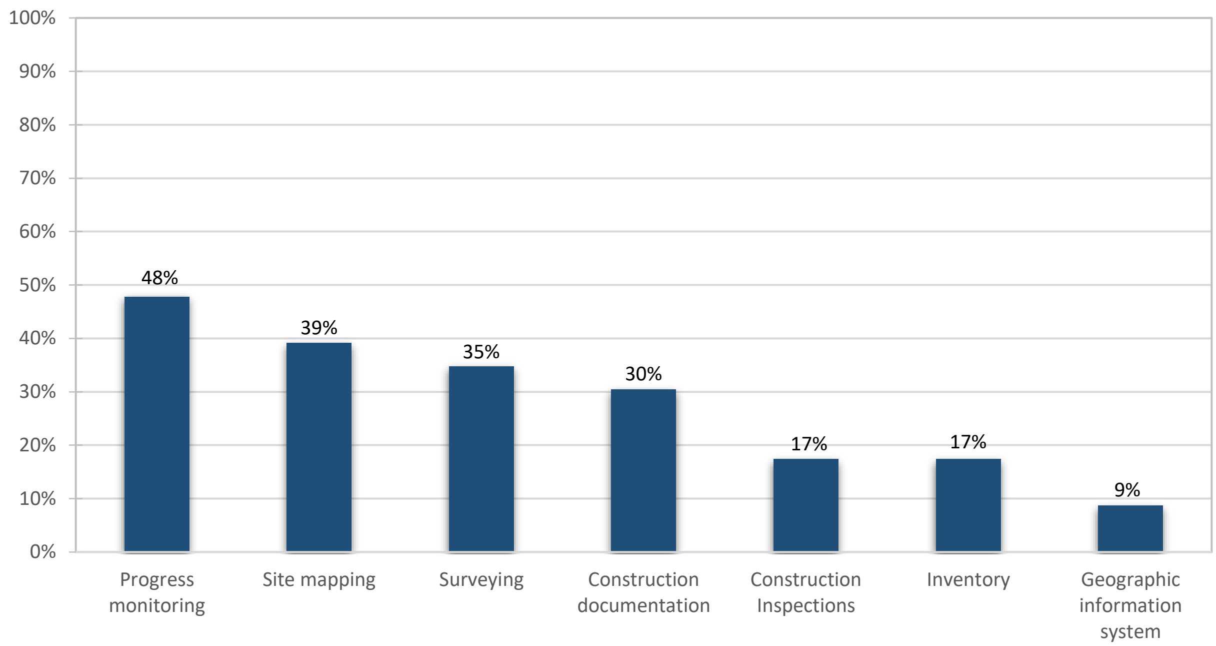

FIGURE 4.17 UAS uses for highway project delivery (n = 23)

Utah DOT shared that

> They are using drones for almost 10% of their projects. Currently, the majority of bridge inspections across the country and in Utah are done by field workers using a combination of trucks, bucket cranes, and climbers. In these situations, the risk for injury or death is higher than one would want. When using drones the Utah DoT realized a 40-60% decrease in manpower for a survey on high-relief terrain. This added with the ability to quickly evaluate and inspect structures and open lanes as quickly as possible has reduced time and investment.

4.8 Emerging Technology Lessons Learned

The participants who mentioned using the technologies on their projects were asked to share their experiences and lessons learned. The common lesson learned associated with each emerging technology are listed below:

Visualization and Modeling Technologies

- Ensure interoperability of different software before making procurement decisions.
- Make sure all stakeholders i.e. agency, GC and subcontractors are using same software and the contract clearly spells out what the agency will provide to third parties in terms of file sharing.
- When dealing with CAD models provided by the client, it is very important to verify the existing conditions in the model with conditions at site.
- Most field crew don't have experience with CAD. Contractor needs to be tech savvy and field crew has to be trained on CAD use to be successful with visualization and modeling.
- Preparation of 3D models takes more time initially and requires investment but the benefits realized are worth the amount expended.

Interconnected Vehicles & Equipment Technology

- Consultant designers don't like to turn over files due to liability issues.
- Before using automated machine guidance at site, it is important to ensure vehicles and equipment are all on the same coordinate system the project was set to. AMG control must be verified multiple times per day.

- Benefits of AMG and string less paving are great, but it takes time to develop specs and standards and getting the right contractors to perform the work.

Instrumentation Technology

- Data comes in large quantities and collection is often the easy part. Processing, storing, sharing, using is the challenge. It is important to identify how data will be gathered and what type or data is required.
- Data from instrumentation is very beneficial for monitoring structural loads, verifying design assumptions, monitoring structural health and in future design considerations and research purposes but the technology use sometimes requires support from IT.

Unmanned Aerial Systems

- Before making use of drones on a project site it's important to get awareness of all FAA regulations and have a licensed surveyor to be in responsible charge.
- Accuracy of data for quantities for certain applications lacks with UAV.
- Non availability of understanding of permitting and pilot licenses procedures and user manuals is restricting the usage of drones.

4.9 Summary

This chapter describes the current practices of the five emerging technologies for delivering highway construction projects, including (1) visualization and modeling technologies; (2) interconnected vehicles and equipment; (3) safety technologies; (4) instrumentation technologies; and (5) unmanned aerial systems. The key finding of these five technologies are identified through analyzing 41 DOT respondents of the national survey distributed to 50 state DOTs. The chapter first presents general findings on these five emerging technologies such as the use of emerging technologies associated with project types, impact of emerging technologies on construction workforces in the highway sectors, and the use of emerging technologies among stakeholders. Next, the chapter discusses the survey results of each emerging technology in detail. This includes specific applications of each technology and how each technology is used for highway construction delivery. Finally, key lessons learned on the five emerging technologies are synthesized as the conclusion of this chapter.

CHAPTER 5 – CASE STUDY

5.1 Introduction

This chapter presents the information on project level implementation of emerging technologies. In the last chapter it was realized that DOTs are using technologies on road widening, new construction and bridge rehabilitation projects among other uses. The following criteria was used to select the contractor:

- Experience in the use of specific emerging technologies;
- Use of a variety of technologies within each of the five technologies included in this study;
- Comprehensiveness and availability of emerging technology documents and data; and
- The willingness of project personnel to participate in the study.

Based on these criteria, Larsen & Toubro Construction, India's largest construction organization and ranked among the world's top 30 contractors, with operations all over the world was chosen to proceed further with the case study. The construction firm operates six related businesses as following:

- Buildings & Factories
- Transportation and Heavy Civil Infrastructure
- Power Transmission & Distribution
- Renewable Energy
- Water & Effluent Treatment
- Smart World & Communication

L&T Construction indicated that digitalization (Embracing technology for change) is the springboard that can launch the construction projects and programs to the next level. The organization started an initiative called “DIGITRANS” or “Digital Transformation at L&T Construction” which is an attempt to utilize power of new and emerging technologies to make significant improvements to the business. DIGITRANS enhances their core operations that utilize man, machine and material, to save costs, improve productivity and efficiency and reduce execution time. The Deputy Managing Director mentioned that they are committing significant investments of money and talent into DIGITRANS and expecting to generate substantial savings from using various digital implementations thereby making the organization more profitable and efficient.

Once the contractor was selected, next step was to identify a project where the five technologies under discussion are implemented. A standard protocol was developed to identify a project best suited for this study as followings:

- Completion status: A project was to be identified which is in execution stage and a major portion of the work is completed which means more related data is available.
- Openness to share information: the project team is ready to share more information and is available for answering the questionnaire with use of technology.
- Experimentation: Identification of project where most if not all the technologies are being used or are to be used.

Following the above-mentioned criteria, seven highway construction projects were initially identified. After screening the initial information, the “Bar- Bilara- Jodhpur” project was selected for conducting a case study in detail. The planning manager was the point of contact for data collection and a survey questionnaire was sent as the first step. Once the response to questionnaire was received, the author conducted phone interviews. In the interview, the planning manager shared that L&T is increasingly using UAS, connected vehicle and safety technologies to streamline and enhance workflows on complex highway projects. The use of these technologies often saving thousands of dollars in man hours. The project description and key findings are discussed in the following sections in detail.

5.2 Project Description

The project details including scope, length of roadways, bridge, utilities. Table 5.1 summarizes the project descriptions in detail.

TABLE 5.1. Projects Details.

S. No.	Item	Description
1	Name of the Project	Four Laning of Bar-Bilara-Jodhpur Section of NH 112 from Km 0.000 to Km 111.000 (Existing Chainage) in the state of Rajasthan under EPC mode
2	Client	National Highways Authority of India
3	General Contractor	Larsen & Toubro Limited
4	Length of project	68 miles
5	Location	The State of Rajasthan is located in the north-western part of India. Section of Road connects western Rajasthan and border areas (Jodhpur-Jaisalmer-Barmer) to eastern part of Rajasthan i.e. Ajmer & Jaipur. This is a major strategic route connecting Jodhpur as an important feeder route during war time. Four

		laning of the section will permit smooth flow of military traffic as well as heavy commercial and domestic traffic. It will also facilitate transportation of mining and agriculture product.
6	Project Cost	USD 90.80 Million
7	Project start date	03/27/2017
8	Duration of Project	910 days
9	Pavement details	Rigid (84.625 Km), Flexible (25.03 Km)
10	No. of bridges	4 Major (2 Reconstruction & 2 Rehabilitation) 9 Minor
11	Culverts	63 nos.

Some progress photos were shared by the team which included concrete piling works, concrete pavement laying, subbase layer installation and curb laying. Some of these pics are shown below

FIGURE 5.1. Progress Photos, Top left (PQC laying work in progress at Ch. 81.275 RHS) and Right (P6 raft concreting work).

5.3 Drone Implementation

Members of project team mentioned that even though this was not the first project where drones were used, because of lack of standardized documents they had to face many challenges such as where to start, how to deal with the problem at hand. He further mentioned building an enterprise drone program involves its own unique set of challenges. Standardizing training and protocols, overseeing safety and ensuring confidentiality all becomes more complex when working with drones on a larger scale.

Highway networks are complex linkages spread over vast areas. The nature of the assets makes it difficult to monitor quickly and efficiently. Construction in difficult terrain further makes the project complex. UASs provide a unique solution to remotely monitor all construction sites in a cost-effective manner. Twenty acres of land were to be surveyed for volumetric analysis of aggregate stockpiles, which with the traditional method of surveying would have taken a week or more to obtain the results. The project team decided to use the drone technology. Scope of work included drone data acquisition and data processing. The main deliverables were digital surface model, ortho-mosaic and point cloud.

In total, 21 gravel stockpiles were surveyed in just 8 hours – a task that would have taken more than a week with two surveyors if the traditional surveying practice were used. Air mapping which involved generating image dataset was created. The images later were stitched together, and point cloud were generated. Next, the use of software (volume editor tool) to quantify cut and fill volumes was conducted for each individual stockpile. Once all the data was collected, next step was assessing the accuracy of volumes obtained from aerial surveys. Each stockpile was surveyed using the GPS method which requires sending a land surveyor to the site with a rover.

Motivation behind using drones on the project

The Planning Manager for the project mentioned that this was not the first project where UAS was used to perform survey works by the organization. He mentioned, as a planning manager, one has to come out with ideas that will prove beneficial and save cost and time for the project. Gathering high-quality data on time is always a challenge. For this reason, the project team made a joint decision to use drones for volumetric analysis of aggregate stockpiles which were located miles from each other. He noted that performing a traditional survey of all the quarries would have been a daunting task.

Challenges in implementing the technology

- **Outsourcing or In-House Drone Program:** It was a difficult decision to pick between in house development of the program or outsourcing the job to a third party. Setting up in house team required investment of time and money in pilot training, education of people on use of technology, getting licenses and acquiring related software along with restricting the use to specified regulations. Whereas outsourcing had its own risk of proprietorship of the data generated from these drone surveys and possible misuse of the information
- **Drone procurement:** The project team did not have any experience in deploying drones for the volume measurement. With a wide range of drone manufacturers and models to choose, it was difficult to determine which drone is right for mapping and volumetric measurement needs. The team had questions on how to start, what all points to consider and what are the risks. Drone technology is exciting, but teams to get overwhelmed at how it works. The interviewee noted that "when you try to sell build in house drone program internally, one has

to carefully decide what benefits one wants from the program and careful measures need to be taken while selecting drones."

- **Data Management and Collaboration**

  There are several challenges of data management such as how the data will be collected, stored, managed, and used. Similarly, it is challenging to determine how it will be shared with stakeholders.

- **Lack of standardized regulations**

  Implementing a technology without a set of standardized documents and a constraint of budget requires good understanding of regulations for seamless project execution. With current Director General of Civil Aviation (DGCA) regulations are still being in the draft stage, it is another risk to make purchases of equipment. For example, a new set of regulations may cause incurred time and money loss.

  After a couple of meetings and discussion, the team decided to hire a subcontractor to the task which the team believed will shift the regular risk away from the project team. The team was sure that the hired contractor will come with their own insurance, training, safety requirements and would be aware of guidelines on UAS "Requirements for Operation of Civil Remotely Piloted Aircraft System (RPAS)".

The use of technology

Typically, survey performed using GPS and rover generates hundred to thousands of data points for a typical stockpile, to an error of less than 5 cm, which is very precise method for determining the X, Y and Z coordinates of each point. However, there are limitations in the number of points that can be taken for a given survey.

Whereas in aerial surveying drones capture geo-tagged images of the site. Once the photos are collected, with high degrees of overlap they are stitched and uploaded into software that then uses photogrammetry to generate a high-resolution orthomosaic map, point cloud and 3D model. Photogrammetry works by identifying points that are common between overlapping photos and then comparing the geo-tagging data and relationship between overlapping photos to model the points in 3-dimensional space. Figure 5.2 shows images obtained from drone survey and a snapshot from one of the software's that is used for volumetric analysis of aggregate stockpiles.

