Automation in Highway Construction Part I: Implementation Challenges at State Transportation Departments and Success Stories

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U.S. Department of Transportation
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Research, Development, and Technology
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FOREWORD

The Federal Highway Administration conducted research to document gaps for implementing automation in highway construction and to develop guidance for State transportation departments to assist them in implementing and using automation to improve project delivery. There are two volumes of the final report. Part I (this volume) presents a description of the key automation technology areas and the associated benefits, challenges, and solutions. Part II presents an overview of enabling technologies and policies for automation in highway construction as well as implementation strategies, design procedures, and practical guidelines to properly generate three-dimensional (3D) models for uses in construction and other phases of highway project delivery.

This volume provides State transportation departments a focus on five key technology areas, taking into consideration that, to be able to fully implement automation during the construction phase of a highway project, technologies are implemented prior to construction during the planning, surveying, and design phases. The key technology areas are remote sensing, underground utilities locating technologies, 3D design, machine control and automation, and field technology and inspection. This volume documents success stories and best practices for automation in highway construction; best uses for individual technologies, including the types of costs and resources required by the industry and agencies for implementing these technologies; and their associated return on investment. Finally, it documents challenges of automation technology in the areas of surveying, utilities, real-time verification, and data management.

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Director, Office of Infrastructure
Research and Development

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16. Abstract

Automation in highway construction includes a growing number of technologies that collect, store, analyze, and process information to make, support, or execute an appropriate action or decision that results in enhanced construction outcomes. The goals of automation in highway construction are to increase speed, efficiency, and/or safety during the construction process. Automation in highway construction is used in conjunction with components, processes, and software that assist in a more efficient system of construction.

The primary objectives of this project were to address gaps identified for implementing automation in highway construction and to develop guidance for State transportation departments to assist them in implementing automation to improve accelerated project delivery. There are two volumes of the final report—one for each of the two objectives.

Part I of the final report (this volume) presents a description of the key automation technologies that were part of this study and the associated benefits, challenges, and solutions.

Part II of the final report, FHWA-HRT-16-031, presents an overview of enabling technologies and policies for automation in highway construction, along with implementation strategies.[1] Part II also includes design procedures and practical guidelines to properly generate three-dimensional models for downstream use in construction and other phases of highway project delivery.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
4D	four-dimensional
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AGC	Associated General Contractors
ALDOT	Alabama Department of Transportation
AMG	automated machine guidance
ASPRS	American Society of Photogrammetry and Remote Sensing
BIM	building information modeling
CAD	computer-aided design
Caltrans	California Department of Transportation
CIM	Civil Integrated Management
CORS	continuously operating reference station
DTM	digital terrain model
EDC	Every Day Counts
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
GNSS	global navigation satellite system
GPR	ground penetrating radar
GPS	Global Positioning System
HMA	hot-mix asphalt
IC	intelligent compaction
ICST	intelligent construction systems and technologies
IMU	inertial measurement unit
Iowa DOT	Iowa Department of Transportation
IT	information technology
KDOT	Kansas Department of Transportation
KYTC	Kentucky Transportation Cabinet
LiDAR	light detection and ranging
MLS	mobile LiDAR system
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
NCHRP	National Cooperative Highway Research Program
NDT	nondestructive testing
ODOT	Oregon Department of Transportation
QA	quality assurance
QC	quality control
PCC	portland cement concrete
PDF	portable document format
PMM	Project Modeling Matrix
PS&E	plans, specifications, and estimates
PxP	project execution plan

RFID	radio frequency identification
ROI	return on investment
SHRP2	second Strategic Highway Research Program
TPF	Transportation Pooled Fund
TRB	Transportation Research Board
TxDOT	Texas Department of Transportation
UDOT	Utah Department of Transportation
VERG	Visual Engineering Resource Group
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington State Department of Transportation

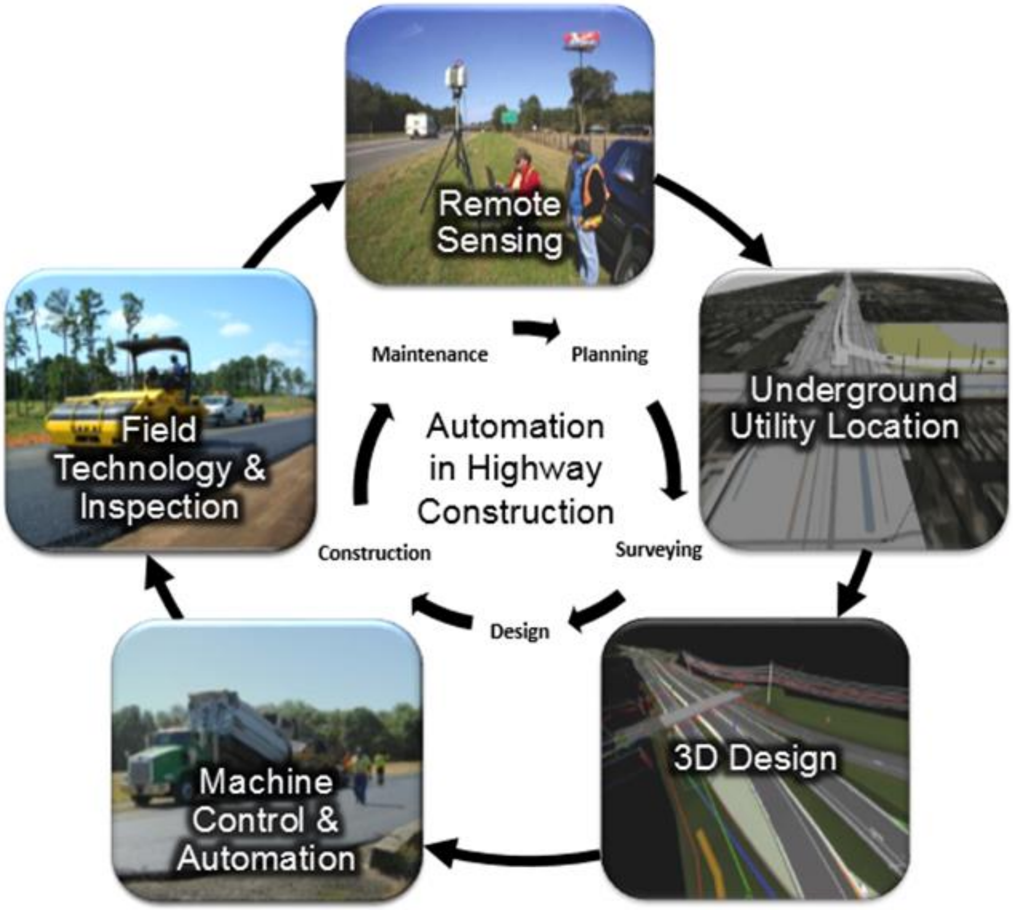
CHAPTER 1. INTRODUCTION

This report presents results of a study to address gaps identified for implementation of automation technology in highway project development through construction. In addition, it presents guidance to assist State transportation departments in determining how to implement and use automation to improve accelerated project delivery. The study involved collecting, organizing, and analyzing data from various State transportation departments.

This effort focused on five key technology areas, taking into consideration that, to fully implement automation during the construction phase of a highway project, technologies (i.e., systems, components, processes, software, etc.) would be implemented before construction during the planning, surveying, and design phases. These key technology areas included the following:

- Remote Sensing.
    - Light detection and ranging (LiDAR), three-dimensional (3D) laser scanning, etc.
- Underground Utilities Locating Technologies.
- 3D Design.
- Machine Control and Automation/Automated Machine Guidance (AMG).
- Field Technology and Inspection.
    - Intelligent Compaction (IC).
    - Nondestructive Testing (NDT) for Quality Assurance (QA)/Quality Control (QC).
        - Ground penetrating radar (GPR), infrared thermal profilers, real-time smoothness profilers, and concrete temperature and maturity meters.
    - Inspection.
        - Telematics, smartphones, tablets, etc.

As shown in figure 1, these key technologies have been used throughout all phases of highway project delivery—planning, surveying, design, and construction.



Source: FHWA.

Figure 1. Diagram. Key automation technologies throughout highway project delivery.

OBJECTIVE

The main objectives of this study were to document the following:

- Automation in highway construction success stories and best practices and uses for individual technologies.
- The types of costs and resources required by industry and agencies for implementation of these technologies and their associated return on investment (ROI).
- Automation technology challenges in the areas of surveying, utilities, real-time verification, and data management.

REPORT ORGANIZATION

In addition to this introductory chapter, this report is organized as follows:

- Chapter 2 describes how the five key automation technology areas were selected.
- Chapter 3 presents a description of each of the automation technology areas and the associated benefits, challenges, and solutions. Chapter 3 also provides an overview of State transportation departments' implementation efforts and success stories for the individual automation technologies, along with an overview of the cost and resulting time/cost savings for the different technology categories.
- Chapter 4 provides an overview of efforts to define and promote 3D and digital data management.
- Chapter 5 provides an overview of the automation technology implementation plans developed by two lead State transportation departments. Lead departments were those that have been pioneers in the use of these technologies.
- Chapter 6 summarizes the conclusions and recommendations for continuing development and implementation of automation technology for highway construction.
- The appendix presents a case study developed with assistance from the Wisconsin Department of Transportation (WisDOT) to illustrate the use of automation technology throughout the different phases of the Zoo Interchange project in Milwaukee.

Part II of the report for this effort is a separate document that presents an overview of enabling technologies and policies for automation, along with implementation strategies for State transportation departments. Part II then presents design procedures and guidelines to properly generate 3D models for downstream use in construction and other phases of highway project delivery.(1)

CHAPTER 2. KEY AUTOMATION TECHNOLOGIES

This effort began with the review and screening of the technologies described in the first generation of the Federal Highway Administration (FHWA) Intelligent Construction Systems and Technologies (ICST) Strategic Roadmap (Roadmap), taking into consideration the recommendations from the Transportation Research Board (TRB) Committee for ICST program review.[2,3] The TRB ICST committee's recommendations included the following new definition of ICST:[3]

> Intelligent Construction Systems and Technologies have the ability to collect, store, analyze, and process information and to make and execute an action or decision that results in quality construction. This is in conjunction with components, processes, and software that assist in a more effective system of construction. (p. 1)

The Roadmap listed technologies recommended during a 1.5-day FHWA ICST stakeholder workshop in 2011 that were not necessarily "intelligent" but accelerated construction, improved quality, reduced cost, or improved safety. Table 1 illustrates how the list of technologies was revised to focus on technologies meeting the definition for ICST along with 3D, advanced, and geospatial technologies that were currently being investigated and/or implemented by State transportation departments to support and enhance the use of automation in highway construction.

Table 1. Original and revised technologies lists.

ICST Roadmap List	Revised List of Automation Technologies

Telematics (Connected Site®, SiteLINK™, iCON™, etc.)
Concrete Temperature and Maturity Meters
Modern Barrier Systems for Construction Traffic Control
Traffic Management Modeling Software
Digital Signatures
AMG
Low Distortion (Planar) Coordinate Systems
Remote Sensing (aerial photography, satellite imagery, LiDAR, and ground-based stationary or mobile 3D laser scanning, etc.)
IC (Soils and HMA)
Stiffness Measuring Devices
Advances in Paving Technologies
NDT Devices for QA
Recycled Pavement Materials
Accelerated Bridge Construction (ABC) Techniques
Advanced Heavy Lift Construction Equipment
3D/4D Engineered Models
Earth Centered/Earth Fixed (Spherical) Coordinate Systems
Transportation Information Modeling (Term was used at the ICST workshop. FHWA is now using CIM.)
Accurate Identification of Subsurface Utilities
Advanced Warning and Speed Control Devices
Automatic Work Zone Condition Updates
	Remote Sensing
	• LiDAR, 3D laser scanning, etc.
	Underground Utilities Location
	3D Design
	Machine Control and Automation
	• AMG.
	Field Technology and Inspection
	• IC.
	• NDT for QA/QC.
	  ○ GPR, infrared thermal profilers, real-time smoothness profilers, concrete temperature and maturity meters.
	• Inspection.
	  ○ Telematics, smartphones, tablets.

Note: Boldface indicates technologies also included on the revised roadmap list.
HMA = hot-mix asphalt; 4D = four-dimensional; CIM = Civil Integrated Management.

Some of the automation technologies listed in table 1, such as machine control and automation, were developed in the 1980s. Skibniewski and Hendrickson reported on the significant potential and feasibility of automation and robotics for road construction and maintenance if substantial investment and research were to be carried out in the 1990s.(4) Note that they discussed benefits similar to the ones observed with present-day automation in highway construction—cost savings, improved productivity, quality, and safety.(4)

In addition, the concept of automation in highway construction throughout project development (i.e., planning, surveying, design, construction, and maintenance) has been under investigation and development for more than a decade by highway agencies worldwide. Heikkilä and Jaakkola defined “the total information process of 3-D road construction” with the diagram in figure 2, which contains four of the five key automation technologies included in this study.[5] Figure 2 shows that the process begins with 3D measurements of the existing conditions during surveying (LiDAR/3D laser scanning), followed by 3D design, machine control and guidance during construction, and 3D measurements for QC.