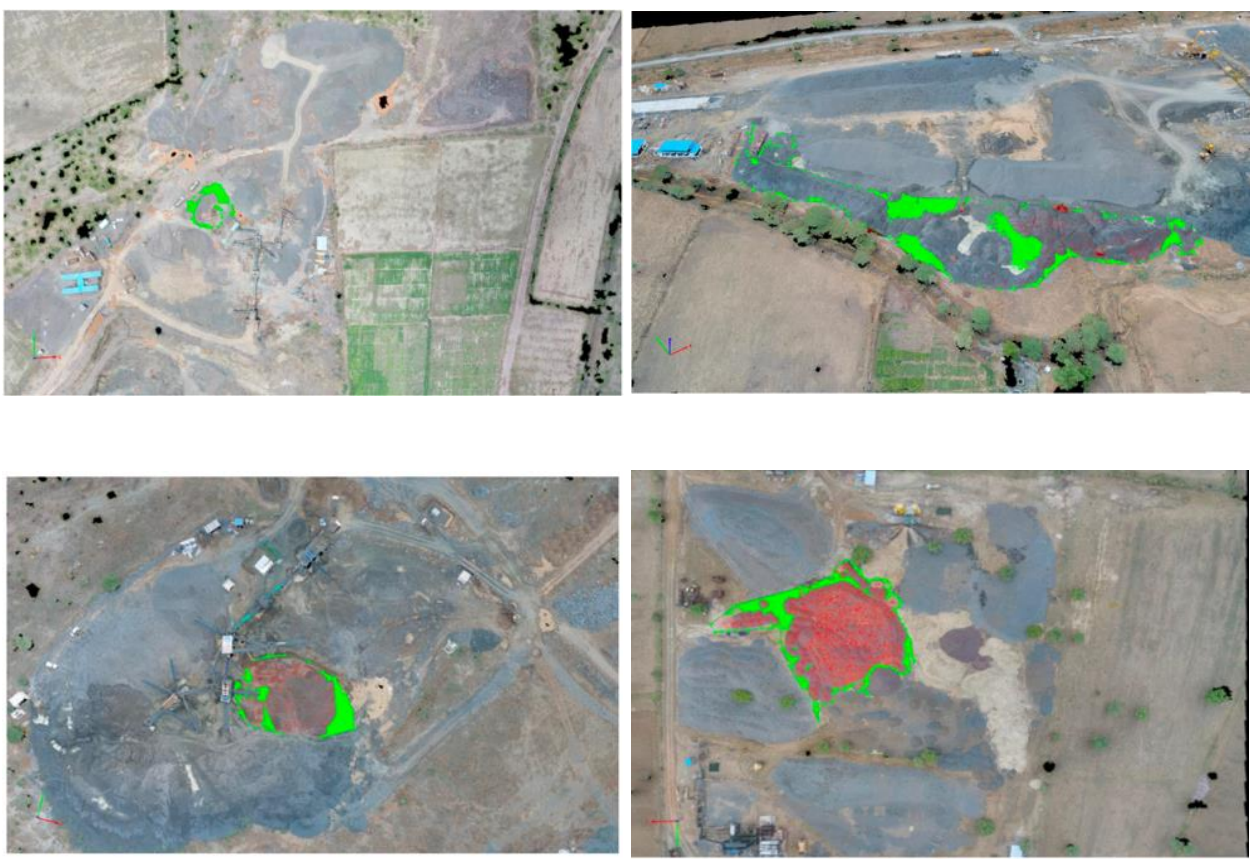

FIGURE 5.2. Stockpile Aerial photos taken by UAS at Quarry Site.

Volumetric data obtained

There were 4 different sites and 21 stockpiles spread over 20 acres of land with sizes varying from 10mm, 20mm, and 30mm to river sand etc. One flight was for 30 minutes and it took merely 8 hours to perform aerial survey of the sites. The volumetric data obtained is presented below.

TABLE 5.2. Volumetric data for different sized aggregates at Site 1 and 2.

Site	***Site 1***			***Site 2***		
Aggregate Size	**10 mm**	**20mm**	**30mm**	**10 mm**	**20mm**	**30mm**
Terrain 3D Area (Sqm)	609.141	641.372	767.656	6974.03	2731.37	5255.69
Fill Volume (Cum)	-103.775	-49.7984	-93.9826	-38.8006	-5.53748	-31.1255
Fill volume error (m3)	0.63159	0.601	0.12177	1.753	0.62123	4.2222
Cut Volume (m3)	308.555	305.614	203.127	9142.38	4499.8	12083.8
Cut Volume Error (m3)	1.4888	0.33445	1.16559	14.01	12.1272	10.4286
Total Volume (m3)	204.78	255.816	109.144	9103.58	4494.26	12052.7
Total Volume Error (m3)	1.1204	0.9355	1.2874	15.763	14.7485	14.651

TABLE 5.3. Volumetric data for different sized aggregates at Site 3 and 4.

Site	***Site 3***			***Site 4***		
Aggregate Size	**10 mm**	**20mm**	**30mm**	**10 mm**	**20mm**	**30mm**
Terrain 3D Area (Sqm)	1149.1	1372.39	1516.75	4086.5	3583.14	4327.94
Fill Volume (Cum)	-64.214	-245.354	-98.6504	-179.543	-9.26022	-20.5221
Fill volume error (m3)	1.4268	2.9569	0.21563	1.926	1.50417	3.94676
Cut Volume (m3)	195.372	973.743	591.416	4747.22	9889.91	10269.1
Cut Volume Error (m3)	5.5089	7.1116	13.2614	19.9089	14.5933	11.902
Total Volume (m3)	131.158	728.389	492.765	4567.67	9880.65	10248.6
Total Volume Error (m3)	6.9357	10.0685	13.477	21.8348	15.6475	14.8488

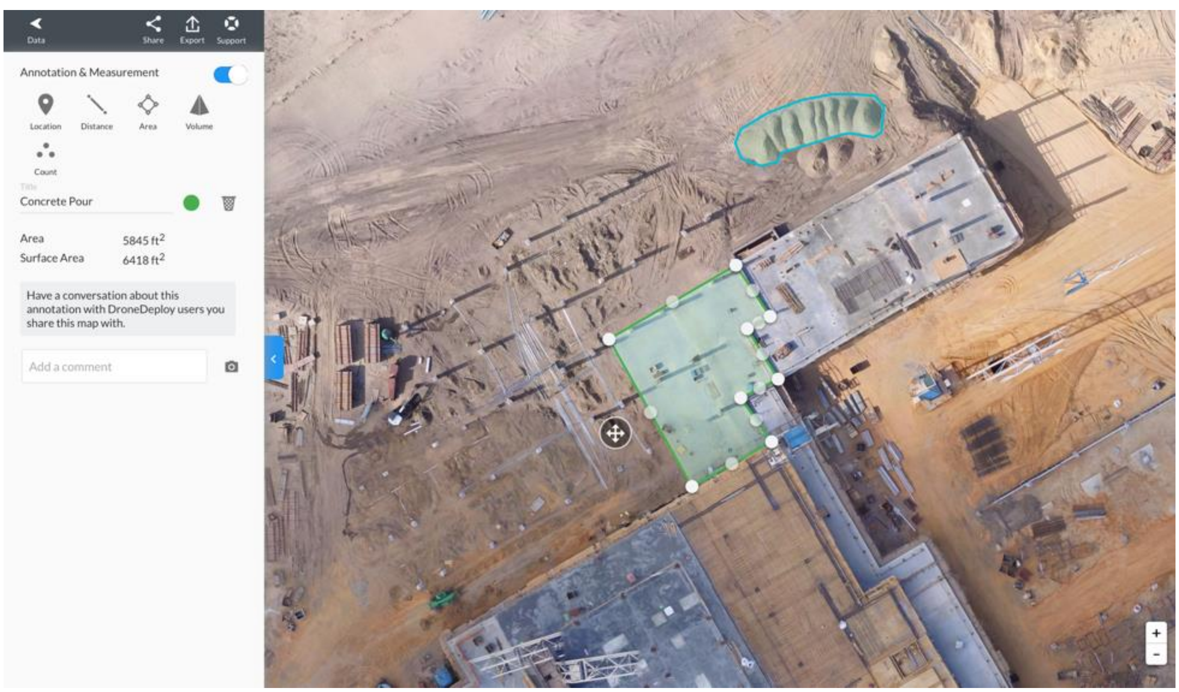

FIGURE 5.3. Drone-deploy software snapshot showing volumetric data analysis options.

Realized Benefits of Using Technology

Improved communication

Communication on any project play a big role and takes a lot of time. Drones take photos that offer tools to quickly and effectively show, rather than tell, what's going on with a project and what needs to be done. Drone technology is a game changer as it is much easier to communicate the project status to the client with a photo rather than preparing a progress report and sharing it with the stakeholders.

Time Savings

As it is evident from the crusher survey results that a drone can deliver the volumetric results much quicker than time taken by a land surveyor. It was realized that a 30 acre of land can be surveyed using a multi rotor drone in 30 minutes without compromising on the results (accuracy). Typically the traditional method of visual surveying by an inspector is slow and expensive. In fact, using drone to perform each embankment/subgrade or pavement can increase the efficiency and productivity of the project team.

High-resolution 3D point clouds generated with drones yield millions of data points. This type of data when viewed in compatible software packages can provide with useful information that can be used for Terrain mapping and change detection, asset management and scheduling, resource location on highway project.

5.6 Other Technologies under implementation

Project team shared that safety technologies (RFID and digital harnessing) and connected vehicle technology (Automated machine guidance and Asset insight for vehicle monitoring) are also being deployed on the project.

Safety technology

There can be no construction without workmen and hence their sustained wellbeing is important for any organization to function efficiently. Giving workmen a safe work environment, ensuring their personal safety, and providing them with all the appropriate tools and protective equipment and the necessary training are important tasks.

Optimizing labor, ensuring their safety and improving their productivity can make a significant positive impact on projects and go a long way towards achieving timely completion and better cost management. Digital technologies have now started to play an increasingly important role in realizing these objectives.

- **RFID:** One of the fundamental applications of digitalization at construction sites is the use of tracking systems such as bar codes and RFIDs. Workmen at select sites of L&T Construction now wear helmets that are RFID-tagged whereby the project safety team can ensure that workmen are confined to their designated areas of operation. Whenever new workmen come onboard a project, they are allotted different colored helmets equipped with RFID irrespective of their work experience during their first month of induction. If such new workmen enter a hazardous zone without permits then the safety personnel get information in no time and action is taken. The introduction of RFID tags has made easier as a large project can be monitored right on computer screens and safety ensured.

- **Digital harnessing:** At the zenith of the digital pyramid at L&T is the 'connected workman' who, with 'wearables' can be 'sensed' which can play a vital role in ensuring their safety. At times, workmen are forced to work in places where they are uncomfortable or even scared like at heights or in confined spaces, using sensors can prevent workers from these hazard environment. For example, sensors in the wearable devices can immediately reveal if there are undesirable fluctuations in heartbeat, pulse rate, blood pressure and the like that can in turn alert the supervisors to take corrective action and thereby prevent an incident. These 'wearables' also detect fatigue and other behavior aspects that are deterrents to performance.

Connected Vehicles, Tools & Equipment

Assets of various types at the project site are connected through sensors. The purpose of being hooking up assets to collect intelligent data that could be used for better understanding of the assets and make inferences through analytics. Some of the equipment linked are motor graders, batching plants, cranes, wheel loaders, excavators, concrete pumps, or power generators. Motor graders form the most important equipment on highway infrastructure projects. The profitability of a road project hinges heavily on how efficiently these motor graders are utilized. Road projects are usually spread over huge areas thus resources are stretched out over different locations. The asset insight (the asset management tool) is currently providing data on 104 motor graders across 25 road projects. Also, knowing the location of critical assets like truck cranes, mobile cranes and boom placers that are always in demand helps plan their allocation and deployment more efficiently. Asset commissioning time is reduced significantly which translates into huge savings.

Batching plants provide a goldmine of information that can have a serious bearing on the profitability of any organization. The interviewee stated that "The dashboard is proving to be very useful for us as it gives insights into the status of equipment, its working details, fuel consumption, vital parameters related to safety, health and maintenance of the equipment on a continuous basis." By being able to extract data and monitor fuel consumption on a real time basis, any anomaly can be instantly detected, and corrective action initiated can translate into considerable cost saving.

4.9 Summary

This chapter describes state of practice of the five emerging technologies for delivering highway construction projects at a project level. The key finding of these five technologies are identified through conducting series of interviews with the project team at Bal-Bilara highway project site. The chapter first presents the protocol for selection of contractor and then the project and what were the factors considered in selecting the same. The chapter then discussed in detail the technologies being used, motivation and process of selection, challenges and benefits of each technology. The team shared information on how significant capital investment is being made to develop in-house programs to innovate, implement and improve these technologies. Next chapter covers the conclusion of the research as a whole and suggests probable future research topics.

CHAPTER 6 – CONCLUSIONS AND FUTURE RESEARCH

6.1 Introduction

The conclusion presented in this chapter are drawn from three main sources of information collected for the synthesis: comprehensive literature review and content analysis; survey of state DOTs; and a case study. Each of these research steps provided insight and a better understanding of the use and coordination of contractor's use of visualization and modeling technologies, interconnected vehicles/equipment/tools technologies, safety technologies, instrumentation, and unmanned aerial systems during construction.

The gaps in knowledge and practice identified in this study serve as a point of departure to explore the potential for future research. This thesis report and future research studies may help guide transportation agencies to effectively and efficiently use emerging technologies for delivering highway projects more productively and accurately.

6.2 Conclusions

Many state DOTs have begun using technologies related to visualization and modeling, interconnected vehicles, equipment, and handheld tools, safety, instrumentation, and unmanned aerial systems for construction delivery, and their use will continue to improve and increase. Based on the data collected from literature, the survey questionnaire, and the case study, the following are the primary conclusions, in no particular order.

6.2.1 Key Findings:

- DOTs tend to allow contractors to use technologies as a part of the means and methods, which is the contractor's discretion as long as it does not require a change order and with the DOTs approval.
- Typically, contractors are more advanced and have realized the benefits in using select emerging technologies than state DOTs. Additionally, many of the technologies discussed in this report are directly used by contractors in which the state DOT provides the guidance and specifications for the use of these technologies and may not directly use the technology during construction.
- DOTs use approaches to investigate, try out, and implement technologies for construction. By first investigating, then piloting, communicating the results, and determining the ability to implement the emerging technology on a regular basis provides DOTs the chance to learn about and use a technology before moving it into every day practice. However, the approaches used for investigating and moving technologies into practice vary among state DOTs, and some use an ad hoc approach.
- A business case is needed in the viable use of construction technologies as state DOTs continue to consider and experiment with many different technologies, but to move an emerging technology into regular practice requires the technology to show its value and potential for large-scale deployment. An innovative technology is to be a solution to a known problem or inefficiency, rather than a solution looking for a problem.
- State DOTs currently use visualization and modeling technologies along with technological instrumentation devices the most often for construction projects and are

typically the most mature in their use, while the use of interconnected vehicles, equipment, and handheld tools beyond machine control guidance is very limited.

- Many technologies and their use are connected to one another and the use of a technology without implementing technologies downstream of the initial technology results in a lack of realizing the fullest potential. A 3D model, which is developed using digital surveying and topographic information, is only as useful as the information provided to contractors for machine guidance controls, which in turn the work associated with AMG needs to be inspected in the field with GPS and other technological devices to measure adherence to the project specifications accurately.
- The use of emerging technologies helps state DOTs make their project workforce more efficient and improve productivity. Technologies associated with site surveying, progress monitoring, and inspections reduces the number of people and worker-hours needed to complete a task or inspection. DOTs may use these unused human resources for other critical areas of a project, making the use of worker-hours more efficient and productive
- Champions for the use of emerging technologies
- Strengths and weaknesses of different technologies

Visualization and modeling technologies

- Moving to a digital project delivery system may require DOTs to supply 3D models as contract documents. However, the legality and accuracy of using 3D models than traditional 2D is under investigation as most DOTs currently supply 3D models for only various portions of a project. Only a handful of pilot projects have incorporated 3D models as contract documents at the time of this study.

- DOTs are challenged by incompatibilities in hardware and software programs in terms of transferring digital data between the DOT and the contractor. Incompatibilities create additional work to manipulate and analyze data, which makes the technology use less efficient.

Interconnected vehicles, equipment, and tools

- The use of interconnected equipment during construction is directly performed by the contractor, while the state DOT typically supports its use and conducting the inspection of the work performed with connected equipment and tools.
- Using AMG for earthwork and paving activities is becoming standard practice for highway projects. Further use of interconnected vehicles and handheld tools is limited regarding their use for construction, although DOTs are using connected agency vehicles with GPS for location tracking and performance and maintenance monitoring.
- Several states are now piloting e-ticketing for asphalt and concrete paving operations. The benefits seen from e-ticketing a streamlined and safer process adheres to FHWA requirements in the tracking of pavement materials for DOT highway projects using federal funds.

Safety technologies

- The use of safety technologies, which the majority of the time is the responsibility of and used by the contractor, increases based on the project size, complexity, and work zone traffic volume levels.
- Some advanced safety technologies are currently proprietary, which limits their use with publicly funded highway projects.

Instrumentation

- State DOTs are increasingly using instrumentation to monitor the progress of work and inspect work put in place. Technological instruments and devices are deployed to field personnel for measuring work and conducting inspections that reduce the need for destructive testing instead of more technologically advanced non-destructive tests of placed materials.

Unmanned aerial systems

- The use of UASs by DOTs tends to be dictated by FAA and state regulations. State DOTs that have authority to use UASs is typically the result of internal champions leading the effort within the department and with the state legislature to use UASs at state DOTs for construction purposes. In some states, contractors are using UAS, even though the state DOT may not have the authority to do so.

6.2.2 Future Research

There are several gaps in the current knowledge regarding use of emerging technologies at agency and project level. Most state DOTs select the technology on a case-by-case basis. For state DOTs to become more consistent, efficient, and effective in understanding, implementing and realizing the full potential of the five technologies, the following items are potentially worthwhile topics for future research studies.

When reviewing the national survey and the case examples, it became clear that DOT employees do not have standardized documents or manuals on the technology use and its implementation, the higher management makes decisions about what technology will be used on which project on a case by case basis and the project team is provided with support either by the management or directly by the vendor/supplier of the technology. There is a need to standardize these documents with combined input from all state DOTs in order to succeed in transforming the face of highway infrastructure projects.

State DOTs mentioned that with use of emerging technologies workforce shortage can be addressed which at times becomes the reason of project delay, several technologies are being experimented with to either remove workforce from harm's way or to complete the daily tasks faster and with greater accuracy. State DOTs are constantly required to do more with less and the use of advanced technologies shows promise to make the construction workforce more efficient and productive. Thus, a possible study to consider is an investigation into the use of advanced technologies and how they potentially offset workforce shortages for constructing highway projects.

Some DOTs mentioned that majority of the workforce at the site level is younger generation who are technology savvy and are open to accepting the use of technologies to simply the tasks so that attention can be given to other necessary tasks, including the study of these technologies into the academia will help the future generation of civil engineers prepare for the projects better before they are appointed on real life projects. A study focusing on how these technologies can be made part of the curriculum and benefits can be realized in the long term seems to be bring promising results. Another topic of interest is developing a free forum for DOTs to share their documentation on the implemented documentation which is available to be used by others at their discussion and also make edits. This way the documents will be updated in real time and benefits can be realized by small contractors equally for construction industry as a whole to grow and increase productivity at project sites.

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APPENDIX A – SURVEY QUESTIONNAIRE

A.1 General Information

1. Please provide the following contact information:

First Name:	
Last Name:	
Phone Number:	
E-mail:	
Agency in which you are employed:	
Current position:	

2. Approximately, how many capital highway construction projects does your agency deliver annually on average?

____

3. Approximately, what is the total capital cost for delivering highway projects annually on average?

____

4. Has your agency implemented the use of the following emerging technologies during construction of highway projects?

Type of Technologies	**Yes**	**No**	**Considering its use, but not yet implemented**	**Don't know**
Visualization & Modeling Technologies	☐	☐	☐	☐
Interconnected Vehicles & Equipment	☐	☐	☐	☐
Safety Technologies	☐	☐	☐	☐
Instrumentation	☐	☐	☐	☐
Unmanned Aerial Systems	☐	☐	☐	☐
Other (please specify): ______________________________	☐	☐	☐	☐

5. What types of construction projects benefit from the use of the following technologies at your agency (Please mark all that apply)?

Project Type	**Visualization & Modeling Technologies**	**Interconnected Vehicles & Equipment**	**Safety Technologies**	**Instrumentation**	**Unmanned Aerial Systems**
Paving	☐	☐	☐	☐	☐
Bridges	☐	☐	☐	☐	☐
Non-bridge structures	☐	☐	☐	☐	☐
Utility location/relocation	☐	☐	☐	☐	☐
Drainage	☐	☐	☐	☐	☐
Other (Please Specify): ________________________________	☐	☐	☐	☐	☐

A.2 Visualization & Modeling Technologies

6. Which of the following visualization and modeling technologies have been used to deliver highway construction projects at your agency (Please mark all that apply)?

Visualization & Modeling Technologies	
☐	Virtual reality
☐	Augmented reality
☐	Virtual prototyping
☐	Wearable visualization devices
☐	Civil Integrated Management (CIM)
☐	3D/4D/5D Building Information Modeling (BIM)
☐	3D/4D/5D Bridge Information Modeling (BrIM)
☐	3D printing
☐	LiDAR
☐	Other (please specify): ______________________________

7. How are visualization and modeling technologies used to deliver highway construction projects at your agency (Please mark all that apply)?

   ☐ Constructability analysis and reviews

   ☐ Documentation of as-built plans and models

☐ Fabrication of structural components

☐ Fabrication of non-structural components

☐ Simulation of bridge construction

☐ Simulation of non-bridge construction

☐ Monitoring construction progress

☐ Utility locations and conflicts

☐ Verification of work completed for payment

☐ Evaluation and monitoring planned activities

☐ Virtual design and construction

☐ Quality control / Quality assurance

☐ Inspections

☐ Other (please specify): ____

8. How frequently are visualization and modeling technologies used for highway construction delivery at your agency?

☐ None

☐ Some specific projects (Please provide examples: ____________________________)

☐ All projects

☐ Not sure

☐ Other (please specify): ______________________________________

9. What are some lessons learned that you can think of in implementing the use of visualization and modeling technologies for construction delivery at your agency?

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A.3 Interconnected Construction Vehicles & Equipment

10. Which of the following interconnected vehicles and equipment have been used on highway construction projects at your agency (Please select all that apply)?

Interconnected Vehicles & Equipment	
☐	Agency vehicles (e.g., fleet vehicles, pickup trucks)
☐	Delivery vehicles (e.g., concrete mixer trucks, dump trucks, material delivery vehicles)
☐	Haul vehicles (e.g., dump trucks, cranes, loaders)
☐	Earthwork equipment (e.g., dozers, backhoes, graders, scrapers, excavators)
☐	Paving equipment (e.g., compactors, asphalt pavers, concrete pavers, planers)
☐	Handheld tools (e.g., saws, drills, jackhammers)
☐	Other (please specify): ________________________________

11. How are interconnected construction vehicles and equipment used for delivery of highway construction projects at your agency (Please select all that apply)?

☐ Location of vehicles

☐ Location of equipment/tools

☐ Accident avoidance

☐ Maintenance of vehicles/equipment/tools

☐ Performance monitoring of vehicles/equipment/tools

☐ Inventory management

☐ Asset management

☐ Mobility tracking

☐ Other (please specify): ____________________________________

12. How frequently are interconnected vehicles and equipment used for highway construction delivery at your agency?

☐ None

☐ Some specific projects (Please provide examples: ____________________________)

☐ All projects

☐ Not sure

☐ Other (please specify): _____________________________________

13. What are some lessons learned that you can think of in implementing the use of interconnected vehicles and equipment for construction delivery at your agency?

____

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A.4 Safety Technologies for Workers and Motorists

14. Which of the following safety technologies have been used on highway construction projects at your agency (Please select all that apply)?

Safety Technologies	
☐	Proximity warning alarms
☐	Wearable technology-enhanced personal protection equipment (PPE)
☐	Work zone intrusion alarms
☐	Mobile dynamic message signs
☐	Stationary dynamic message signs
☐	Variable speed zones
☐	Dynamic lane merging
☐	Automated cone placement and retrieval
☐	Health monitoring equipment
☐	Vehicle-to-Infrastructure (V2I) communications
☐	Vehicle-to-Vehicle (V2V) communications

☐	Other (please specify): ____

15. How are safety technologies used for delivery of highway construction projects at your agency (Please select all that apply)?

☐ Accident avoidance

☐ Intrusion detection

☐ Real-time information for motorists

☐ Removing workers from harm's way

☐ Enhanced protection for workers

☐ Quality control / Quality assurance

☐ Incident tracking and data collection

☐ Traffic control/management in the work zone

☐ Other (please specify): ______________________________________

16. How frequently are safety technologies used for highway construction delivery at your agency?

☐ None

☐ Some specific projects (Please provide examples: ______________________________)

☐ All projects

☐ Not sure

☐ Other (please specify): ______________________________________

17. What are some lessons learned that you can think of in implementing the use of safety technologies for construction delivery at your agency?

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A.5 Instrumentation Technologies during Construction

18. Which of the following instrumentation technologies have been used for highway construction projects at your agency (Please select all that apply)?

Instrumentation Technologies for Construction	
☐	Audio/Video/Closed Circuit Television (CCTV)
☐	Radio frequency identification (RFID)

☐	Remote sensing (e.g., LiDAR)
☐	Sensors for measuring/monitoring structural integrity (e.g., gauges for stress, strain, deformation, seismic/vibration, current/voltage)
☐	Sensors for measuring/monitoring environmental conditions (e.g., heat, temperature, light, presence of toxins)
☐	Sensors for measuring specifications (e.g., compaction, depth, penetration)
☐	Infrared sensors (e.g., motion detectors, object detection)
☐	Other (please specify): ____________________

19. How are instrumentation technologies used for delivery of highway construction projects at your agency (Please select all that apply)?

☐ Recording placement of work for as-built purposes

☐ Monitoring progress of work (e.g., time-lapse audio and video)

☐ Evaluating boundary conditions of structural members (Note: Boundary conditions define the support conditions of structural members and its surrounding environment)

☐ Evaluating forces of structural members

☐ Monitoring of highway assets

☐ Verifying design during construction

☐ Location of construction materials

☐ Location of utilities

☐ Identifying optimal conditions for placement of work (e.g., compaction, paving)

☐ Quality control / Quality assurance

☐ Inspections

☐ Other (please specify): ____

20. How frequently are instrumentation technologies used for highway construction delivery at your agency?

☐ None

☐ Some specific projects (Please provide examples: _____________________________)

☐ All projects

☐ Not sure

☐ Other (please specify): _______________________________________

21. What are some lessons learned that you can think of in implementing the use of instrumentation technologies for construction delivery at your agency?