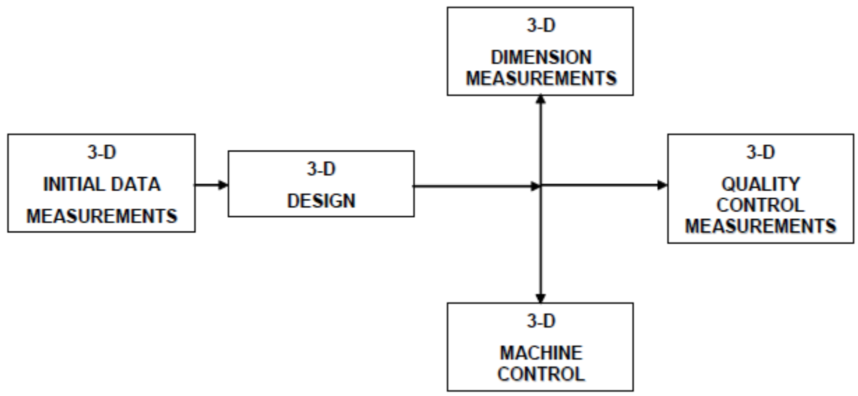


Figure 2. Diagram. The total information process of 3D road construction—one description level.[5]

CHAPTER 3. AUTOMATION TECHNOLOGY IMPLEMENTATION AT STATE TRANSPORTATION DEPARTMENTS

For this effort, the research team conducted a detailed literature review to identify the benefits, challenges, solutions, and available standards/specifications for each of the key automation technologies. The findings are discussed in the following subsections. Next, in an effort to document the success stories from lead State transportation departments with respect to the different automation technologies, the team conducted a site visit to WisDOT, followed by a series of conference calls and correspondence with staff of the Iowa Department of Transportation (Iowa DOT), Missouri Department of Transportation (MoDOT), and Oregon Department of Transportation (ODOT). Staff of the Alabama Department of Transportation (ALDOT) and Georgia Department of Transportation (GDOT) explained that they were in the beginning stages of automation and 3D technologies implementation; nevertheless, they also shared information on their implementation efforts. Feedback from all of these agencies is presented in subsequent subsections covering each automation technology. The appendix presents a case study that illustrates how WisDOT has been using automation technology throughout the different phases of a major interchange reconstruction project.

Note that all of the lead State transportation departments interviewed had established a network of Global Positioning System (GPS)/global navigation satellite system (GNSS) continuously operating reference stations (CORSs), which have facilitated the implementation and use of automation in highway construction. These efforts, many in cooperation with other agencies such as the National Geodetic Survey, have supported the implementation and use of automation technology, from surveying to mapping utilities to construction. Projects located in areas covered by a CORS network have not required surveyors and contractors to set up a base station, which has facilitated project control development and resulted in time and cost savings. Additional opportunities for time and cost savings are presented in this report if the contractor equipment has been able to connect to the CORS networks for AMG and inspection purposes.

The following subsections describe each of the five key highway construction automation technologies and their associated benefits, challenges, and solutions. An overview of State transportation departments' implementation efforts and success stories is also presented. At the end of each subsection, available cost and resulting time/cost savings information is presented for each technology. Note that cost and ROI information was scattered, and many of the case studies available had been conducted at a project level and thus did not represent agencywide figures.

REMOTE SENSING (LiDAR AND 3D LASER SCANNING)

In this report, the term "remote sensing" is used to describe 3D remote data acquisition using technologies such as LiDAR and other 3D imaging devices. Other remote sensing technologies include GPR, road profilers/scanners, and other sensors (i.e., sign reflectivity). The accuracy and precision have varied among these different technologies. For example, 3D laser scanners could measure millions of data points per second and generate a very detailed point cloud dataset. Remote sensing manufacturers and solution providers included FARO®, Leica Geosystems®, RIEGL®, Trimble®, Topcon®, and Zoller + Fröhlich®.

Benefits of this technology have begun with survey data collection time and cost savings, followed by increased productivity (e.g., less rework) throughout the entire project delivery process. There has been improved quality with the increased level of detail, accuracy, and scalability. For example, when high-definition surveys were provided to contractors during the pre-bid stages, the increased accuracy and detail reduced uncertainty and allowed those contractors to submit more competitive bids. More accurate earthwork volume calculations were also possible.

Another benefit of using remote sensing has been improved safety, because the noncontact technologies minimized or eliminated the time field crews were exposed to traffic and other dangerous conditions. Also, noncontact technologies minimized or eliminated impacts on environmentally sensitive areas. Finally, the use of remote sensing technology during survey phases has provided a building block for information modeling in design and as-built construction documentation.

Based on a 2012 survey, Cawley et al. stated that more than half of the State transportation departments were using some type of LiDAR technology.(6) LiDAR technology has included three different forms: airborne, terrestrial mobile, and terrestrial static. Airborne LiDAR has used airplanes or drones equipped with laser scanners, GPS devices, and inertial measurement units (IMUs) to enable accurate and detailed capturing of the 3D geometry of ground surfaces and objects via aerial surveys. The level of detail was able to be enhanced using a smaller beam width, multiple pulses in the air, and full waveform digitization.

Terrestrial mobile LiDAR systems (MLSs), also referred to as mobile laser scanning systems, continue to be widely investigated and implemented at State transportation departments. For transportation applications, mobile systems have offered increased accuracy when compared with airborne systems and increased efficiency when compared with static systems. Therefore, there has been strong interest in MLSs. Figure 3 shows an example of an MLS. Typical components included a vehicle, multiple 3D/LiDAR scanners, positioning hardware (GPS/GNSS receiver, IMU, distance measurement indicator), cameras (photo/video), a data acquisition system, and an in-vehicle computer monitor.

Source: FHWA.

Figure 3. Photo. An example of a terrestrial MLS.

Some transportation applications have required a static scanning system for high-definition surveys. Figure 4 and figure 5 show an example of a terrestrial static LiDAR system. The scanner was mounted on a tripod, and data could be acquired from the side of the road. Multiple positions were usually required to fill in occlusions. Georeferencing of the scan data was accomplished using reflective targets set up over control points or through a GPS/GNSS device mounted on top of the scanner. A camera was also mounted or integrated into the system to obtain calibrated images with red, green, and blue colors, corresponding to each scan position.

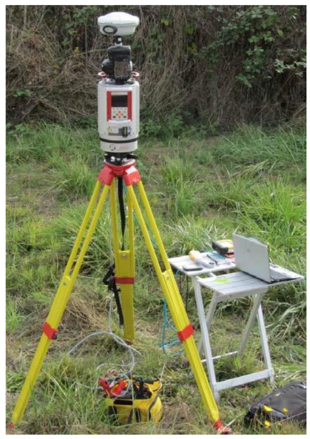


Figure 4. Photo. A terrestrial static LiDAR system.[7]

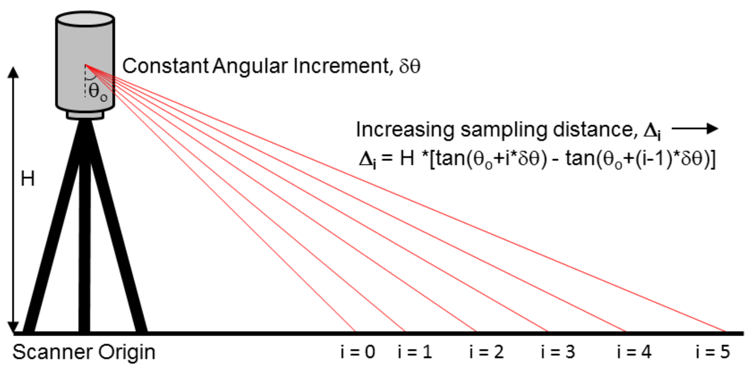


Figure 5. Diagram. A terrestrial static LiDAR system.[7]

Key products of laser scanning systems have included a georeferenced point cloud and the associated high-resolution imagery, which were used to produce computer-aided design (CAD) models and digital terrain models (DTMs). A screenshot of a laser scan point cloud from a terrestrial mobile laser scanning system is presented in figure 6.

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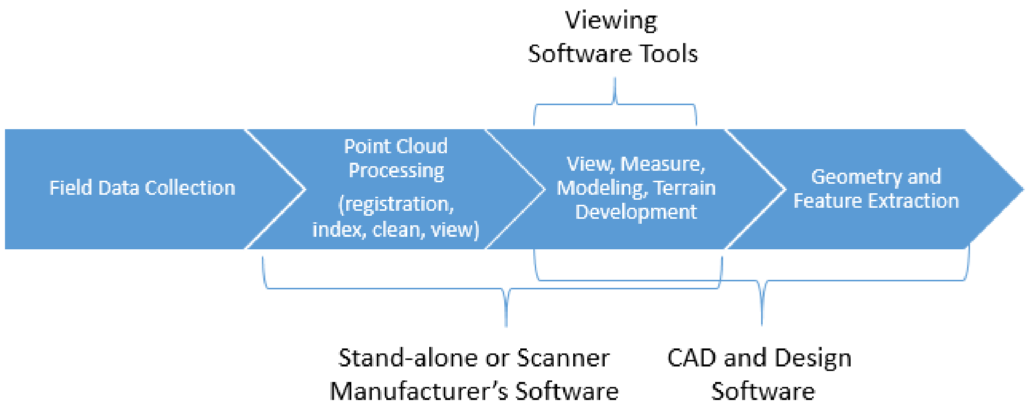
Figure 6. Screenshot. View of point cloud from terrestrial mobile laser scanning system.[8]

Note that point cloud processing has required the use of multiple software packages, knowledgeable technical staff, and increased processing time to integrate LiDAR data into transportation workflows. Figure 7 shows a brief overview of the point cloud processing activities. Figure 7 illustrates that point cloud processing has not been a dynamically linked process but rather one that involves importing/exporting files between the different software tools that are available.



© 2014 Gant.

Figure 7. Flowchart. Point cloud processing pipeline (after Gant).[9]

In general, airborne LiDAR surveys have been used for preliminary engineering of highway projects; mobile laser scanning has been used for shoulder-to-shoulder corridor mapping; and static laser scanning has been used for surveying highway structures, such as bridges and tunnels. The products of laser scanning systems have been most relevant to the following automation in highway construction applications:

- Engineering Surveys, CAD models, and DTMs used for 3D design, machine control, and automation.
- Clash detection (i.e., clearance data for overpasses, bridges, signs, power lines).
- Periodic scans for estimates of percent completion, quantities, inspection/QC, and as-builts at project completion.

Implementation Efforts at State Transportation Departments

As they have done with any other emerging and innovative technology, State transportation departments have been conducting research, demonstrations, and/or pilot projects to compare MLS technology with traditional surveying. For example, Iowa DOT conducted a comparison of MLS with traditional surveying using a total station for an interchange project.(10) This project allowed Iowa DOT to become familiar with MLS issues such as accuracy, specifications, data content itself, and data storage. Iowa DOT was able to confirm the reported benefits for this technology over traditional surveying, such as increased accuracy, safety, and efficiency. In addition, Miller et al. identified the steps/challenges that needed to be overcome next, such as developing specifications and software improvements to fully use the technology.(10)

Additional recent studies by State transportation departments to understand better transportation applications of LiDAR technology included work by the North Carolina Department of Transportation and WisDOT.(11,12)

At a national level, Olsen et al. developed guidelines for the use of MLSs in transportation applications.(13) These guidelines (presented in National Cooperative Highway Research Program (NCHRP) Report 748) encompass applications from project planning, design, and construction to operations and maintenance and address data collection methods, formatting and management, storage requirements, QA, translation and formatting of derived products, etc.(13) Olsen et al. established data collection categories based on the transportation applications and the required accuracy and point cloud density.(13) Based on NCHRP Report 748, Williams et al. have summarized the existing LiDAR guidelines (figure 8), including work by the California Department of Transportation (Caltrans), Texas Department of Transportation (TxDOT), MoDOT, and the American Society of Photogrammetry and Remote Sensing (ASPRS).(13,14) Note that the Florida Department of Transportation developed MLS guidelines based on NCHRP Report 748 and Caltrans guidelines.(13,15)

Existing Guidelines	
General Geospatial	**Key Points**
Federal Geographic Data Committee (FGDC) 1996 National Standard for Spatial Data Accuracy (NSSDA)	95% confidence evaluation, 20 control points, methodology on how to compute accuracy statistics
National Digital Elevation Plan (NDEP) 2004	DTM certification, reporting of accuracy across many different remote sensing platforms. Discusses Fundamental, Supplemental, and Consolidated Vertical Accuracies (FVA, SVA, CVA)
Mobile LiDAR (Current)	
CALTRANS Chapt. 15 Survey Manual 2011 Florida DOT 2012	TLS and MLS specifications, various classes of data (Type A-high accuracy, Type B-lower accuracy), requirements for: mission planning, control placement, system calibration, overlap requirements, QA/QC
NCHRP Report 748 (Olsen et al. 2013)	Guidelines for the use of mobile LIDAR for use in transportation applications. Focuses on accuracy (network and local) at 95% confidence levels as well as point density through the use of Data Collection Categories. The primary audiences of the document are management and staff who will be developing statements of work for MLS use in transportation.
Mobile LiDAR (Development)	
TxDOT	In development
ASPRS Mobile Mapping Committee	At outline stage
MoDOT 2010	Evaluation of MLS usage for DOT activities
Airborne LiDAR	
FAA 2011	Includes LIDAR (airborne, static, and Mobile) standards and recommended practices for airport surveys. System calibrations, data processing.
NOAA 2009	Use of LIDAR for shoreline and flood mapping.
USGS (2012)	V1.0. Base Specification. Post spacing, overlap requirements, classification, metadata example, DEM., vertical accuracy assessment, glossary of terms.
ASPRS Vertical	Applying FGDC and NDEP guidelines to airborne LIDAR. Land cover types. Selection of checkpoints.
ASPRS Horizontal	Considerations (and difficulty) of horizontal accuracy verification.
ASPRS Geospatial Procurement Guidelines	Draft phase. Distinguishes between professional\ technical services and commercial geospatial products.
FEMA Guidelines	LIDAR use in floodplain mapping.