____

____

____

A.6 Unmanned Aerial Systems (UASs)

22. How are UASs used for delivery of highway construction projects at your agency (Please select all that apply)?

☐ Construction progress monitoring

☐ Construction documentation

☐ Construction surveying

☐ Site mapping

☐ Inventory of materials/equipment

☐ Geographic information systems (GIS)

☐ Remove workers from hazardous situations

☐ Construction site security

☐ Asset management

☐ Safety management / Safety inspections

☐ Quality control / Quality assurance

☐ Inspections

☐ Traffic control and surveillance

☐ Other (please specify): ____

23. How frequently are UASs used for highway construction delivery at your agency?

☐ None

☐ Some specific projects (Please provide examples: ______________________________)

☐ All projects

☐ Not sure

☐ Other (please specify): ____

24. What are some lessons learned that you can think of in implementing the use of UASs for construction delivery at your agency?

____

____

____

____

A.7 Final Thoughts

25. Which of the project stakeholders use the following technologies during construction of highway projects (Please select all that apply)?

Stakeholders	Visualization & Modeling	Interconnected & Vehicles	Safety Technologies	Instrumentation	Unmanned Aerial Systems
DOTs	☐	☐	☐	☐	☐
Contractors	☐	☐	☐	☐	☐
Construction Managers	☐	☐	☐	☐	☐
Program Managers	☐	☐	☐	☐	☐
Contractors	☐	☐	☐	☐	☐
Vendors	☐	☐	☐	☐	☐
Manufacturers	☐	☐	☐	☐	☐
Fabricators	☐	☐	☐	☐	☐
Other (Please Specify): ____________________	☐	☐	☐	☐	☐

26. Does your agency use any of the following technologies to help meet workforce needs during construction of highway projects (*NOTE: Meeting workforce needs relates to the ability of your agency to leverage the use of specific construction technologies to offset a lack of human resources available*)?

Type of Technology	**Yes**	**No**	**Don't know**
Visualization & Modeling Technologies	☐	☐	☐
Interconnected Vehicles & Equipment	☐	☐	☐
Safety Technologies	☐	☐	☐
Instrumentation	☐	☐	☐
Unmanned Aerial Systems	☐	☐	☐
Other (Please Specify): ________________________________	☐	☐	☐

27. Does your agency have a manual or document(s) that specifically describes the use of the following technologies on highway construction projects?

Type of Technology	**Yes**	**No**	**Don't know**
Visualization & Modeling Technologies	☐	☐	☐
Interconnected Vehicles & Equipment	☐	☐	☐
Safety Technologies	☐	☐	☐

Instrumentation	☐	☐	☐
Unmanned Aerial Systems	☐	☐	☐
Other (Please Specify): ________________________	☐	☐	☐

____

____

____

____

28. Are you willing to discuss your emerging technologies practices for construction delivery of highway projects with the research team in a structured interview?

☐ Yes

☐ No

If the answer is "No", can you please direct us to someone else in your agency?

Contact name:	
Phone number:	

E-mail:	

29. Does your agency use any other emerging technologies in highway construction project delivery not related to the technologies specifically discussed in this questionnaire? If yes, please explain:

____

____

____

____

30. Do you have any other information or final thoughts that you would like to share with the research team that might add value to this study?

____

____

____

____

APPENDIX B – AGGREGATED SURVEY RESULTS

B.1 General and Demographic Information

Table B.1 summarizes state DOTs responding to the survey.

Table B.1 State DOTs responding to the survey

No	State DOT	No	State DOT
1	Alabama	22	Nebraska
2	Alaska	23	Nevada
3	Arizona	24	New Hampshire
4	California	25	New York
5	Colorado	26	North Dakota
6	Connecticut	27	Ohio
7	Delaware	28	Oklahoma
8	Georgia	29	Oregon
9	Hawaii	30	Pennsylvania
10	Idaho	31	Rhode Island
11	Illinois	32	South Carolina
12	Iowa	33	South Dakota
13	Kansas	34	Tennessee
14	Kentucky	35	Texas
15	Louisiana	36	Utah
16	Maine	37	Vermont

17	Massachusetts	38	Washington State
18	Michigan	39	West Virginia
19	Minnesota	40	Wisconsin
20	Missouri	41	Wyoming
21	Montana		

B.2 Survey Analysis

- Figure B.1 displays the result to the question if DOTs are using technology for transportation project delivery. They were asked to pick from five emerging technologies that are being extensively used by different agencies and stakeholders.

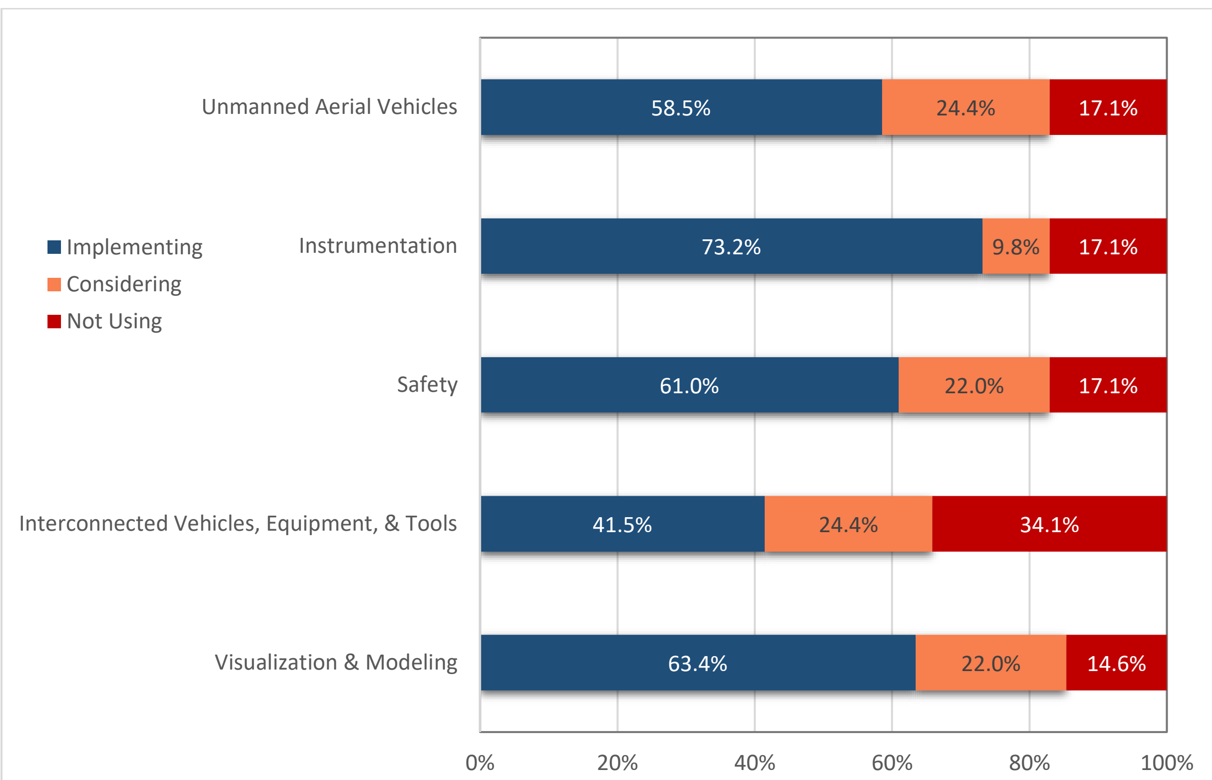

FIGURE B.1 DOTs and technology use (n = 41)

- There were 41 responses to the question, 26 state DOTs (63.4%) reported that they have used Visualization and modeling tech while 17 (41.5%), 25 (61%), 30 (73.2%) and 24 (58.5%) mentioned having used Interconnected Vehicles/Equipment/Tools, Safety, Instrumentation, or UAV technology respectively.

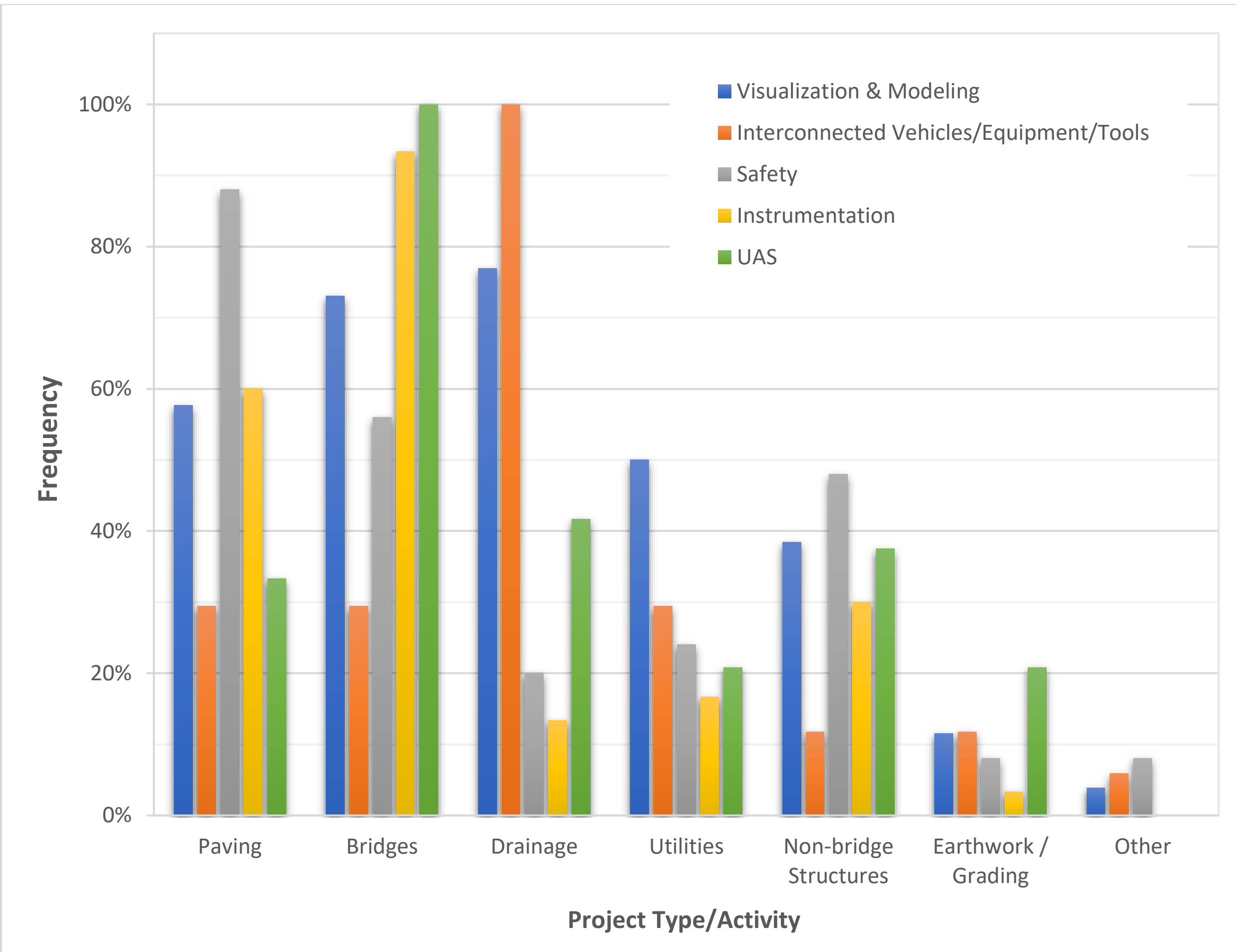

FIGURE B.2 DOTs and uses of technologies vs. project type (n = 41)

- Figure B.2 displays the result to the question, what type of projects benefit from the use of five emerging technologies under discussion. The results show how technology use has increased in the last decade, the Construction industry which has always been considered tradition because of lack of innovation is accepting the use of technology for process improvement.

- Figure B.3 shows different visualization and modeling technologies that DOTs are practicing on their projects. The results were put into two categories, being DOTs having employed the technology on either of their projects or others that are still piloting the technology.

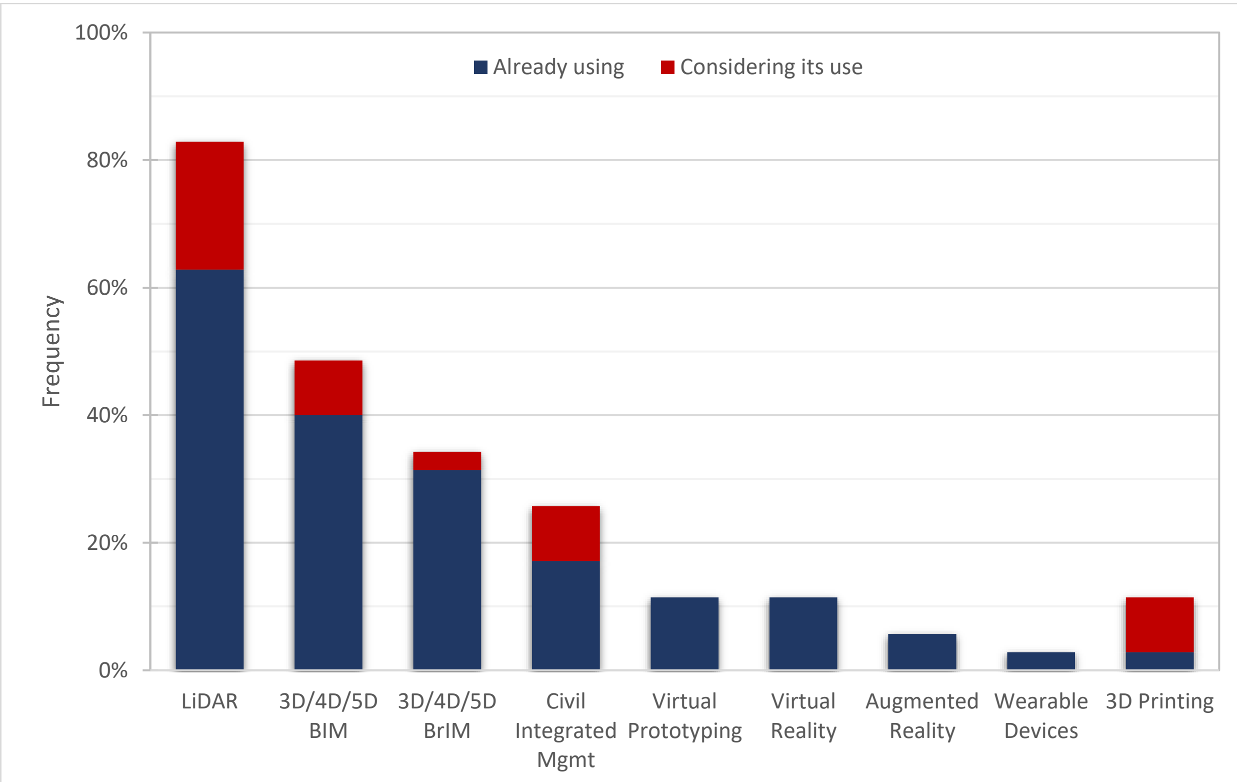

FIGURE B.3 Visualization and modeling technologies in use by state DOTs (n = 35)

- The respondents who mentioned using visualization and modeling technologies were asked to highlight how these technologies benefit their projects. Figure B.4 shows the consolidated results to the question.

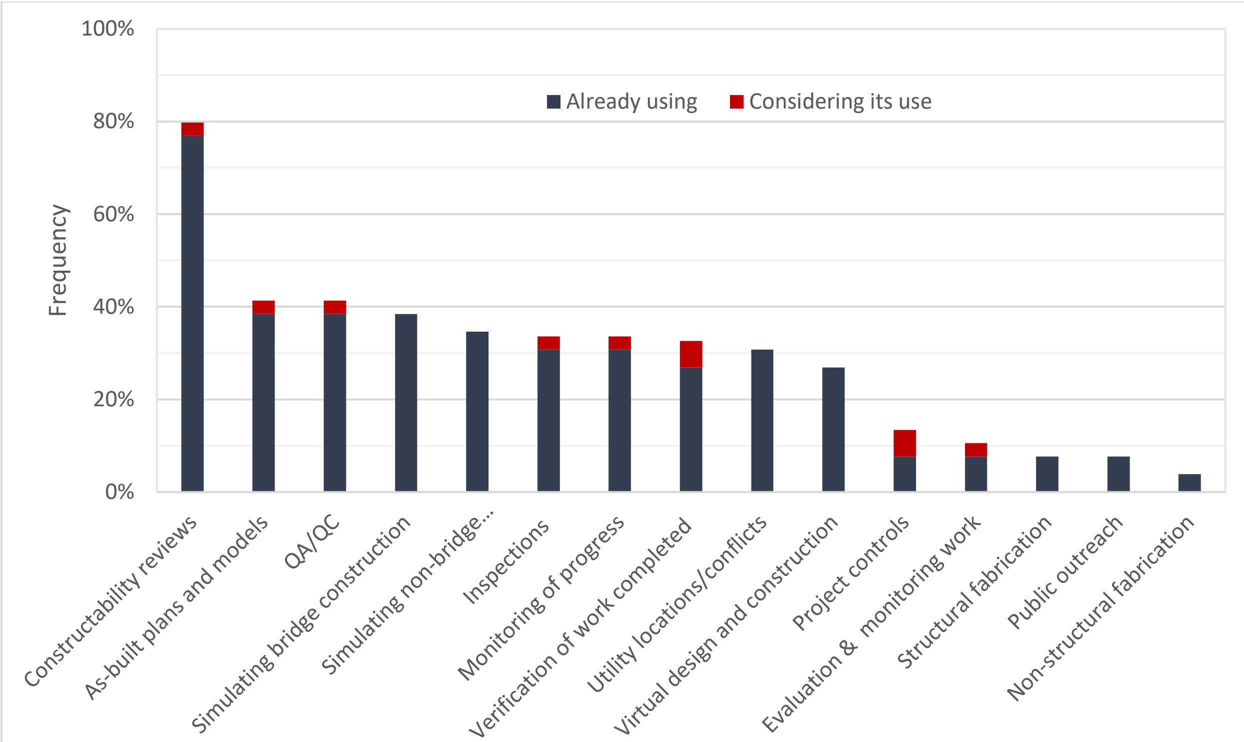

FIGURE B.4 Visualization and modeling technologies for highway project delivery (n = 35)

- The respondents were to share how frequently visualization and modeling technologies are used for highway construction delivery at their agency. Fig B.5 shows the responses.

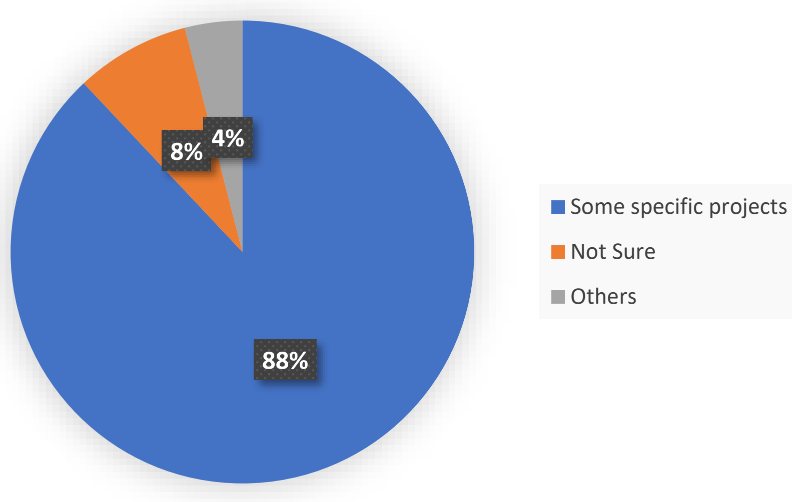

FIGURE B.5 Frequency of visualization and modeling technology use (n = 26)

- Figure B.6 shows different interconnected vehicles/equipment/tools DOTs are employing on their projects.

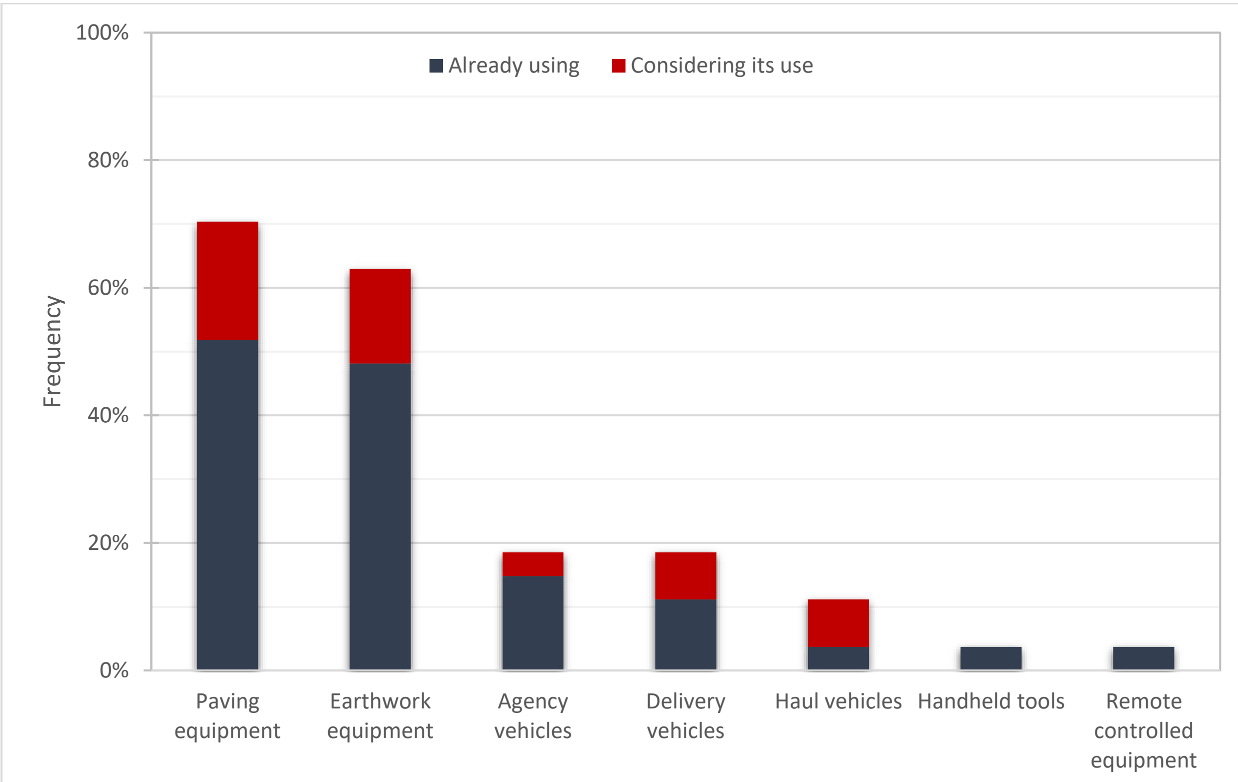

FIGURE B.6 Interconnected vehicles/equipment/tools in use by State DOTs (n = 27)

- The respondents who mentioned using interconnected vehicle technologies were asked to share how these technologies benefit their projects. Figure B.7 shows the consolidated results to the question.

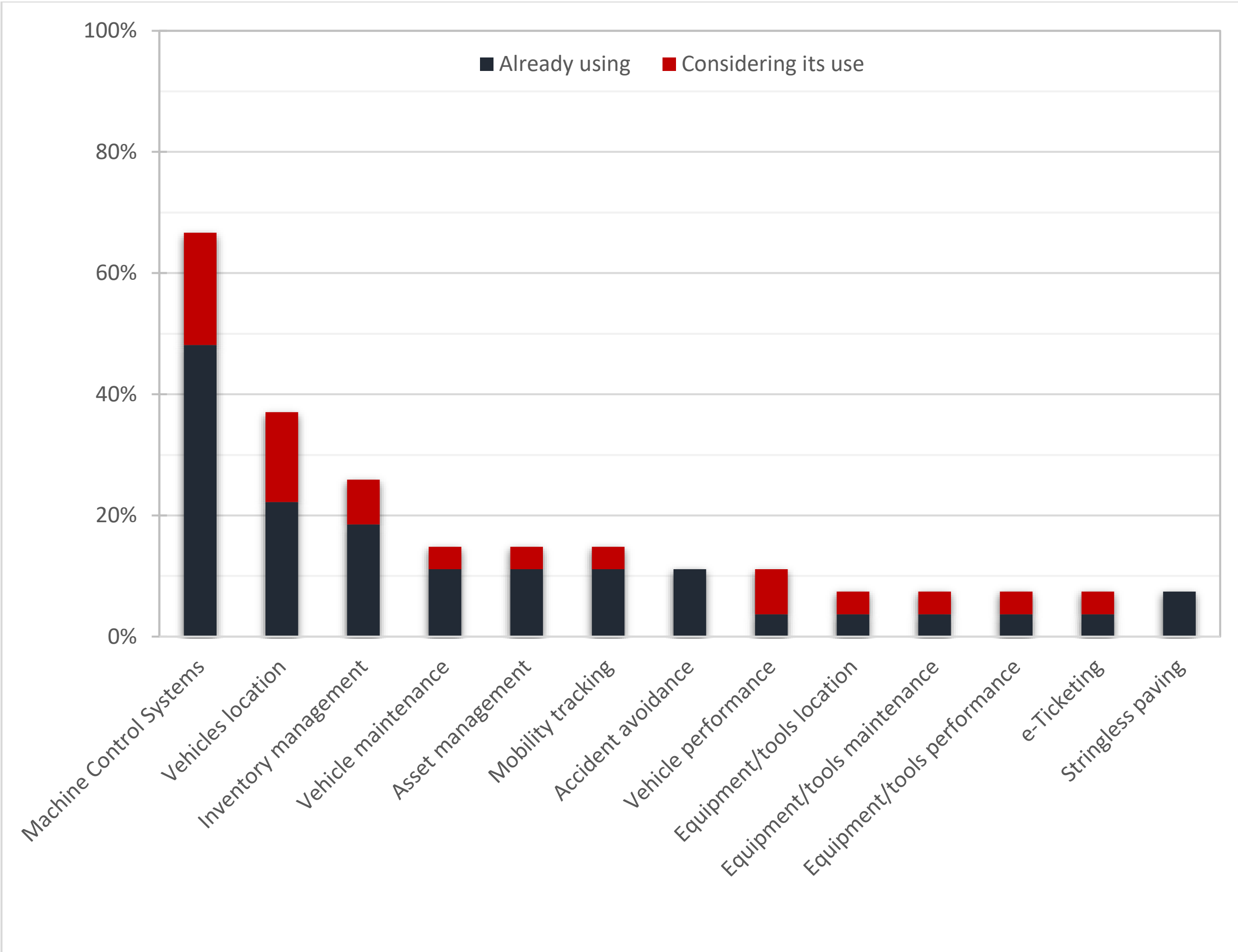

FIGURE B.7 Interconnected vehicles/equipment/tools for highway project delivery (n = 27)