Figure 8. Table. Summary of existing LiDAR guidelines.[14]

A summary of the implementation challenges and reported solutions for remote sensing technology, particularly MLSs, is presented in table 2. Key references included NCHRP Report 748, NCHRP Synthesis 446, and the WisDOT 3D Technologies Implementation Plan. (See references 13 and 16–18.)

Table 2. Summary of identified LiDAR technology challenges and solutions.

Challenge	Solutions
Cost	Olsen et al. stated the following:(16) • Agencies had acquired and shared resources between them. For example, the Oregon LiDAR consortium coordinated LiDAR acquisition among several State and Federal agencies, pooling resources to reduce acquisition costs. • This solution was more applicable to network-level applications and less applicable to the project level and automation in highway construction. Singh stated the following:[1] • The Oregon LiDAR consortium consisted of high-altitude, airborne LiDAR for coverage of wide areas. Standards were a lot tighter than those typically used for the rest of the country. Oregon was working to make standards even more stringent and the data more usable for highway engineering.
Lack of standards, metadata. Data sharing with existing CAD and GISs maximizes the investment, but interoperability and integration can be challenging.	Olsen et al. stated the following:(13) • ASPRS had developed the LAS format (current version 1.4), which was the most commonly used format for airborne laser scanning. This format had been integrated into several software packages. • The ASTM E57 subcommittee developed an additional format, E57 for 3D imaging systems. This format had additional benefits, including advanced, integrated image support and internal data structure support. Integration for the E57 format in software was limited; however, support was growing rapidly.(19)

Data management.
Managing and storing the extremely large datasets that result from laser scanning can be a challenge. In addition, a centralized data model to support data sharing is encouraged.
	• The ASTM E57.04 subcommittee has been working to address interoperability and data transfer issues.
	• WisDOT created regional Survey Data Coordinator positions to facilitate data flow between design and construction and to provide assistance with development and implementation of standards and procedures for data collection. As of January 2013, reported challenges were the following:
	  o Large volumes of data must often be transferred by shipping hard drives.
	  o For megaprojects (i.e., Southeast Freeways Program), consultants have been managing LiDAR data.
	  o Information technology (IT) upgrades (i.e., network bandwidth, storage, backup, and archival) are required.
	  o Significant office work is required.
	• Iowa DOT had dedicated IT staff in its design section to support 3D design efforts, including the following:
	  o They were storing raw LiDAR data in a different location, and LiDAR products for each project (i.e., topography and DTM surface) were stored with the project files (i.e., ProjectWise).
	• Consultants were using services such as Amazon Web Services™ and TopoCloud™ to handle large volumes of point cloud 3D data. There has been a trend toward use of Web-based point cloud viewing/rendering, modeling, facilities management, and app hosting. Challenges included the following:

[1]Singh, R. Personal interview (via conference call). April 11, 2014.

Challenge	Solutions
	○ Security, downtime, login issues, expertise, and Internet speed/network bandwidth.
Immature software and lack of automated processing. Processing often requires use of multiple software packages. It should be noted that knowledgeable technical staff, increased processing time, and new software may all be required to integrate LiDAR data into transportation workflows.	• WisDOT, as of January 2013, was taking the following step: ○ The central office was deciding on an appropriate software platform for raw data reduction and feature extraction and training.
Specialized training. The full range potential of LiDAR applications across State transportation departments is not fully understood and documented.	• TRB LiDAR Webinars (NCHRP Project 15-44) were developed.(20) • *LiDAR News* e-Magazine is published.(21) • SPAR 3D Webinars and Blogs provide information.(22) • Rönnäng presented a good example of how the 3D laser scanning technology was implemented by Volvo in the manufacturing industry.(23) Volvo worked with technology vendors and consultants to develop their scanning procedures and workflows before beginning in-house scanning.
Lack of guidelines, specifications. Accuracy, resolution, point cloud density, QC/QA, deliverables.	• ASPRS Mobile Mapping Committee has been developing guidelines. • For WisDOT, in 2012, mobile LiDAR data were collected by consultants, and a specification was developed based on U.S. Geological Survey, Caltrans, and other States. An integrated surveys specification for LiDAR was combined with photogrammetric and ground surveys. • NCHRP Project 15-44, Report 748 provides guidelines.(13) • Pilot projects have been useful to develop draft guidelines/specifications.
Data collection issues. Neighboring vehicles can block data collection (MLS).	• Rolling lane closure can be used to prevent vehicles from blocking the system.
Equipment availability.	• Information from LiDAR vendors/service providers can be used.

LAS = LASer; GIS = geographic information system.

Success Stories

This study found that several State transportation departments owned terrestrial static systems, and a few others, such as Caltrans and ODOT, owned mobile systems. A brief summary of recent implementation efforts by ODOT,[2] Utah Department of Transportation (UDOT), and ALDOT is provided in the following subsections.(24,25)

ODOT

This study found that ODOT owned stationary scanning systems that were used for scanning all the tunnels and bridges in its network (figure 9). ODOT also owned a mobile scanning system that was initially purchased for asset management, but ODOT was working with the manufacturer to develop procedures and algorithms to improve point cloud density/accuracy and potentially use it for engineering applications in the future. ODOT has also participated in the Oregon LiDAR Consortium, which has conducted high-altitude, airborne LiDAR for coverage of

[2]Ibid.

wide areas. Oregon was working to make standards more stringent and the data more usable for highway engineering. Combining all these resources—aerial, mobile, and stationary—has provided ODOT with a lot of useful information on LiDAR and 3D data. ODOT was also working to make that data accessible online.

Figure 9. Photo. Static laser scanning of bridge structure at ODOT.[26]

UDOT Case Study: Using Asset Management Mapping Grade LiDAR for Design[24]

UDOT hired consultants to evaluate the accuracy and effectiveness of using existing asset management, mapping-grade LiDAR data for design surveys. The pilot project was conducted for a section of I-80 (figure 10). For a period of 6 months, the consultants worked on the following tasks: point-cloud calibration, point-cloud accuracy verification, supplemental and design surveys, documentation, and analysis. Searle and Sridharan reported that accuracies of ±1.2 inches (3 cm) were achieved, which were similar to traditional surveying methods and sufficient for design surveys.[24] Supplemental surveying was needed for vegetated slopes, occlusions, etc. Savings by using existing mapping-grade data for design were reported to be 24 percent for cost and 22 percent for time, as well as increased safety.

Figure 10. Photo. View of I-80 test section.[24]

ALDOT: Evaluating Mobile Scanning Data for Use Within a State Transportation Department[25]

The Survey Office at ALDOT investigated the use of mobile scanning to obtain pavement elevations at an accuracy suitable for resurfacing projects involving cross-slope correction, checking of guard rail heights, clear zones, etc. Typically, those projects would require extensive surveys, adding time to the project schedules. ALDOT decided to evaluate mobile laser scanning and investigate the following potential benefits for this application, as presented by Russell:[25]

- Increased safety for the field crews and traveling public because there would be no traffic congestion due to lane closures.
- Time savings, in that survey delivery time for an average project (10 mi (16.1 km)) was estimated to be 6 weeks or less.
- Increased level of detail, accuracy, and scalability, which translated into efficiency and improved quantity estimates because scanning would provide more information on rutting and pavement condition and additional information on guard rails, bridges, overhead utilities, signs, etc.

For this evaluation, ALDOT conducted a pilot project to determine whether the mobile scanning contractors in the State/region were capable of performing this type of work. ALDOT worked with the four vendors in the State willing to participate at their own expense and scan a section of the future I-22 (also known as Corridor X; figure 11) recently surveyed by ALDOT with conventional methods (e.g., total stations at 50-ft (15.2-m) intervals) and with solid control points in place.

Figure 11. Photo. View of pilot section along I-22, Corridor X.[25]

Russell reported that the point-cloud data delivered massive data files, which could be difficult to manage even with new software tools.[25] As for the data quality and comparison with the conventional survey, ALDOT found that 90 percent of the scan data tested within 0.05 ft (1.52 cm), 70 percent tested within 0.03 ft (0.91 cm) (absolute accuracy), and 75 to 85 percent had a relative accuracy of ±0.03 ft (0.91 cm) across the travel lane. ALDOT deemed the scanned data to be suitable for designing resurfacing projects.

Technology Costs and Resulting Savings

The benefits associated with the remote sensing technology were previously described, including improved safety, time and cost savings, increased productivity, and improved quality with the increased level of detail, accuracy, and scalability. However, benefit–cost and ROI information was scattered, and many of the case studies available had been conducted at a project level and thus did not represent agencywide figures. The following bullets present the information gathered throughout this project:

- As of December 2014, remote sensing technology cost ranged from $50,000 to $120,000 for a static scanning system and from $250,000 to $1,000,000 for mobile scanning systems.

- For the UDOT case study, Searle and Sridharan reported savings of 24 percent for cost and 22 percent for time, as well as increased safety, by using existing mapping-grade data rather than traditional surveying for a design project.[21]

- Detailed studies were needed to assess benefit–cost and ROI. For example, when high-definition survey data were released to bidders/contractors at advertising, cost savings might not be reflected in lower bids but rather in more consistent bids, because contractors would spend less time surveying and more time estimating. It was difficult to quantify this impact, but it would mean less risk for bidders. The use of high-definition surveys with 3D laser scanning technology has helped reduce construction contingencies.

- Hurwitz et al. conducted a survey to assess the state of the practice regarding MLSs at State transportation departments.(27) With responses from each of the 50 State transportation departments, 6 additional transportation agencies, and 14 MLS services providers, they found that cost was one of the most significant challenges for adoption of this technology, and more evidence and education was needed regarding benefit–cost comparisons.

- Yen et al. presented a benefit–cost analysis for the use of mobile scanning for the following highway applications: roadside feature inventory, bridge clearance measurement, and Americans With Disabilities Act feature inventory.(28) They explained that these programs were well defined in most State transportation departments, and the corresponding data regarding historical and current expenditures were available to conduct such benefit–cost analysis.(28)

  Note that most laser scanning applications for automation in highway construction, such as engineering-grade surveys, machine control and automation, and construction inspection, were continuing to be under evaluation and implementation at State transportation departments, and there were not enough data for a comprehensive benefit–cost analysis as conducted by Yen et al.(28)

UNDERGROUND UTILITIES LOCATION

Accurate identification of subsurface utilities has involved a combination of 3D modeling software and underground location technology such as geophysical techniques. More accurate information regarding existing utilities has been needed, especially for urban environments, to identify conflicts during design and avoid guesswork and digging during construction. In addition, this information would assist in completion of as-built utility plans for use in future projects and maintenance. Figure 12 is an example of a 3D underground utility map.

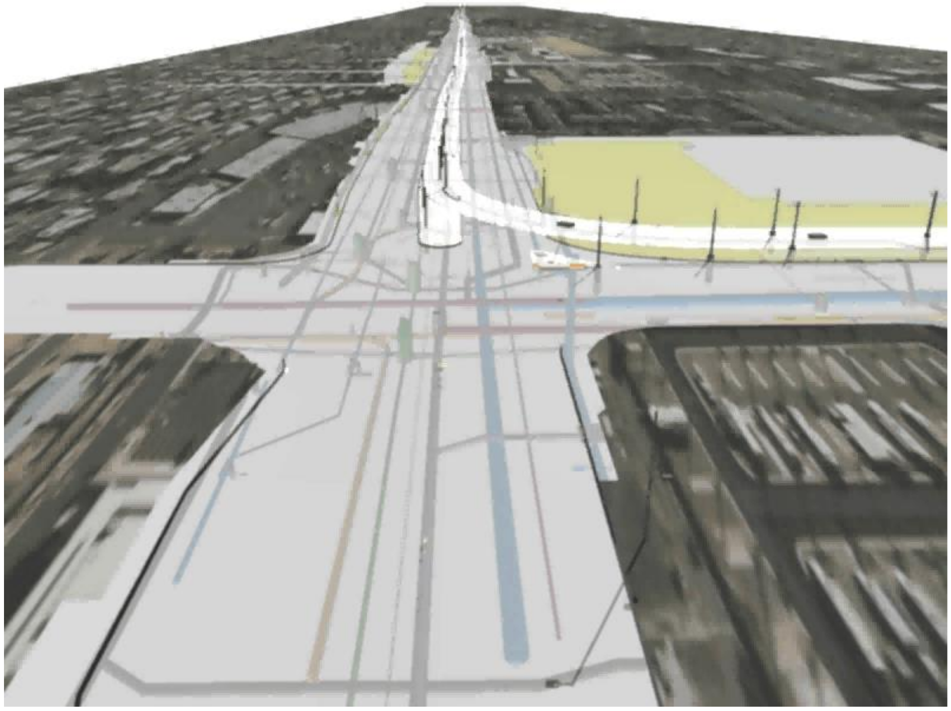


Figure 12. Screenshot. 3D underground utility map.[(29)]

According to the second Strategic Highway Research Program (SHRP2), "Current technologies and tools can only find 80–90% of existing utilities. Finding the other 10–20% and successfully managing utility conflicts require new tools." (p. 1)[(30)] Utility conflicts identified during design and construction phases of highway projects have resulted in significant cost, delays, change orders, claims, and damages. Therefore, several SHRP2 projects were dedicated to developing new tools to help locate and characterize underground utilities as well as new tools to identify utility conflicts and solutions.

The following bullets list the three SHRP2 efforts and corresponding products most relevant to automation in highway construction and 3D technologies. It was understood that further development was required to make the prototype technologies viable.

- R01A *Technologies to Support Storage, Retrieval, and Utilization of 3-D Utility Location Data*: This effort has been to develop a state-of-the-art model and guide for using and managing 3D utility data. The system would leverage geographic information systems, GPS/GNSS devices, and other technologies to acquire, store, visualize, and integrate 3D positional and structural information.[(31)]

- R01B *Utility Locating Technology Development Utilizing Multi-Sensor Platforms*: Two functional prototypes were developed—a multichannel GPR system to locate utilities in one pass and a new multisensor platform that combines electromagnetic induction and 3D GPR to produce utility location data.[(32)]

- R01C *Innovation in Location of Deep Utility Pipes and Tunnels*: Two technologies were developed to expand the zone in which underground utilities could be located and identified. Prototype long-range radio frequency identification (RFID) and low-frequency acoustic location technologies were developed and tested.(33)

There was also ongoing FHWA research entitled "Feasibility of Mapping and Marking Utilities" to document the barriers for State transportation departments managing utility installations within the right-of-way.(34) Table 3 summarizes the challenges and solutions based on the SHRP2 projects on utilities and the referenced FHWA study.

Table 3. Summary of identified challenges and solutions for underground utilities location.

Challenge	Solutions
Unknown or mistakenly recorded utilities.	R01A: This effort produced a state-of-the-art model and guide for using and managing 3D utility data.(31) Possible solution: requirement for placement of tracers in utility permits. Need specifications for placement, QA/QC, coordination, inspection, recordkeeping, etc.
Locating underground utilities across a variety of soil conditions.	R01B: Two functional prototypes were developed: a multichannel GPR system to locate utilities in one pass and a new multisensor platform that combines electromagnetic induction and 3D GPR to produce utility location data.(32)
Locating deep underground utilities.	R01C: Two technologies were developed and tested to expand the zone in which underground utilities can be located and identified: prototype long-range RFID and low-frequency acoustic location technologies.(33)
Utility characterization. Technology has been ineffective in finding targets beneath clutter of other utilities and buried objects or significant depths in incompatible soil conditions, as has been the case with electromagnetic locating equipment and conductive soils.	Utility marking and RFID systems could help with utilities location.
Lack of ROI information and data management (storage issues).	FHWA research has been ongoing for "Feasibility of Mapping and Marking Utilities."

Implementation Efforts at State Transportation Departments

The State transportation departments that were interviewed for this effort indicated that the implementation of underground utilities-location technology has been limited. Owing to existing workflows and policies, transportation departments have had to use the inaccurate, low-quality information that utility companies were providing them. In addition, for highway projects, the liability for utility conflicts and relocation has been placed on the contractor.

The State transportation departments' survey by Quiroga et al. found similar trends, with only a few agencies using 3D technologies for utility installations.[34] Quiroga et al. discussed in detail these and other challenges for transportation agency management of utilities in the right-of-way and in trying to transition 3D utilities data.[34] Figure 13 shows a comparison between two-dimensional (2D) traditional utility plans and the desired 3D model, including the tunnel and other underground infrastructure.

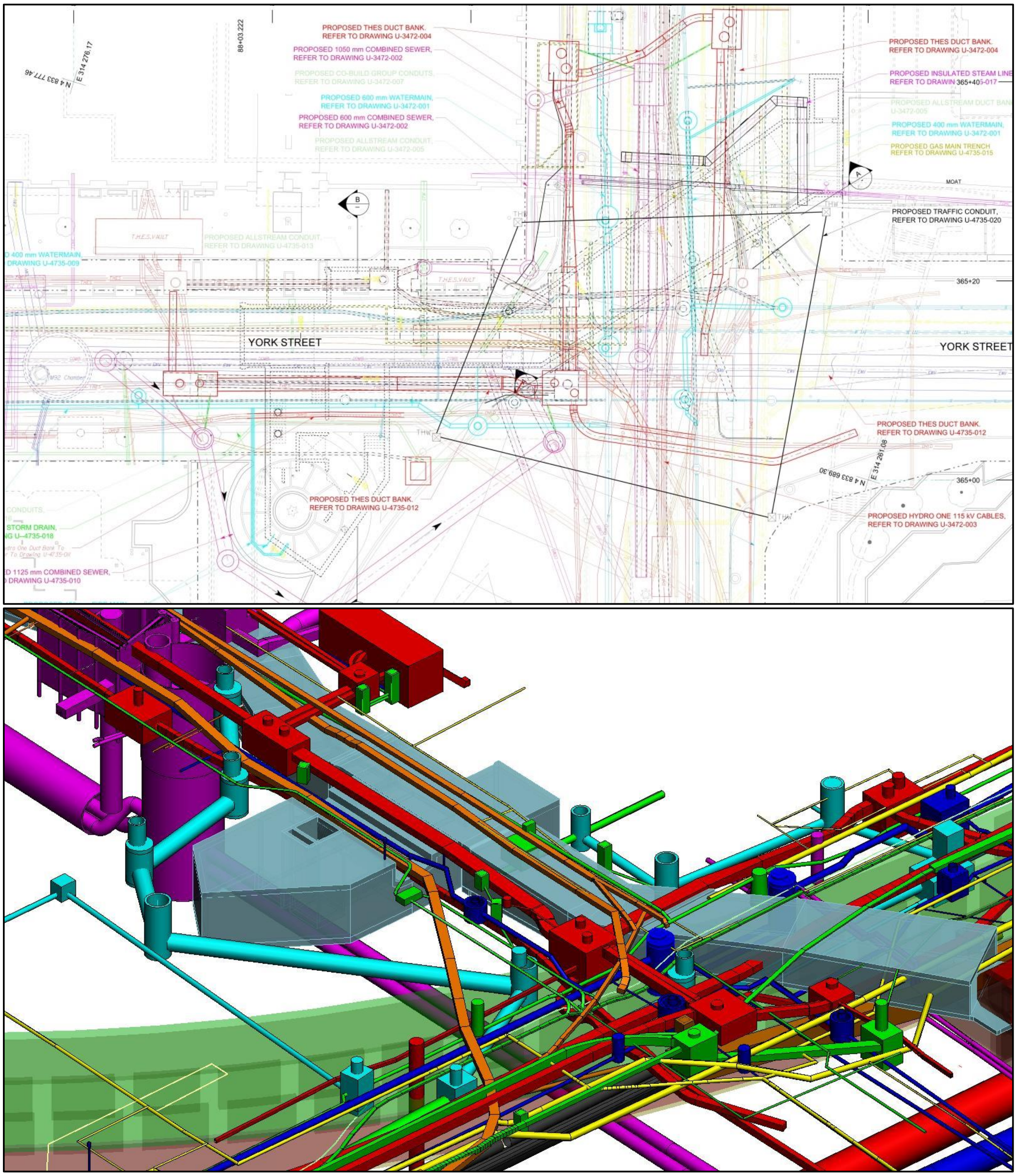


Figure 13. Screenshot. Comparison between 2D plan view (top) and 3D model (bottom) for Northwest PATH Pedestrian Tunnel, Toronto, Canada.

3D DESIGN

3D design is a key process for implementing automation in highway construction. Singh explained that the implementation of CAD software, such as MicroStation® and AutoCAD®, and InRoads® and GEOPAK® (for road design) had transitioned agencies to use of “pseudo” 3D surveys and design because the state of the practice was not producing truly 3D and complete roadway models.[(35)] For example, all major components would need to be 3D (i.e., bridges and other structures), and base maps would need to depict elements below, on, and above the ground surface (i.e., utilities) within the project limits.[(35)] WisDOT also referred to this issue, making a distinction between the “3D surface model” (mainly for AMG and controls) and the “roadway model” (documents elements from design to construction).[(18)]

Lead agencies have been working toward this concept of complete roadway models, also referred to as “3D engineered models,” in most cases for major/megaprojects and supported by consultant services. Gilson described how large transportation projects involved multiple design and construction teams, and the 3D modeling was critical for stakeholder communication and coordination.[(36)] These 3D engineered models have been a collection of elements that comprise all aspects of design and have been considered 4D models when schedule information was incorporated and five-dimensional models when cost information was added.

Benefits of 3D models from design have been creation of more accurate construction documents and 3D as-built plans, visualization for engineering analysis and communication with the public, detection of issues before construction, conflict resolution applications (i.e., utilities), AMG, and quantities calculations. There has been a significant ongoing initiative by FHWA to assist State transportation departments transitioning from 2D to 3D design—FHWA Every Day Counts (EDC): 3D Engineered Models for Construction—which has involved a series of webinars, training, technical publications, a website, and a technical services support center.

Note that State transportation departments have also been investigating 3D modeling of structures, and the benefits would be similar to those previously listed for 3D roadway modeling. Because bridges and other structures have been designed using different software tools, there would be possible interoperability issues that would need to be addressed when trying to integrate with the complete roadway model. There has been ongoing industry collaboration to address 3D modeling of structures, including the FHWA EDC2: 2014 3D Modeling for Structures Workshop hosted by the Pennsylvania Department of Transportation.[(37)]

Implementation Efforts at State Transportation Departments

Many State transportation departments explained how the transition from 2D to 3D design has been driven by contractors using AMG and by having to reengineer 3D models from 2D plans. (See references 17, 18, 35, and 38–40.) Contractors have also used 3D models for bid preparation (i.e., more accurate earthwork quantities), clash detection, field inspection, etc. Soon after beginning to consider 3D design to support construction, agencies recognized there were many other benefits of using 3D modeling throughout all phases of a highway project, including planning, design, maintenance, and operations.

Figure 14, a modified version based on Arena, illustrates the then current and desired workflows from design to construction at State transportation departments.(41) The desired workflow would remove the ambiguity from 2D paper plans, the significant time and expense to produce them for the owner, and the time and expense to interpret and translate them for contractors.

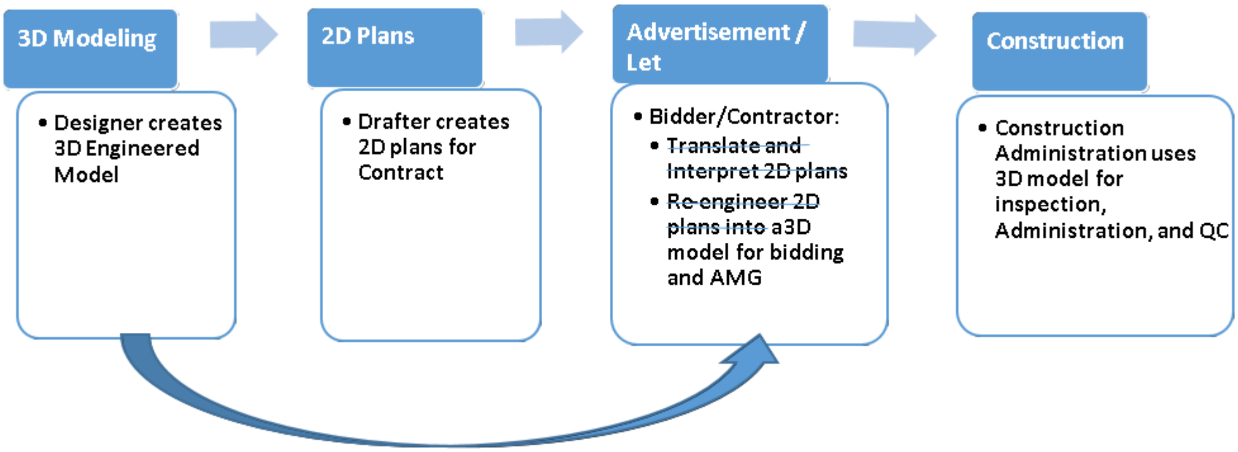


Figure 14. Flowchart. Traditional 2D design workflow versus 3D workflow (after Arena).(41)

State transportation departments have confronted one major roadblock when they realize that 3D design would front-load cost/time in the design phases, requiring more efforts to produce accurate 3D design models when compared with traditional 2D plans. To address this issue, ODOT has provided guidelines for surveyors, designers, and project managers to determine the increased tolerances and level of detail required for 3D design, incorporate additional time into project schedules to allow for 3D modeling, and conduct reviews and QA/QC of the digital files.(42)

Additional challenges have included the required software and training; required technical infrastructure; revision of standards, procedures, and contract documents; and resistance to change. To add to the complexity of all these challenges, State transportation departments have had to make this transition to 3D design in a production environment characterized by shrinking budgets and accelerated project schedules. Agencies indicated their understanding that the transition from 2D to 3D design would involve major organizational changes and revision of existing policies, processes, and workflows.

A summary of the challenges and reported solutions for 3D design, particularly implementation aspects, is presented in table 4.

Table 4. Summary of identified challenges and solutions for 3D design.