- The respondents were to share how frequently visualization and modeling technologies are used for highway construction delivery at their agency. Fig B.8 shows the responses

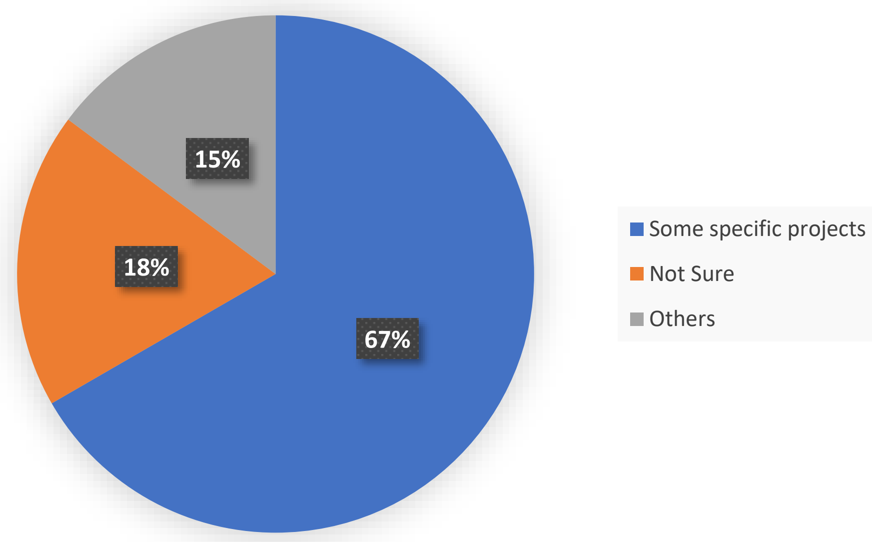

Figure B.8 Frequency in the use of interconnected vehicles/equipment/tools (n = 17)

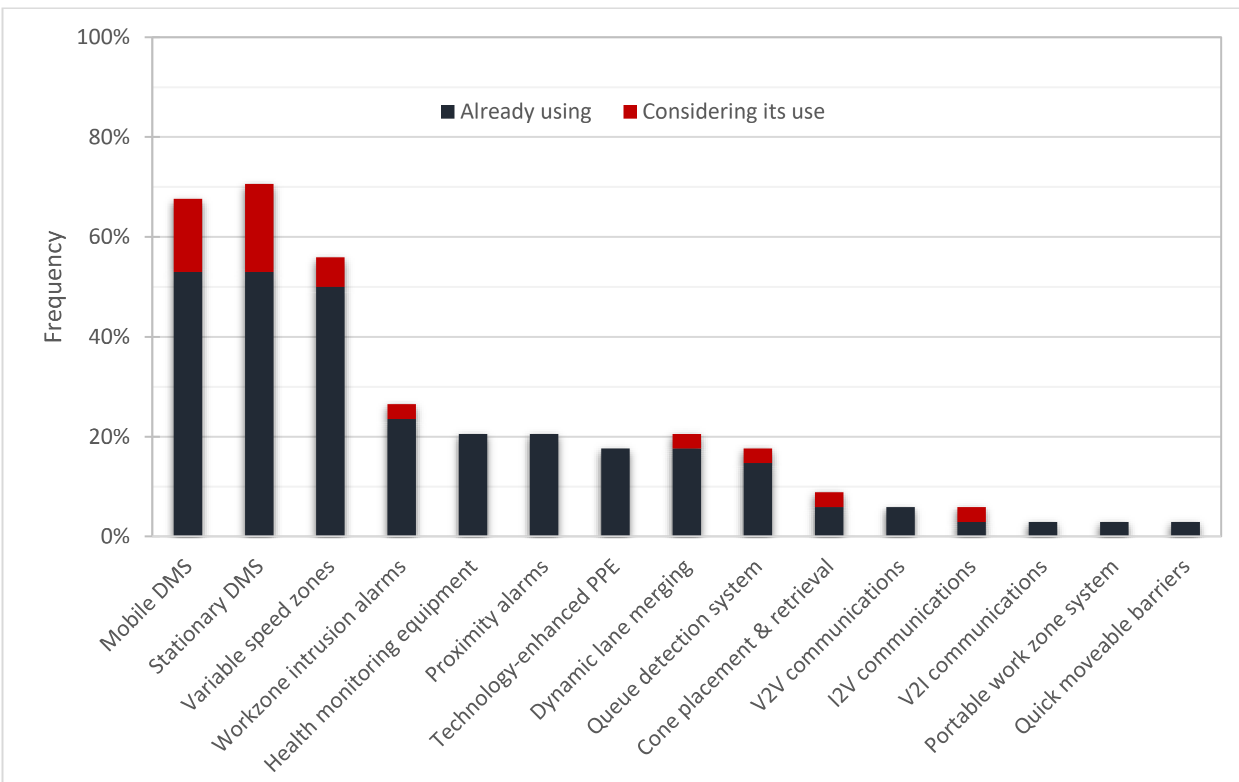

FIGURE B.9 Safety technologies in use by state DOTs (n = 34)

- Figure B.9 shows different safety technologies DOTs are experimenting with on projects.

- Figure B.10 shows results to the question of how safety technologies benefit their projects.

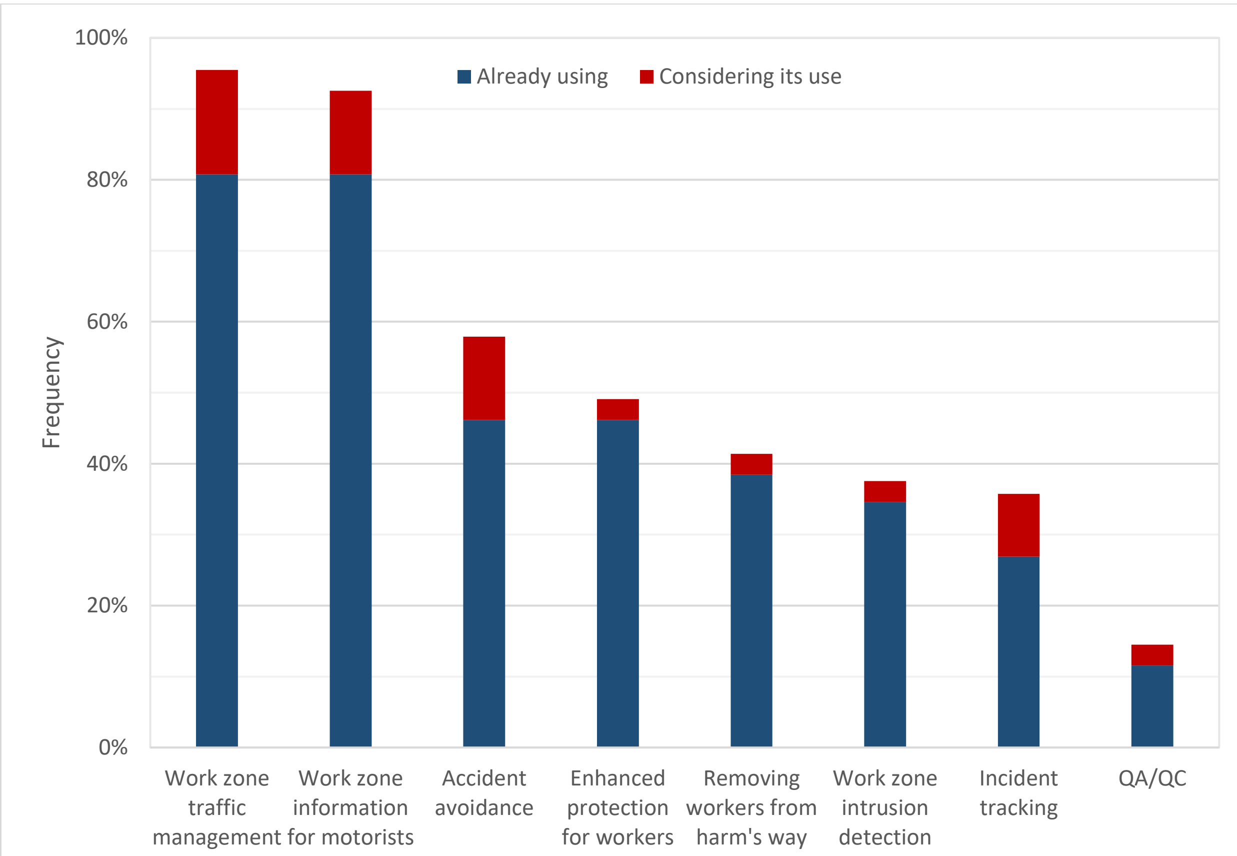

FIGURE B.10 Safety technologies used for highway project delivery (n = 34)

- The respondents were to share how frequently visualization and modeling technologies are used for highway construction delivery at their agency. Utah DOT shared they use safety tech on 25-30% of their projects while Nevada, New York, and Texas DOTs mentioned that all their projects are implementing the technology. Figure B.11 shows the responses.

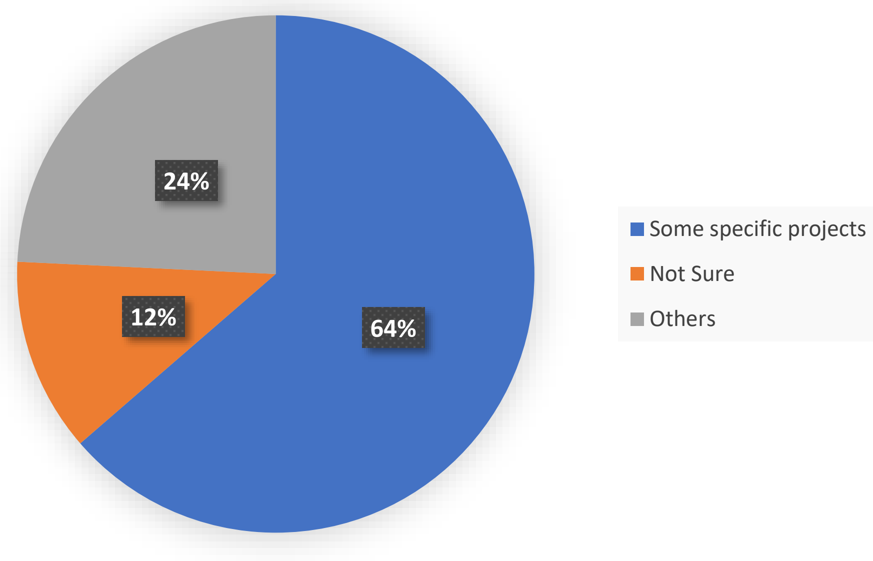

FIGURE B.11 Frequency in using safety technologies (n = 26)

- Figure B.12 shows different instrumentation technologies DOTs are using on their projects.

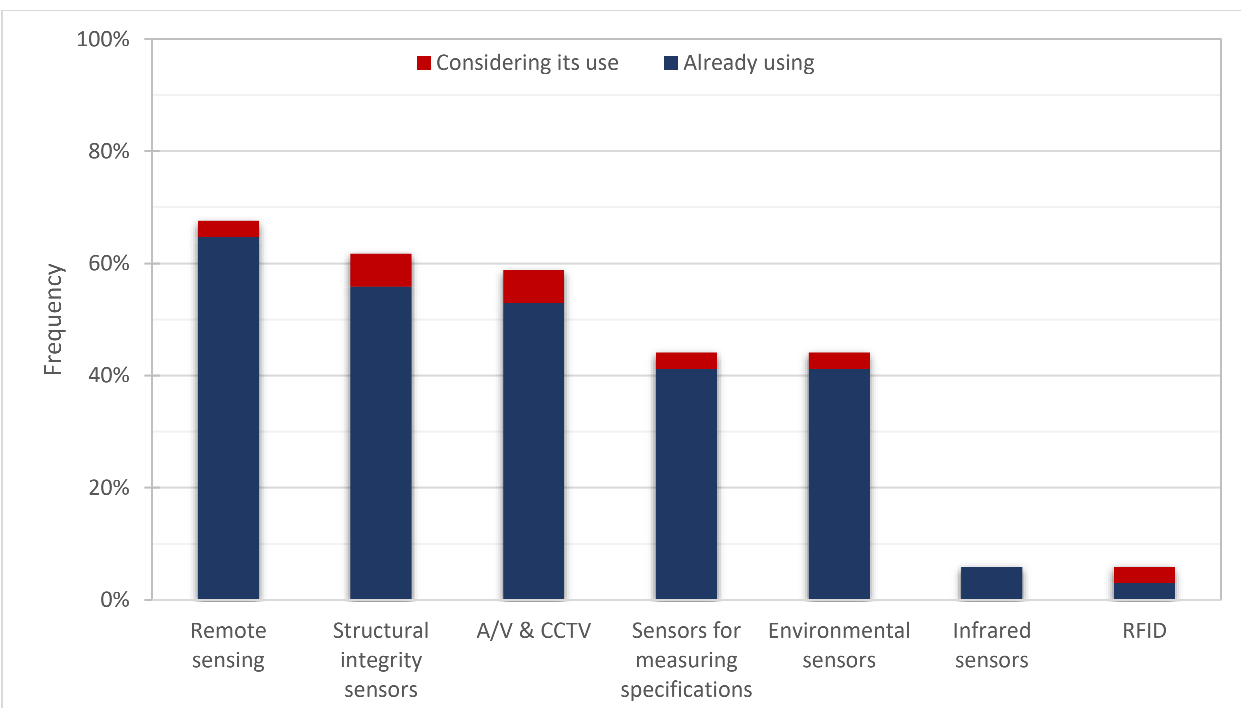

FIGURE B.12 Instrumentation technologies in use by state DOTs (n = 34)

- Figure B.13 shows results to the question of how instrumentation technologies are used on their projects.