Challenge	Solutions
Cost: 3D design front-loads cost/time in the design phases.	• WisDOT's approach has been to begin with 3D design for mega/large projects where the expense was justified and then use the experience to develop an agencywide implementation plan.
Lack of standards: Different formats have been used by different modeling technologies, which could result in interoperability issues.	• Several State transportation departments have conducted meetings with industry associations (e.g., Associated General Contractors (AGC)) and contractors to understand their needs, including data type and format requirements. • There has been collaboration with technology vendors (i.e., Bentley® and Autodesk®), equipment manufacturers (i.e., GOMACO®, Caterpillar®, etc.), and GPS/GNSS equipment makers (Trimble®, Leica®, etc.). • Support and collaboration has occurred with LandXML and TransXML initiatives. • Industry Foundation Classes have provided specifications.
Data management: Security and version control are required.	• Iowa DOT has had dedicated IT staff in the design section to support 3D design efforts.
Specialized training and software: Transitions to InRoads® and Civil 3D® software.	• Different State transportation departments have handled transition and training for the 3D software and design process individually because, in many cases, it has required organizational and cultural changes. Lead State transportation departments have had the following: o Leadership teams with buy-in from upper management. o Pilot projects to illustrate utilities and benefits. • Partnerships can be developed with consultants and software vendors. • FHWA 3D webinars and workshops, Web page, and TechBriefs have been good sources.
Lack of guidelines and specifications	• ODOT has provided guidelines for surveyors, designers, and project managers to determine the increased tolerances and level of detail required for 3D design, incorporate additional time into project schedules to allow for 3D modeling, and conduct reviews and QA/QC of the digital files. • Draft/generic models can be used to illustrate implementation steps for 3D design.
Contractual and legal issues (2D plans versus 3D model deliverables)	The FHWA 2014 workshop manual recommended the following:(43) • Take incremental steps toward this goal, (e.g., Kentucky has replaced Mylar plans with a portable document format (PDF) sealed with a digital signature). • Other agencies have released 3D models to contractors for information only, with disclaimers maintaining 2D plans control in the event of inconsistency with the 3D models.
Model certification/ review: Validation of exchanged data is required, especially when using in construction.	WisDOT has conducted design-construction reviews for megaprojects where designers, consultants, construction, and industry personnel take time for interfacing and reviewing the 3D model.

Success Stories

The following subsections provide summaries of published reports, website postings, and team interviews with State transportation departments that had implemented and used 3D design routinely for project development and delivery.

ODOT Website

In January 2014, ODOT published "Chapter 16: 3D Roadway Design" as part of its *Highway Design Manual*, providing guidance for delivering 3D design files for use by contractors (AMG) and construction administration/inspection personnel.(44) ODOT has used MicroStation® and InRoads® (drafting and roadway design software), and provided the corresponding files to its construction project managers (in-house users). Different files were provided to contractors during the bidding phase (existing ground surface, finish grade surface, and primary alignments in LandXML format and cross sections in PDF), and later, more extensive files were provided to the awarded contractor's surveyor during the construction phase. ODOT has also been working on digital design workflows to create finish grade surfaces and export the files to the required format (i.e., LandXML); the draft document can be found online.(45)

The following documents were used by ODOT to reach the level of its 3D design capability:

- *Issues Brief—3-Dimensional (3D) Roadway Design: Developing ODOT's Roadway Design Crews to Deliver 3D Digital Buildable Design Files*:(46) This document discusses the establishment of the 3D Roadway Design Committee and its work plan to create standards for true 3D design data, policies for a "Digital Engineering Data Packet," and a training plan for design personnel.

- *3D Roadway Design Committee Milestone #2: Scoping Document*:(46) This document lists the tasks to define the "Digital Engineering Data Packet" and develop the *3D Roadway Design Manual*.

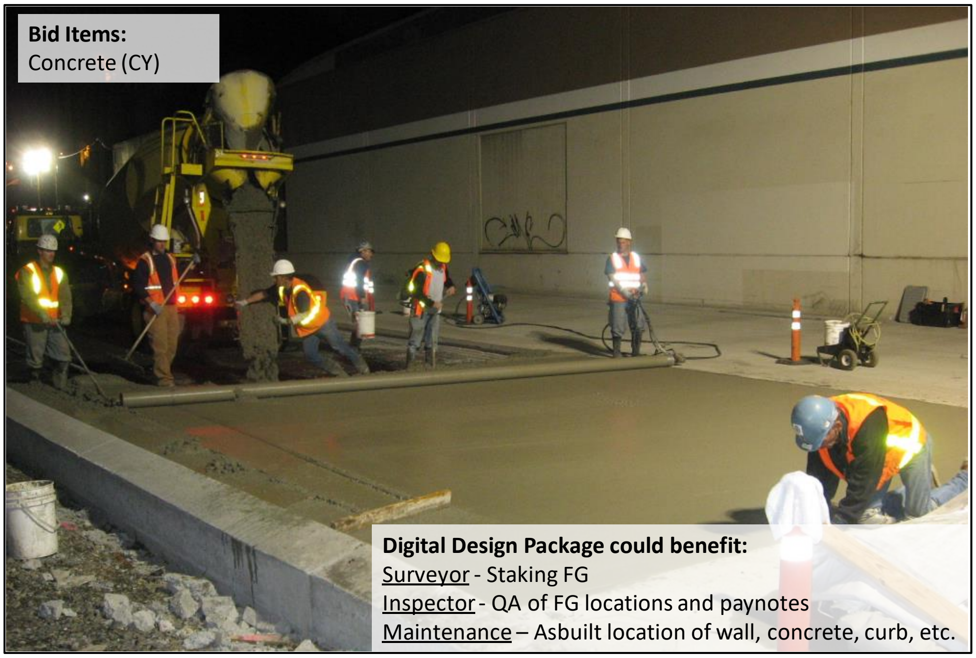
- *Responsibility and Assignment Matrix for 3D Roadway Design Committee*:(46) This matrix assigns tasks and deadlines for the 3D Roadway Design Committee.

Arena explained that the initial belief was that 3D modeling and digital design packages would benefit projects with a significant earthwork component because the main application of 3D design data in highway projects has been AMG for earthworks/grading.(41) However, subsequently, more technologies have become available that use 3D design data in construction, such as stringless milling and paving. Furthermore, the 3D model and digital design data are used during other stages, such as bidding (estimating quantities), inspection (determining pay items and QC of finished grades), and maintenance. Therefore, ODOT has recommended evaluating each project on a case-by-case basis to determine whether 3D design would be warranted.

Figure 15 through figure 18 present examples of ODOT projects that have not involved earthworks but where the 3D design data were still useful during construction. Figure 15 shows a photo of a project in which the main activities were mill and inlay and curb relocation. Figure 16 shows a photo for a project in which the main pay item was concrete for retaining walls and adjacent pavement. Figure 17 shows a photo for a project in which the main activity was installation of drainage swale. Figure 18 shows a photo for a project in which a guardrail and a median wall were installed. In all these cases, the surveyor could use the 3D model and digital data for construction staking and verifying quantities instead of having to refer to the 2D paper plans and to interpolate between cross sections. The inspector could use the same information for the QC of the curb and wall locations, finished grade, and pay quantities. In addition, a record of the exact location of the structures (curb, walls, and guardrails) and finished grade for future maintenance projects would be produced.

LF = linear feet; SF = square feet; C/F = cut and fill; FG = final ground.

Figure 15. Photo. Example of mill and inlay project and 3D data uses in construction.[41]



CY = cubic yard; FG = final ground.

Figure 16. Photo. Example of concrete placement and 3D data uses in construction.[41]

© 2014 D. Arena.
LS = lump sum; FG = final ground.

Figure 17. Photo. Example of drainage work and 3D data uses in construction.(41)

© 2014 D. Arena.
LF = linear feet; LS = lump sum; CY = cubic yard; T = tons; C/F = cut and fill; EP = edge of pavement.

Figure 18. Photo. Example of median work and 3D data uses in construction.(41)

WisDOT

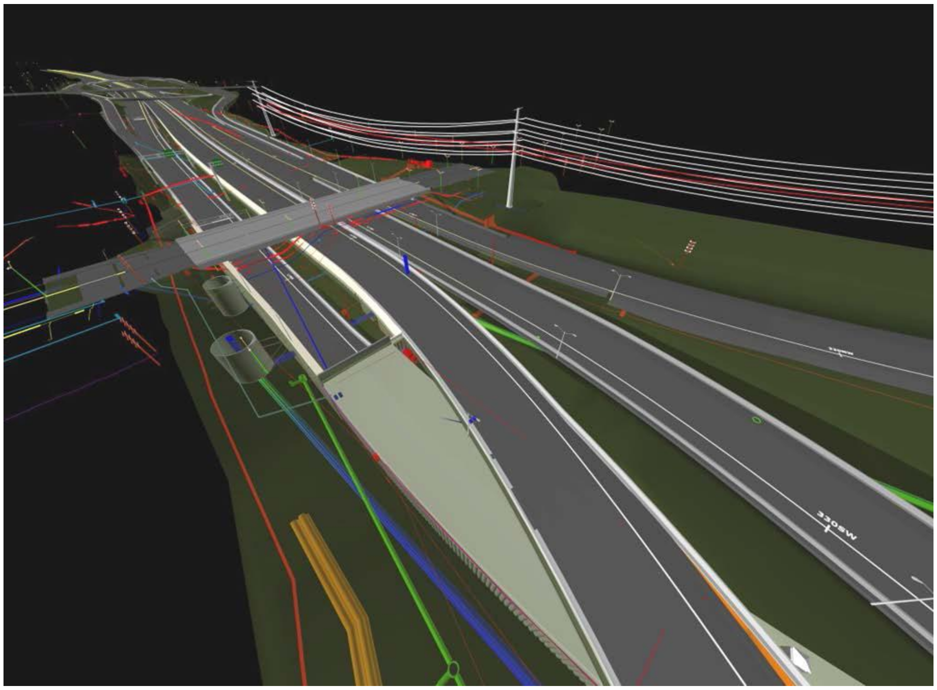
Key references that document WisDOT's 3D design efforts include *3D Technologies Implementation Plan*, *3D Design Terrain Models for Construction Plans and GPS Control of Highway Construction Equipment*, and the FHWA TechBrief *Understanding the Benefits of 3D Modeling in Construction: The Wisconsin Case Study*. (See references 17, 18, 38, and 47.)

WisDOT began with the transition from MicroStation® and CAiCE™ (drafting and roadway design software) in July 2013 and July 2014, respectively. The new software used by WisDOT was Autodesk®'s Civil 3D®, and all new projects designed by WisDOT (in-house and consultant) should be completed using this software.

WisDOT has been implementing 3D design for its Southeast Freeways Program (Milwaukee) megaprojects. The southeast region of Wisconsin has had the largest projects in the State and separate budget/funding that allowed for the cost of implementing 3D design. For its Zoo Interchange project, WisDOT has not only been developing 3D models to support AMG but also conducting clash detection analysis during the design phases of the project. The WisDOT headquarters design division has been taking into account the lessons learned from the Southeast Freeways Program 3D efforts to develop guidelines and 3D model standards for statewide implementation.

Initially, for the Southeast Freeways Program megaprojects, WisDOT lacked in-house expertise in 3D design but created partnerships with consultants to attain the required expertise. For these megaprojects, collocation of consultants at the transportation department office has been key.

Parve reported ROI information for another WisDOT megaproject, the Mitchell Interchange, which was constructed with 2D plans and for which a 3D model was developed post construction (figure 19).[(43)] Based on clash detection analysis, it was estimated that millions ($9.5 million) could have been saved if 3D models had been used in the design phases to conduct clash detection and reduce change orders. Parve reported that savings appeared to be greater for the areas of structures (bridges) and drainage, as opposed to earthworks and excavation as typically assumed.[(47)]



© WisDOT.

Figure 19. Screenshot. 3D design view of the Mitchell Interchange I-94/I-43 corridor.[48]

MoDOT Website

MoDOT has used MicroStation® and GEOPAK® (drafting and roadway design software), and its specifications for electronic design files for AMG are available online.[49] MoDOT has required delivery of electronic design data to support AMG for all of its projects containing cross sections, regardless of the size of project or amount of earthwork.

At MoDOT, the following design files have been required: GEOPAK® coordinate geometry database, MicroStation® design master plan drawing, master profile drawing and cross sections survey control file, 3D existing ground model, superelevation transitions, 3D digital design models for proposed finished grade and any alternate models such as the subgrade depicted in the cross sections, soil report, and contents file report.

MoDOT's efforts to implement 3D design date back to 2004 during meetings with AGC of Missouri. Implementation has been a collaborative effort, and initially, it was determined that providing digital/electronic data, not necessarily the complete 3D model, was useful for contractors. MoDOT began by providing contractors with alignments, profiles, cross section reports, plan views, geometry, superelevation, etc. This information was not the 3D model but rather the data to build it. When new software tools became available for 3D design, policy was modified to include more 3D modeling and information.

As of December 2014, full 3D models were not provided for every project, but the electronic data were provided. For recent projects (e.g., major interchanges), where 3D models were available from design, MoDOT provided them to contractors for information only (with disclaimer and special job provision). The contract document consisted of the final, sealed plans.

Note that MoDOT had not developed a formal written implementation plan but instead created internal action teams and brief one- or two-page documents listing its 3D initiatives and the corresponding progress.

Kentucky Transportation Cabinet

Schneider and Littleton provided an overview of Kentucky's 3D design implementation efforts.[(40)] The Kentucky Transportation Cabinet (KYTC) conducted a pilot project to (1) develop best modeling practices for design so better models could be provided to contractors and (2) develop a new policy to require better 3D models from design. For the pilot project, an in-house 3D model was used as the final plan set to release for bidding. Input from the Kentucky Association of Highway Contractors was obtained to address issues with file formats, size, accuracy, and required elements such as cross sections.

Special provisions were developed and special notes were included to do the following:

- Address conflicts and discrepancies between 2D plans and 3D electronic files.
- Require the use of the provided 3D model for AMG.
- Have inspectors use the 3D model.
- Indicate that the 3D model supersedes 2D plans with the intention to instill confidence in the 3D model.
- Use earthwork quantities from 3D software (InRoads®) instead of end-area volumes.
- Require notifying KYTC regarding errors in the 3D model and giving 72 h for KYTC to correct them.
- Require progress meetings to exchange feedback on 3D model and pilot.

KYTC noted that as 3D modeling capabilities increased, policies and specifications must change. It found that its main challenge was to ensure that construction specifications better accommodated the development and use of 3D models as formal contract documents.

Iowa DOT

Kennerly explained that Iowa DOT began the transition from 2D to 3D design in 2003; one of the goals was to provide contractors with the necessary files for machine-control grading.[(48)] Since then, Iowa DOT has been working with industry—AGC, equipment manufacturers, and software vendors (Caterpillar®, Topcon®, Leica®, Trimble®, Bentley®, etc.)—and continued to conduct periodic meetings to keep up with new technologies, applications, and software. Currently, Iowa DOT has been using MicroStation® (drafting) and GEOPAK® Corridor Modeler (roadway design).

Kennerly explained that Iowa DOT initially "pulled 2D cross sections into a 3D model; omitted intersections and bridge berms due to their complexity, limitations in software and lack of experience; provided files to contractors in different formats post letting."[50] He reported that, subsequently, Iowa DOT "create[s] the 3D model first; provide[s] files to contractors in LandXML format pre-letting as part of the bidding package."[50] Iowa DOT has used 3D design for all projects where earthwork and paving cross sections were developed. Note that the 2D paper plans have continued to be the controlling contract document.

GDOT

GDOT has used MicroStation® and InRoads® (drafting and roadway design software). Different files have been provided to contractors when the project was let to construction (e.g., existing ground surface, finish grade surface, and primary alignments in LandXML format; and end-area and GPS grading reports). However, GDOT's most recent 3D efforts (2013 to 2014) focused on visualization for engineering analysis and communication with the public.

A unique example at GDOT has been a project in the northern, mountainous region of the State where safety improvements are being planned for the intersection of State Routes 9 and 60 (figure 20). The project has involved work in an area with Native American burial grounds, including a grave in the triangle at the intersection (figure 20). The project has proposed a roundabout to help realign the sharp curve at the intersection and also address other safety issues.

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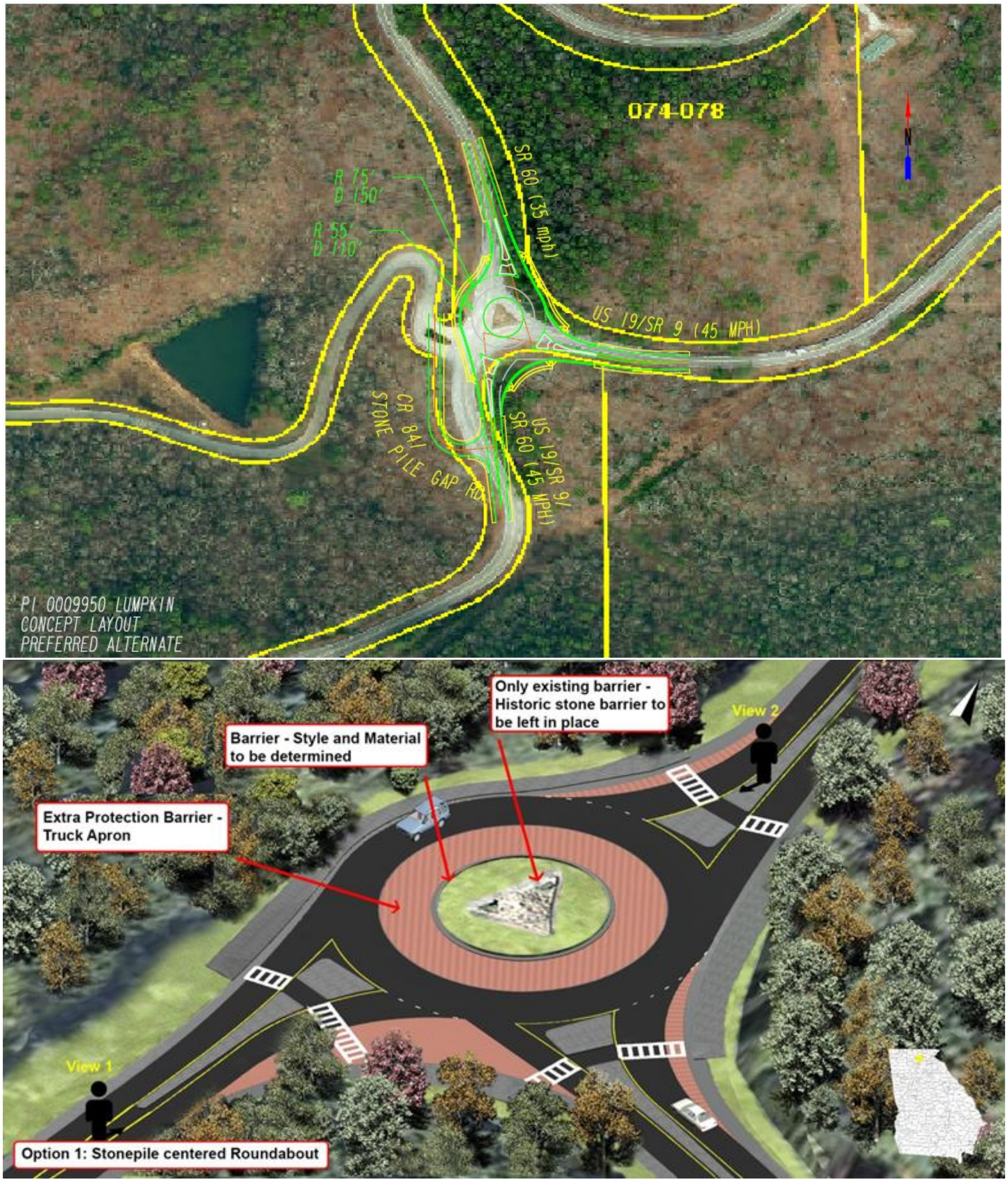
Figure 20. Screenshot. Intersection of US 19/State Route 9 and State Route 60, Lumpkin County, GA (Google Maps™).[51]

GDOT's Visual Engineering Resource Group (VERG) and environmental offices are working together to create 3D models to produce renderings to better communicate the proposed alternatives to the tribal leaders throughout the Nation (figure 21 and figure 22). Each of the figures presents a roundabout option, with the top image showing the original 2D plan and the bottom image showing the rendering with 3D modeling. Prior efforts to communicate using 2D plans and layouts did not successfully portray how the project would look or show that there would be no impacts on the burial grounds.



© GDOT VERG.

Figure 21. Diagrams. Comparison between 2D plan view and visualization with 3D modeling for Option 1: Stonepile-Centered Roundabout.

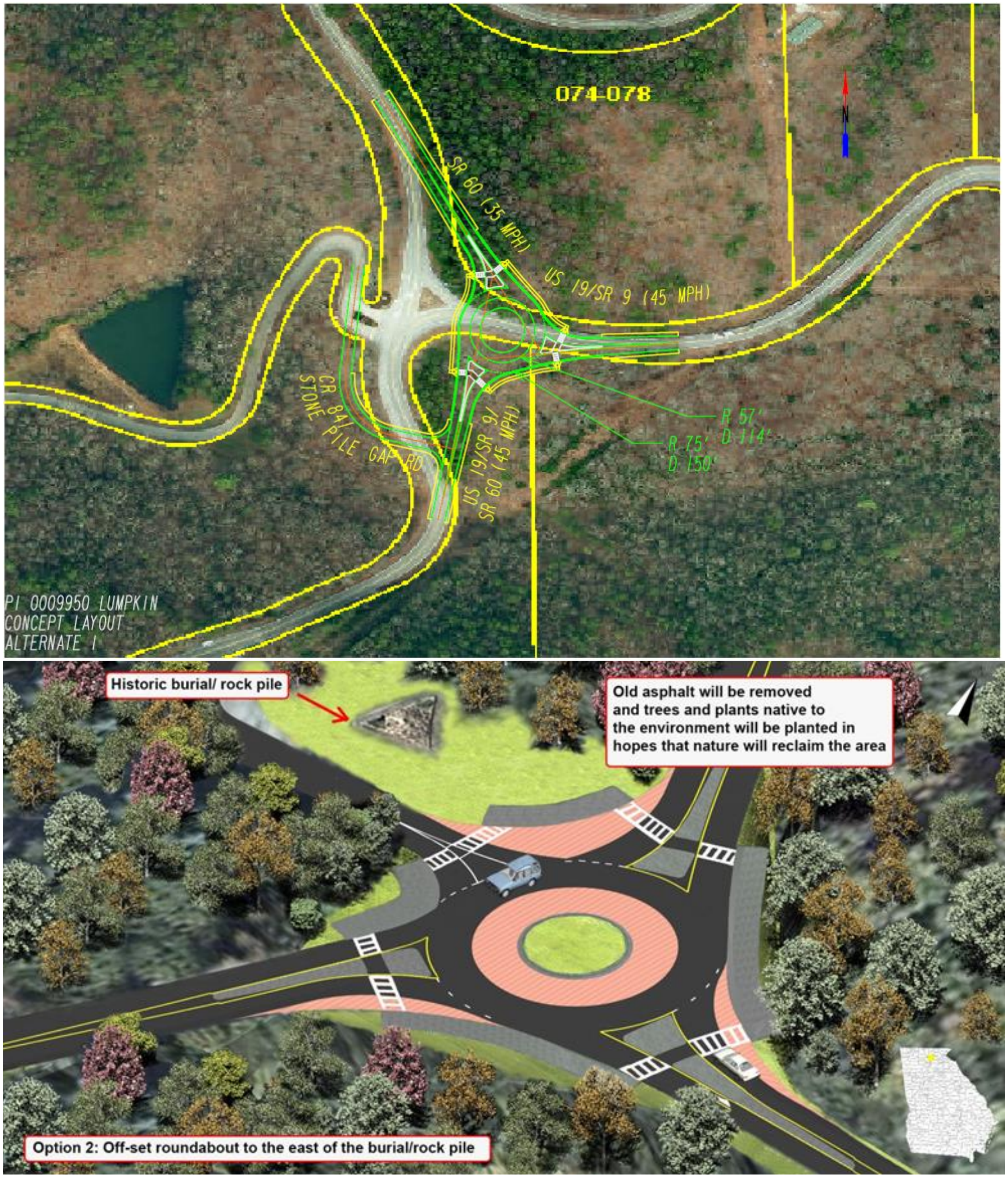


Figure 22. Diagrams. Comparison between 2D plan view and visualization with 3D modeling for Option 2: Offset Roundabout.

GDOT's VERG indicated its next step would be to investigate how it could transfer these 3D models from preliminary engineering to its designers to facilitate subsequent 3D modeling and design efforts. Similarly, it would explore what type of data designers could provide to the VERG to expedite and enhance the production of visual deliverables.

Technology Costs and Resulting Savings

The benefits associated with the 3D design were previously described and include more accurate construction documents and 3D as-built plans, visualization for engineering analysis and communication with the public, detection of issues before construction, conflict resolution applications (i.e., for utilities), AMG-ready files, and quantities calculations. However, benefit–cost and ROI information was scattered, and many of the case studies available had been conducted at a project level and thus did not represent agencywide figures. The following information was gathered throughout this project:

- It was difficult to quantify the cost of 3D design software because most agencies already owned roadway design software, and the transition to 3D design represented upgrading to a newer version. Cost was also incurred for training and hardware, but it varied significantly from agency to agency. Furthermore, lead State transportation departments reported that 3D design software implementation was a major undertaking lasting more than 5 years.

- Lead State transportation departments reported that there was no direct method to document ROI information for the transition to 3D design. For example, one of the main benefits of transportation agencies providing 3D models for construction was the increase in efficiency for contractors in their operations. However, it was difficult to quantify efficiency. The cost of contractors creating the 3D model for AMG from 2D plans ranged from $50,000 to $250,000, depending on the size of the project.

- Another benefit difficult to quantify was that providing the 3D model to contractors shared the design intent, removing the ambiguity of 2D plans, which reduced risks and resulted in more consistent competitive bids. Note that sometimes more than one technology was implemented at the same time, so it was difficult to gauge which technology resulted in the cost savings in the bids. For example, at the same time 3D data were provided, alternate technical concepts and pavements were also implemented.

Construction departments at transportation agencies may be able to track cost/ROI savings. However, contractors would know more about the cost savings achieved as a result of receiving a 3D model from design or creating one, but they would not typically share that information because it would give them a competitive advantage.

CONSTRUCTION AUTOMATION

Singh defined “machine guidance” as a “system [that] uses automation to provide the equipment operator a visual indicator of the position of the cutting edge (blade, bucket, screed, etc.) relative to the design surface being constructed. The operator controls everything.” (Slide 5)[(52)] On the other hand, with machine control, “the cutting edge of the equipment is fully controlled by automation. The system is connected to and controls the hydraulics while the operator simply drives the equipment and manages the automation” (figure 23). (Slide 6)[(52)] Note that the term "automated machine guidance" and its abbreviation (AMG) is widely used to refer to both machine guidance and machine control and is therefore used in this report.

Source: FHWA.