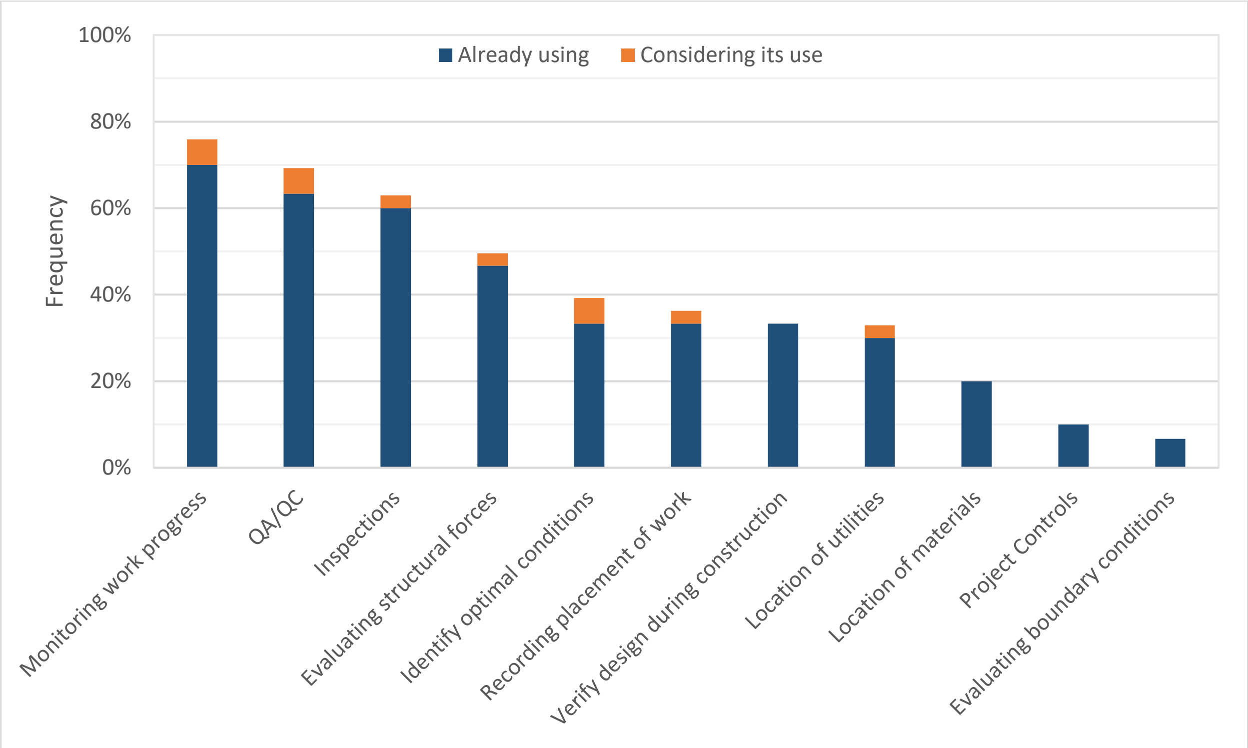

FIGURE B.13 Instrumentation technologies used for highway project delivery (n = 34)

- The respondents were then asked to share how frequently instrumentation technologies are used for highway construction delivery at their agency. Utah DOT stated that they use instrumentation on 35-45% of their projects while Washington, South Carolina, Kentucky, Alaska, and Arizona DOTs mentioned they use instrumentation technologies on all projects. Figure B.14 shows the responses.

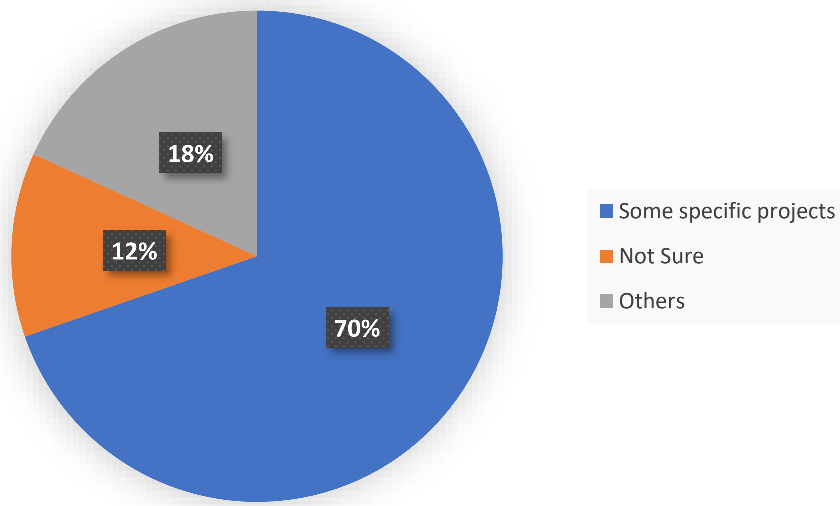

FIGURE B.14 Frequency in using instrumentation technologies (n = 30)

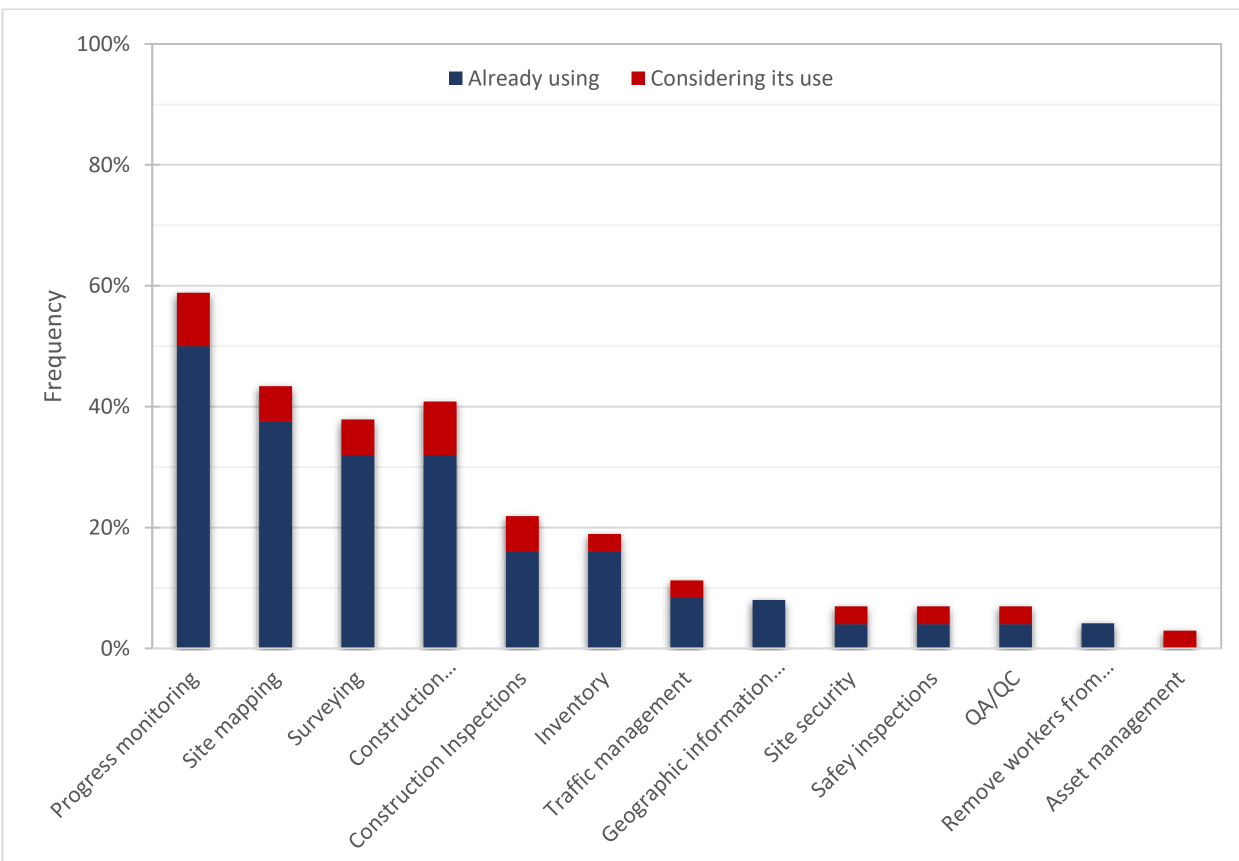

FIGURE B.15 UAS uses for highway project delivery

- Figure B.15 shows how unmanned aerial Systems are being used in highway projects.

- The respondents were to share how frequently drones are used for highway construction delivery at their agency. Utah DOT shared that they use UASs on about 10-12 projects a year while, while most DOTs mentioned they are using the technology on specific projects. Nebraska, Wisconsin, Idaho and California state haven't yet explored their use. Figure B.16 shows the responses.

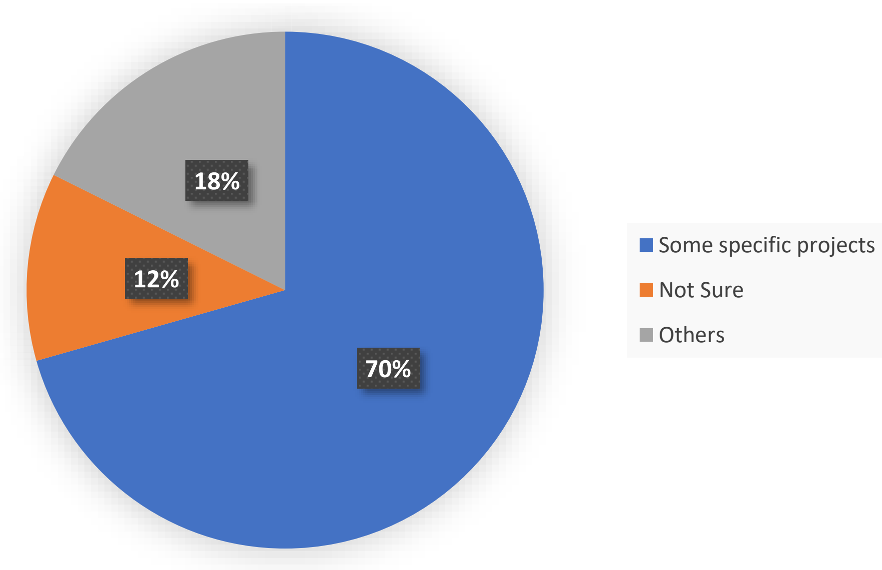

FIGURE B.16 Frequency in using instrumentation technologies (n = 30)

- Figures B.17, B.18, B.19, B.20, and B.21 show the results regarding which stakeholders are using these technologies.

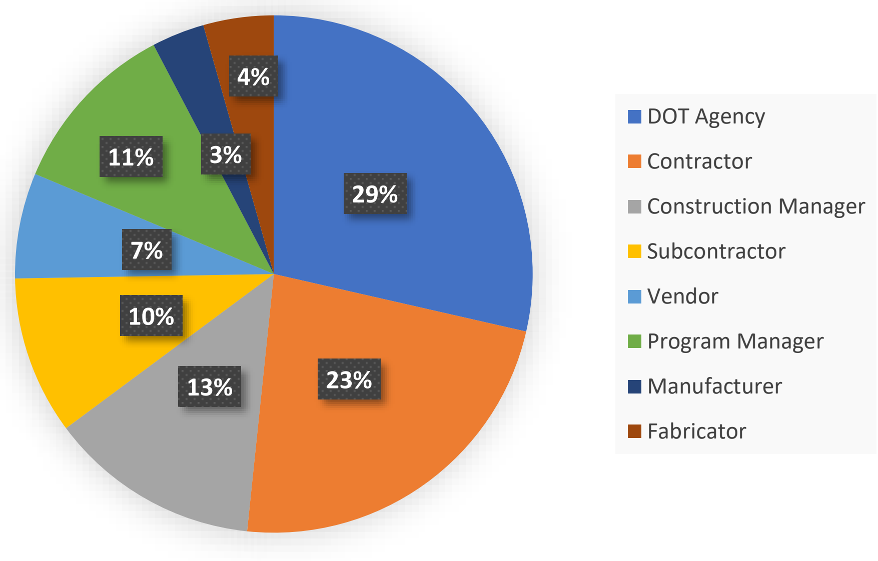

FIGURE B.17 Stakeholders using visualization and modeling technologies

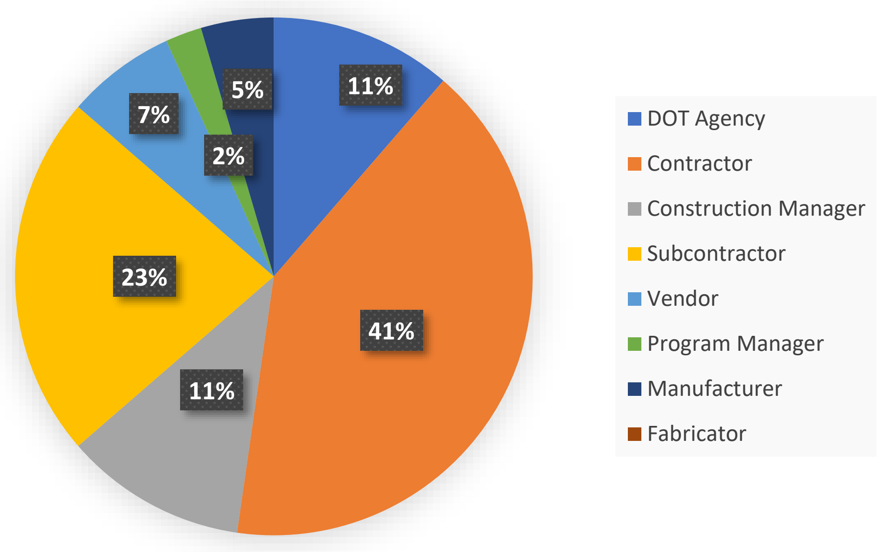

FIGURE B.18 Stakeholders using interconnected vehicles/equipment/tools technologies