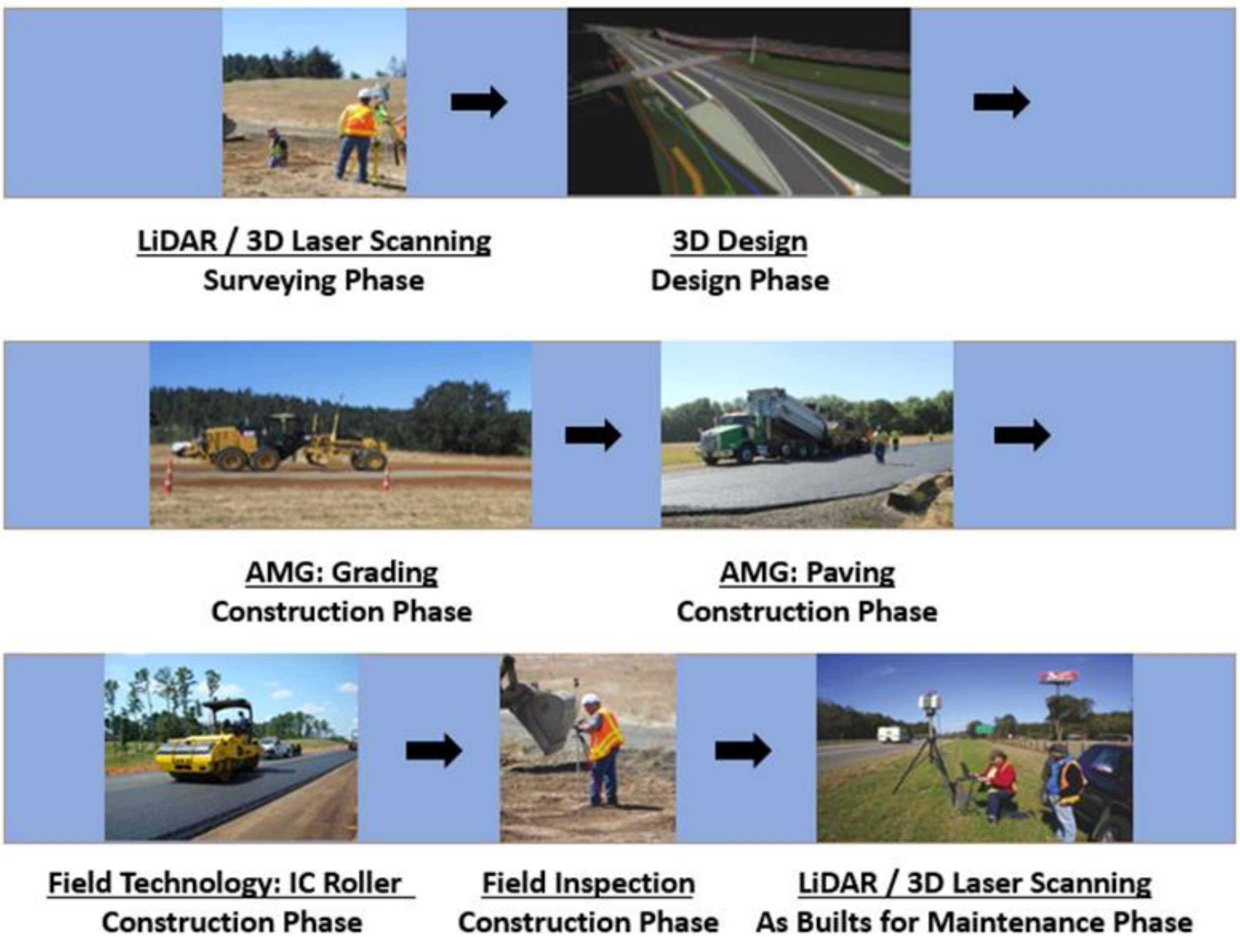
Figure 23. Photo. AMG equipment for earthworks.

This technology has involved heavy construction equipment guided or controlled using position location information (such as from a GPS/GNSS device or land-based positioning system) (figure 24). For highway projects, 3D design data have typically been used to control dozers, motor graders, trimmers, excavators, milling machines, and pavers. Existing equipment may be retrofitted for AMG as well. Systems have been available from multiple vendors, including Trimble®, Leica®, Topcon®, Caterpillar®, GOMACO®, Wirtgen®, etc.

Source: FHWA.

Figure 24. Photo. GNSS-guided subgrade motor grader.

Figure 25 illustrates how the 3D design models created with 3D laser scanning data and 3D design are used during construction operations, such as earthworks and material placement, paving, and compaction, followed by field inspection and scanning of the final product for as-builts.



Source: FHWA.

Figure 25. Flowchart. Automation technology used throughout a highway project timeline.

Benefits of AMG have included better control of quantities, increased productivity (24/7 operations), increased accuracy and precision (fewer backfill/earthworks errors), more uniform surfaces, reduced surveying costs and time, and fuel savings owing to fewer passes. There has also been increased safety with fewer people setting up stakes and checking grades. There has even been the possibility of generating as-built plans with stringless pavers and other equipment systems output.

International efforts for AMG in roadway construction were most notable in Europe and also began with earthworks operations. Heikkilä and Jaakkola reported that AMG was broadly used in Europe, especially in the Scandinavian countries.[53] Heikkilä and Tiitinen presented a summary of several large AMG research projects conducted in Europe.[54] Table 5 summarizes the highlights for those projects.

Table 5. European research projects on AMG (after Heikkilä and Tiitinen).[54]

Project	Years	Funded by	Highlights
Computer Integrated Road Construction Project	1997–1999	European Union	Documented AMG benefits, such as labor, cost, equipment usage, and materials savings.
Open System for Road Information Support	2000–2003	European Union	• Addressed topics of interoperability and information management throughout construction. • Documented cost savings resulting from use of AMG and digital data for contractors and owners. These include cost and time savings, reduced risk, etc.
Intelligent Road Construction Site	2000–2004	Tekes and Finnish owners and companies	Documented increased productivity with AMG for road grading.
Road Construction Production Study[49]	2006	Caterpillar®	• Compared two identical roads constructed with conventional methods and AMG. • Documented AMG savings, such as time, equipment usage, fuel consumption, and increased accuracy.

Implementation Efforts at State Transportation Departments

Lead transportation agencies have been working since the early 2000s to support AMG use by conducting pilot projects and updating workflows and specifications. Typical specification language has been as follows:

> The Contractor may use equipment with AMG that results in the same or better accuracy as conventional construction. Fewer grade stakes are required for work completed using GNSS enabled AMG.

Because 2D plans have continued to be the contract document, disclaimers have been included as follows:

> It is the Contractor's responsibility to confirm that the designed surface model agrees with the Contract Plans prior to using the model for AMG operations.

In addition, State transportation departments have typically required contractors to submit GNSS/AMG work plans that discussed how GNSS-enabled AMG technology would be used on each project and that contained information such as the following:

- Which portions of the contract would be done using GNSS-enabled AMG and which portions would be done using conventional survey.
- Equipment description.
- Qualifications of contractor staff.
- How project control is to be established.
- Site calibration procedures.

The main barriers to implementing AMG in State transportation department projects have involved the lack of 3D engineered models from design or, when they were available, issues with quality and compatibility/interoperability, lack of specifications and inspection procedures (i.e., no stakes for inspectors to check), lack of training/education (e.g., designers, inspectors, and equipment operators), lack of interest by contractors, and perceived cost. In addition, this technology has continued to evolve; for example, GPS precision in the vertical plane is insufficient for AMG. Therefore, other technologies, such as a laser-based total station, can be used to achieve precision requirements in the vertical plane.

In March 2013, the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Construction, Computers and Technology Section, published the *AMG Quick Reference Guide for the Implementation of Automated Machine Guidance Systems*, which provides guidance for the implementation of AMG.(55) The appendices for this document contain excerpts of State transportation departments' specifications, special provisions, workflows, and implementation plans for AMG. The guide refers to AMG implementation plans and guidance by Minnesota, California, Wisconsin, and New York. For example, the guide indicated that Caltrans used the following criteria, either individually or in combination, to determine whether AMG should be used for its projects:

- Large amount of earthwork paving.
- New alignment.
- Good GNSS available.
- Design based on DTM.

A summary of the challenges and reported solutions for AMG is presented in table 6.

Table 6. Summary of identified challenges and solutions for AMG.

Challenge	Solutions
Perceived cost	• Education and unbiased publications with project data documenting cost and time savings.
Lack of 3D models: In most cases, 3D models have not been provided by agencies as part of the plans, specifications, and estimates (PS&E), or when they were available, there were issues with quality and compatibility and interoperability for construction applications.	• Reengineering of the 3D model from 2D plans by contractors. • Pilot projects to evaluate 3D surface model standards and data flows. • Transitioning to 3D design by State transportation departments, in many cases delivering 3D surfaces/models from design and support AMG use by contractors. o Because contractors have different software to prepare models for AMG, the file format needs to be neutral. • Iowa DOT reported that many paving contractors preferred 3D line strings because they were more accurate, and grading contractors preferred them because they made it easier to delineate break points.
GPS/GNSS availability	• Agency tests and demonstrations of CORS availability.
Lack of training/education: For all parties: designers, inspectors (i.e., GPS equipment calibration), equipment operators, etc.	• Pilot projects to illustrate utilities and benefits.

Lack of specifications and inspection procedures: that is, no stakes for inspectors to check (GPS equipment is used instead).	• Specification and special provisions developed by State transportation departments, many based on pilot studies.
	• NCHRP 10-77, a project to develop AMG guidelines to carry out the following:
	  o Include technical procurement specifications for AMG technology.
	  o Provide guidance on the use of such technology in construction projects.
	  o Address implementation of AMG technology into construction techniques (including provision of electronic files and models to support the AMG process).
	• AASHTO's *AMG Quick Reference Guide for the Implementation of Automated Machine Guidance Systems*, which includes the following:(55)
	  o Compilation of specifications, special provisions, workflows, and implementation plans for AMG.

Success Stories

The following subsections provide summaries of published reports, industry presentations, and team interviews with State transportation departments that have implemented and used AMG routinely for project development and delivery.

Iowa DOT

Iowa DOT has been considered one of the pioneering transportation agencies implementing AMG. Kennerly explained that Iowa DOT conducted its first pilot project for machine-guided construction in 2006, and since then, it has "let approximately 61 machine-control grading projects, and 17 machine guided paving projects (including 2 PCC [portland cement concrete] overlays), involving 27 contractors."[50]

To reach this point, Iowa DOT transitioned from 2D to 3D design and modified its process to provide contractors with files for AMG grading. It also worked with contractors (i.e., AGC) to determine AMG data requirements and file formats. Electronic files for AMG were developed once the design was 100 percent complete and then provided pre-letting to contractors "for information purposes" because the 2D plans were still the controlling document. The following documents provide more details on Iowa DOT's design policies and construction specifications for AMG:

- *Design Manual*: Section 20B-71, "Electronic Files Supplied by the Office of Design," provides details of the electronic design files that need to be submitted for projects, including LandXML files for AMG.[56]

- *Design Manual*: Section 20H-10, "Creating XML Machine Guidance Files," describes the process to create the LandXML files.[57]

- *Standard Specifications*, Section 1105.17: "Automated Machine Guidance," discusses the use of electronic design files in construction and contractor responsibilities.[58]

As of 2014, Iowa DOT was working on the process to review the model before providing it for use in construction.

ODOT

ODOT has also been viewed as a pioneering State transportation department, having begun AMG implementation in 2002, starting with subgrade grading and aggregate base placement. As of 2014, it was implementing AMG for other activities such as paving. ODOT explained that agencies should recognize that a lot of work needed to be done to produce, review, and sign the design data that were provided to contractors for AMG.

The following documents provide more details on ODOT's design policies and construction specifications for AMG:

- *Highway Design Manual*: "Chapter 16, 3D Roadway Design," is intended to provide guidance for the delivery of roadway digital design files for use by contractors and construction administration staff.[44] Digital design packages to be provided by the roadway designer include the eBIDS Handoff package (used as an eBIDS reference document during the bidding phase) and the Construction Survey Handoff package (used by the contractor's surveyor during the construction phase).

- *Highway Design Manual*: "Appendix M, Digital Design Packages," includes digital design deliverable checklists, timelines for developing the digital design package, naming conventions, and example packages.(59)

- *Highway Design Manual*: "Appendix N, Digital Design Workflows," is a draft document that will include workflows to create finish grade surfaces for roadway projects.(60)

In 2010 and 2014, ODOT conducted the Design to Dozer and Design to Paver conferences, respectively, to provide information and demonstration of 3D design, AMG, and related construction technologies. The presentations and documents from both conferences are available online and have become key references for automation in highway construction.(61,62)

Technology Costs and Resulting Savings

The benefits associated with the AMG were previously described and include better control of quantities, increased productivity (24/7 operations), increased accuracy and precision (fewer backfill/earthworks errors), more uniform surfaces, reduced surveying costs and time, and fuel savings because of fewer passes. There has also been increased safety owing to fewer people setting up stakes and checking grades. There has even been the possibility to generate as-built plans with stringless pavers and other equipment systems output.

As noted by Heikkilä and Tiitinen, "There have been only a few scientific papers focused on the economic benefits and savings achieved by the aid of automation for road processes—no detailed and comprehensive research has been reported." (p. 1)(54) This has not prevented use of AMG, but there is a strong need for research to quantify the benefits of AMG to support widespread implementation by both contractors and owner agencies.

Cost and ROI information were scattered, and many of the case studies available had been conducted at a project level and thus did not represent agencywide figures. The following information was gathered throughout this project:

- As of December 2014, AMG equipment cost ranged from $300,000 for a dozer or excavator to $1,500,000 for a milling machine or paver. Retrofit kits varied in price and could cost up to $100,000.

- As previously mentioned, there was no direct method to document ROI information for the use of AMG equipment because the cost to create the 3D model was being shifted to the design phases with the State transportation departments' transition to 3D design.