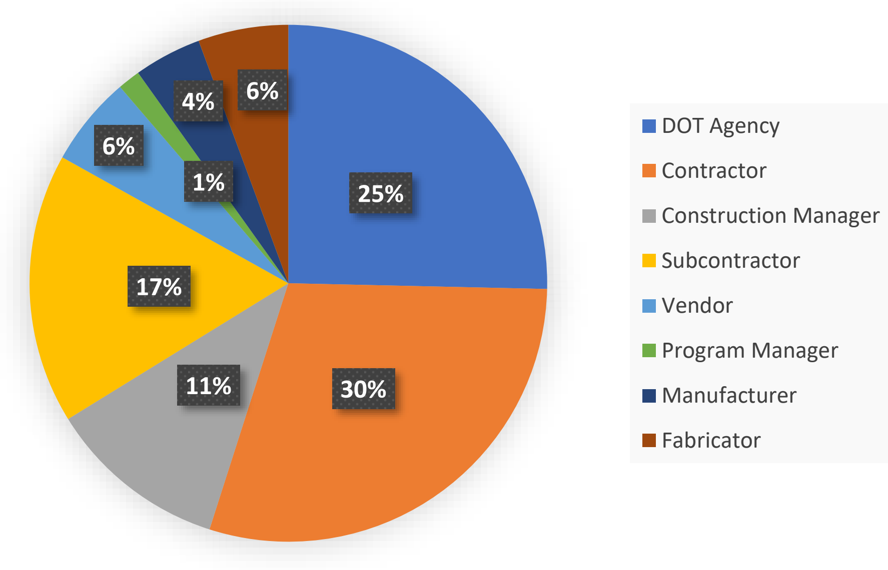

FIGURE B.19 Stakeholders using safety technologies

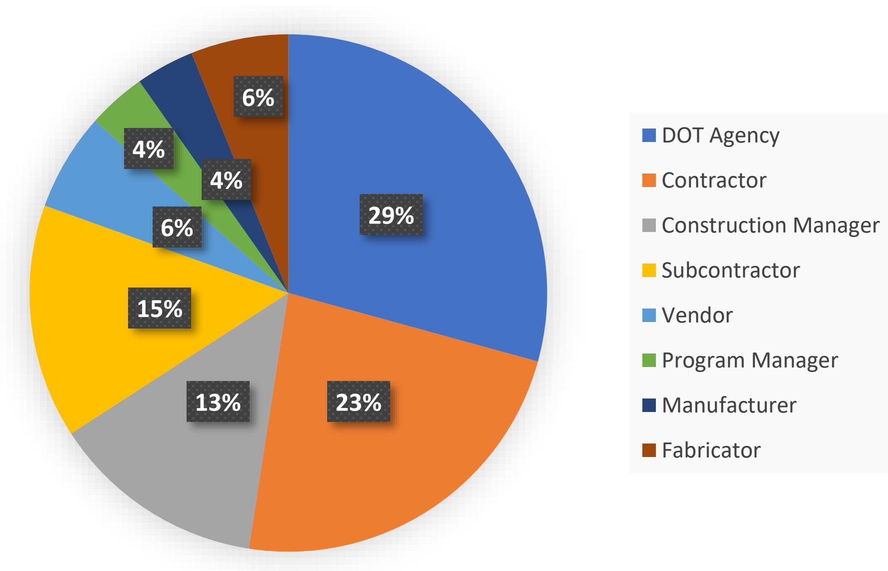

FIGURE B.20 Stakeholders using instrumentation technologies

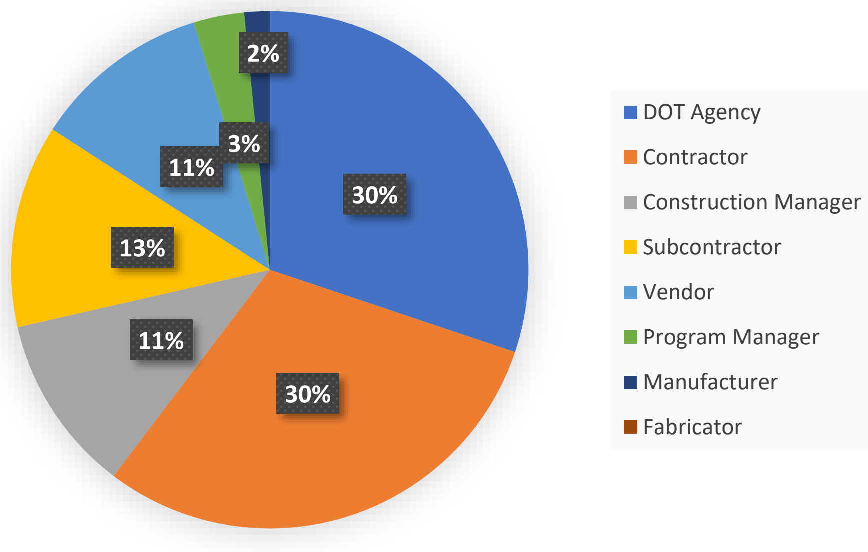

FIGURE B.21 Stakeholders using UASs

- Survey participants were asked to share the lessons learned from implementation of technologies on transportation projects; the combined responses are put together in Table B.2 for visualization and modeling technologies, Table B.3 for interconnected vehicles/equipment/tools, Table B.4 for safety technologies, Table B.5 for instrumentation technologies, and Table B.6 for UASs.

Table B.2 Lessons learned from State DOTs responses for visualization and modeling technologies

Count	Visualization and modeling technologies
1	Double check all data generated.
1	Engage the contracting industry to ensure inoperability across systems is not unnecessarily impacted

1	Be clear on specifications for the contractor requirements.
1	Need to get in-house staff the correct software to effectively utilize information being provided by the Developer.
1	It's not well understood
1	Make sure everybody is using the same software and that the contract documents clearly spell out what the agency will provide to third parties in terms of file sharing.
1	Have not used this technology so much for actual construction delivery, but more as supplemental information to illustrate complex construction sequences and staging through animation to contractors at constructability meetings, or to the public through project websites or at public hearings.
1	Start small and grow.
1	Helpful to anticipate which projects and at which phase visualization will be needed. Currently it is a specialized service and budgets/contracts need to provide the means for compensation
1	Very important to verify the existing conditions in the model are the same as what exists at the site and come to a formal agreement between contractor and NYSDOT these existing conditions before work begins.
1	Useful in some circumstances, but can be costly. Very good for public presentations, safety awareness, etc.
1	Contractors and agency staff are on board however should not be one size fits all
1	The modeling saved the department from a potential claim due to utility conflicts during construction.

1	Building the 3D model from paper plans is challenging due to hand manipulation of electronic data; versus creating the model to create the plans; QC/QA model provide broad "corrective" comments to contractor for correcting model instead of cross section by cross section to match design plans
1	Collect as much final utility information provided up front and as soon as possible before the model.
1	Consistency in naming conventions, defining correct attributes for lines / elements. And integration of data between design, construction, and maintenance disciplines. Simple Model/plan viewer is critical. Most field crew don't have experience with CAD Contractor needs to be tech savvy to be successful with visualization and modeling Standards for Modeling need to be developed. Modeling Design initially takes more time than previous methods
1	Benefit analysis is helpful in gaining buy in, proficiency with tools takes time to gain, understanding the differences between engineering models and 3D is a challenge, managing files (EDMS) is a challenge, build in GIS data early on

Table B.3 Lessons learned from State DOTs responses for interconnected vehicles/equipment/tools

Count	**Interconnected vehicle/equipment/tools**
1	Ensure vehicles and equipment are all on the same coordinate system the project was set to. Verify AMG control multiple time per day.

1	We are all learning in this space - we just need to outfit our equipment and learn as we go
1	Consultant designers don't like to turn over files due to liability issues
1	Better understanding of designers for needs of contractor end user with respect to preparation of CAD plans
1	Grades must be validated, and local monitoring performed.
1	Conflicts with existing specifications, tolerances, quality assurance.
1	Takes time to develop specs and standards and getting the right contractors to deliver is important. Most importantly, is to try to get something going. The benefits of AMG and string-less paving are great.

Table B.4 Lessons learned from State DOTs responses for safety technologies

Count	**Safety technologies**
1	Important to understand the data and technology. Benefits can be hard to measure as no two projects are identical.
1	Make sure that the safety program people within the agency talk to the construction folks and reach out to contractors before deciding on appropriate programs to spend money.
1	It can't be overstated; Messaging must be concise and informative. Desensitizing the road user through slogan messages has obvious negative results
1	Effective work zone management does make a direct difference in reducing the likelihood of secondary crashes

1	Use of proprietary systems difficult due to restrictions for sole source specifications
1	Messaging needs to be instant and well in advance. We have had crashes in the backup queues outside of construction signing.
1	Drivers have avoided driving over temporary rumbles bringing them into oncoming traffic.
1	Disincentives for non-performance is key, maintenance of the systems are critical. Must validate sign messages.
1	One size does not fit all
1	Security/remote access is important, so unauthorized modification of message boards is prevented.
1	Not one size fits all for some technology Piloting these technologies requires the DOT (or contractor) to be proactive in purchasing safety equipment Change Order is a contract mechanism to add these technologies to projects

Table B.5 Lessons learned from State DOTs responses for instrumentation technologies

Count	**Instrumentation Technologies**
1	Pay close attention to as-built conditions prior to a bridge rehab. Design engineers should field verify conditions before making assumptions.
1	Redundancy always helps in instrumentation

1	Additional data from instrumentation is very beneficial for monitoring structural loads, verifying design assumptions, and in monitoring structural health. It is also valuable for future design considerations, and research purposes.
1	Sustainable use of systems often requires support by IT
1	Training must be provided to ensure staff is utilizing the sensing equipment correctly
1	Better and less invasive technology allows for faster and more accurate measurement of various performance measures.
1	Reoccurring training on field equipment is needed
1	Good technologies that need to be calibrated to give you accurate information.
1	We haven't done a lot in this area, but remote cameras are a great way to document progress of the work New technology should not be more difficult to use than what it is replacing or have more requirements than needed; i.e., don't make its use more complicated than needed.
1	Data comes in large quantities and collection is often the easy part. Processing, storing, sharing, using is the challenge.

Table B.6 Lessons learned from State DOTs responses for unmanned aerial systems

Count	Unmanned Aerial Systems
1	Review legality of project area with regard to flying UAS
1	Understand the FAA restriction to their full extent.

1	We have a dedicated UAS team that is fairly new at this time. Be very aware of all FAA requirements.
1	Double check all data. Also, if using these for any type of official survey, a licensed surveyor need to be in responsible charge.
1	Good tool - we need to use it more often, but it's one more cost to a project
1	We need to understand and follow
1	We are currently managing a Drone Pilot program, valuable to rely upon distinct expertise in this area
1	We are just beginning our program and have primarily used the technology to assess damage to infrastructure caused by flooding. Have also used the technology to assess historical drainage features
1	Easy to perform, provides a quality record. May be used for public presentations of construction project progress.
1	UAS usage policy under development to comply with FAA rules and regulations.
1	The value of the technology is still being determined.
1	1. Importance of standards 2. Importance of understanding permitting and pilot licenses Accuracy of data for quantities for certain applications is lacking with UAV

APPENDIX C – CASE STUDY INTERVIEW QUESTIONNAIRE

The objective of this study is to examine the use of emerging technologies for highway construction projects. Specifically, the synthesis will (1) identify and document technologies currently in use to deliver construction projects; (2) determine benefits and drawbacks of using emerging technologies; (3) identify opportunities to improve construction delivery; (4) identify barriers in applying specific technologies to construction delivery; and (5) document lessons learned in the application of specific emerging technologies. This study focuses on the five specific technology areas shown in Table C.1.

TABLE C.1. Use of technologies for highway construction projects

No	Technologies	Examples
1	Visualization and modeling technologies for constructability, communication, and documentation during construction	• 3D and 4D modeling • Virtual and augmented reality • Virtual design and construction • Building and Bridge information modeling • Civil integrated management
2	Interconnected technologies for construction vehicles, equipment, and tools	• Location of vehicles • Performance and maintenance of vehicles/equipment/tools • Automated machine guidance for earthwork and paving equipment

		• e-Ticketing
3	Safety technologies used during construction	• Variable speed zones • Proximity and intrusion warning alarms • Queue detection systems • Communication systems for motorists
4	Instrumentation and sensors to measure short-term or locked-in boundary conditions or member forces for specialty projects	• Stress and strain gauges • Sensors to measure environmental conditions • Sensors to measure specifications • Ground penetrating radar
5	Uses of unmanned aircraft systems for construction monitoring, documentation, surveying, and inventory	• Construction surveys • Inspections • Site mapping • Asset management/Inventory
6	Any other promising technologies	• Remote controlled trench compactors • Intelligent compaction and thermal profiling • Portable rumble strips • Robotic rebar tying machine

Interviewee(s): ____

Time and Date: ____

Discussion Points

1. Please indicate the technologies from Table 1 that have been used for your project. Could you share some sample documents of using these technologies?

2. What were the driving forces for using these technologies? How do you decide which technologies were used for this project?

3. Does your organization provide training for employees to use the technologies for this project?

4. Please indicate and explain the primary barriers your organization had to address to implement these technologies.

5. What are the success factors of implementing technologies for this project?

6. What are lessons learned from these technologies for this project?

7. Does your organization have manuals or documents that describe the use of the technologies for this project? Could you share these documents with us?