    - Some transportation agencies conducted simple comparisons by looking at pay items. For example, for some years, it can be observed that the pay item for contractor-furnished staking showed a reduction from $30,000 to $0. This was an indication that AMG was being used and affected the construction bids. A similar trend can be observed with the pay item for stringline.

- Anecdotal information from paving contractors claimed that the paving quantity overruns were reduced to approximately 3 percent when performing PCC paving with AMG equipment, while overruns ranged between 7 and 12 percent without AMG.
    - Similarly, earthwork volume overruns were estimated to be reduced by 3 to 6 percent when using AMG.

The following paragraphs present examples from industry publications on cost/time savings comparisons.

The 2006 Caterpillar® study referenced in table 5 compared the construction of two identical segments constructed with conventional methods versus use of AMG.(63) It reported 95-percent time savings just for surveying, 101-percent gain in overall jobsite productivity (in terms of percentage of time used by employing AMG for the different operations (earthmoving, grading, etc.)), higher and more consistent accuracy, and 43-percent fuel savings on average.

MachineGuidance.com.au published a cost comparison for traditional survey versus machine control use based on data from four highway construction projects, with reported estimates of 80-percent survey budget savings for the projects using AMG.(64) Although the project names were kept confidential, no two construction sites are the same and cost comparisons were challenging, information was presented in terms of project and survey budgets, survey personnel, and machine-control equipment as shown in table 7. From this study, it was concluded that construction sites with significant survey requirements and project budgets obtained the most cost savings with AMG usage.

Table 7. Comparison of two traditionally surveyed projects against two machine control–guided projects.(64)

Element	Project A	Project B	Project X	Project Y
Project budget (CPI adjusted)	$66 M	$177 M	$840 M	$195 M
Comparative budget difference	1 time (control site)	2.7 times	12.7 times	3 times
Traditional surveys required (estimate)	6	16	76	18
Total survey personnel used	6	16	20	6
Total machine control used	0	0	22	8
Estimated survey savings: traditional survey versus machine-guided construction	N/A	N/A	$18.4 M (88%)	$3.5 M (80%)

N/A = not applicable; CPI = Consumer Price Index.

Another publication by MachineGuidance.com.au, *3D Precision Paving*, reported a 50-percent schedule/time savings owing to use of 3D construction technologies for the I-84 milling and repaving in Oregon.(65) Similar comparisons were presented by the MachineGuidance.com.au website for productivity, i.e., *Machine Guided Productivity*, and the Leica Geosystems® website for cost savings in terms of crew/wages (i.e., “Project Savings at Deer Park”).(66,67)

FIELD TECHNOLOGY AND INSPECTION

A number of existing, market-ready technologies for construction QC and monitoring have had limited deployment by State transportation departments. This section provides an overview of some of these technologies—IC, GPR, infrared thermal profilers, and real-time profilers. Key references include intelligentcompaction.com, NCHRP Report 626 (*NDT Technology for Quality Assurance of HMA Pavement Construction*), and SHRP2 Reports S2-R06C-RR-1 (*Using Both Infrared and High-Speed Ground Penetrating Radar for Uniformity Measurements on New HMA Layers*) and S2-R06E-RR-1 (*Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction*).[68–70]

The last part of this section focuses on field inspection tools available at the time of this report to assist construction administration personnel, such as tablets, smartphones, GPS rovers, and telematics.

IC

IC has been described as an equipment-based technology for better QC that results in longer pavement lives. Figure 26 shows an example. IC machines are vibratory rollers with accelerometers mounted on the axel of drums, a GPS device, infrared temperature sensors, and on-board computers that can display color-coded maps in real time to track roller passes, surface temperatures, and stiffness of compacted materials. The IC technology can be applied to all pavement layer materials from the ground up. Single-drum IC systems are used for soil compaction, and suppliers in the United States have included Ammann®/Case®, BOMAG®, Caterpillar®, Dynapac®, Sakai®, Volvo®, and Wirtgen®/Hamm®. Double-drum IC systems are used for asphalt compaction, and suppliers in the United States have included BOMAG®, Caterpillar®, Sakai®, and Wirtgen®/Hamm®. After-market IC retrofit systems from Trimble® and Topcon® can also be used on selected models of conventional single- and double-drum rollers.

Source: FHWA.

Figure 26. Photo. An example of IC for asphalt.

A Transportation Pooled Fund (TPF) Study (TPF-5(128)) led by FHWA and completed in 2011 involved 17 demonstration projects around the country.(71) The study provided a comprehensive list of recommendations for this technology on compacting granular soils, cohesive soils, granular subbase, stabilized base, and asphalt materials. There was also an NCHRP IC study on the soils application. Both the FHWA TPF and NCHRP IC studies provide guidance for future IC-related construction specifications.(72,73) In 2013, FHWA began national deployment of IC by conducting workshops and IC equipment demonstrations around the United States as part of the EDC2 initiative. FHWA has since completed a research project entitled *A Study on Intelligent Compaction and In-Place Asphalt Density*.(74) Also, FHWA and TxDOT were conducting research to evaluate IC retrofit systems from 2013 to 2015, with the final report expected thereafter. A new NCHRP project 24-45 was expected to address layer mechanic properties from IC measurements from 2015 to 2017.

Benefits of this technology have included determining and achieving the optimal number of roller passes to prevent under/overcompaction, which translates into fuel/operation savings and improved quality. Uniformity and consistency have also been benefits of IC.

Barriers to implementation of IC technology have included cost, lack of training, large data volumes, lack of standardized data, and an initial lower speed of operation owing to learning curves.

NDT Devices for QA

This category includes NDT devices for QA, such as GPR, infrared thermal profilers, real-time smoothness profilers, and concrete temperature and maturity meters. Some of these technologies, although mature, have not been in common use. Other technologies have been under development.

These technologies have required skilled technicians for both operation and data analysis. There were multiple manufacturers. The main benefit of these technologies has been elimination/reduction of coring new and existing pavements/structures and other destructive and/or labor-intensive testing methods. In addition, there has been improved quality with faster feedback and continuous and more complete coverage.

Barriers for deployment/implementation have included lack of training/education and skilled operators and technicians, special certification requirements, and lack of analysis software.

The main references for each of these NDT technologies are summarized in the following subsections.

GPR

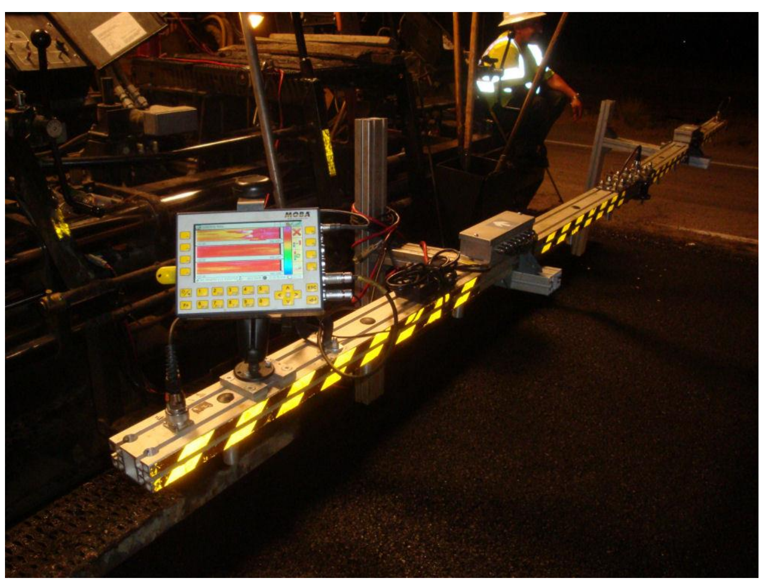
Von Quintus et al. conducted a field evaluation of selected NDT technologies, including GPR, to determine their effectiveness for QA of asphalt pavement and base layer construction.(68) GPR was found to be acceptable to measure density, air voids/percent compaction, and layer thickness during construction. Figure 27 shows an example.

Source: FHWA.

Figure 27. Photo. An example of GPR.

Paver-Mounted Thermal Profilers

SHRP2 Report S2-R06C-RR-1 summarizes the results of an SHRP2 project that evaluated and demonstrated infrared sensors and radar systems suitable for testing the entire surface area of the asphalt pavement at the moment the hot-mix asphalt (HMA) was laid down.(69) Products of the study included recommendations for equipment and testing protocols. Use of the infrared thermal profile system (such as PAVE-IR™ from MOBA®) would allow contractors to detect temperature segregation problems behind the paver in real time and make adjustments during construction (figure 28). The project team developed a GPR-based system to measure density after the HMA was compacted and also improve QC.



Source: FHWA.

Figure 28. Photo. An example of a paver-mounted thermal profile system, PAVE-IR™.

Real-Time Smoothness Profilers

SHRP2 Report S2-R06E-RR-1 summarizes the results of an SHRP2 project that evaluated and demonstrated two technologies (GOMACO® Smoothness Indicator and Ames Engineering Real-Time Profiler) to measure smoothness of concrete pavements during construction.[70] Use of this technology would allow contractors to identify the influence of design and construction factors in roadway smoothness during construction to make adjustments during construction and achieve a smoother surface. Traditionally, smoothness testing would be conducted days after construction once the concrete hardened. The expense of grinding would also be reduced. Figure 29 shows an example of a PCC real-time profiler.

Source: FHWA.

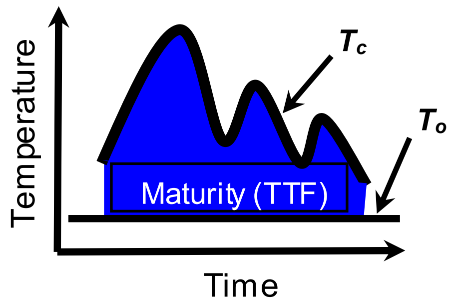
Figure 29. Photo. An example of a PCC real-time profiler.

Concrete Temperature and Maturity Meters

This technology involves monitoring temperatures of concrete at early ages to improve overall QA, prevent cracking, estimate strength, and determine the optimal time for surface texturing, post-tensioning, joint sawing, opening to traffic, and form removal. This method has been a more accurate way to estimate the in situ strength of concrete and can reduce the use of traditional, less representative testing (concrete cylinders). Systems have been available from multiple manufacturers, and a corresponding ASTM standard specification has been developed (ASTM C1074-11).[75] Figure 30 shows an example of a concrete maturity meter, and figure 31 shows a concrete maturity curve.

Source: FHWA.

Figure 30. Photo. An example of a concrete maturity meter.



Source: FHWA.

Figure 31. Chart. An example of a concrete maturity curve.

Field Inspection

This section discusses field inspection tools, such as tablets, smartphones, and telematics, to assist construction project personnel. This technology would allow construction and field personnel to connect with the information from design and the 3D model/surfaces. Construction inspectors need to verify that contractors are complying with plans and specifications and are keeping records. Use of these more advanced tools, such as tablet PCs, has allowed access to surface models (instead of 2D paper plans) and creation/saving/transferring of electronic records (instead of paper forms) and GPS equipment to check grades.

In addition, this study found many tools that could be used for inspection and construction administration that did not need to have a GPS device (or a very accurate GPS device). For example, tablets, smartphones, and digital cameras could be used for real-time production reporting, quantity tracking, and as-built documentation.

Commercial software such as Bentley® OnSite® has been available to facilitate the integration of the inspection process with tablets and 3D/electronic data. State transportation departments, such as the New York State Department of Transportation, that were already using Bentley® software for design (MicroStation® and InRoads®) and data management (ProjectWise®) have added Bentley® OnSite® to expand their 3D capabilities to the field.(76) With this tool, inspectors can use data directly from surfaces/DTMs created with Bentley® software and other electronic project information from Bentley® ProjectWise®.

This study found that there also were more advanced communication systems, referred to as telematics, such as Connected Site® from Trimble®, Sitelink™ from Topcon®, and iCON™ telematics from Leica Geosystems®, to connect all 3D clients at a specific project (i.e., surveying, design, AMG contractors, etc.). Machines would need to be connected to a central server, which provided a "virtual connection" via a wireless network (cellular service or Wi-Fi) and included a GPS component. If the system included video, it could be used to monitor safety, security, compliance, materials delivery, etc. Benefits from this technology have included real-time data to monitor productivity, immediate responses to resolve problems, reduced downtime, improved exchange of information, and increased security and safety. In addition, this technology reduced the need for continuous, rigorous inspection or frequent visits to a site. Its use also avoided the need for personnel to go back to a site just to check on a specific item/feature.

The main benefits for these tools have included increased efficiency, productivity, improved communication, and safety. The main barrier for newer construction inspection technologies has been cost, so their use has mainly represented benefits for larger contractors/projects. However, when used, owner agencies have benefited as well. In general, there was a lack of awareness and training/education regarding this technology. Lastly, a reliable wireless network would be required at the sites. Table 8 summarizes challenges and solutions for field technology and inspection.

Table 8. Summary of identified challenges and solutions for field technology and inspection.

Challenges	Solutions
Cost	• Education and unbiased publications with project data documenting cost and time savings.
Lack of awareness	• Demonstrations and publications by national agencies, such as FHWA, NCHRP, SHRP2, etc.
Lack of training/education	• Pilot projects to illustrate utilities and benefits. • Case studies. • Customized workshops focusing on advanced technologies for field technicians and inspectors.
Equipment availability IC and NDT technologies: real-time profilers	• Collaboration and surveys of equipment vendors.
Improvements for analysis software NDT technologies for QA: real-time smoothness, GPR, etc.	• Veta software for IC by FHWA and Minnesota Department of Transportation (MnDOT). • Research/development projects by national agencies, such as FHWA, NCHRP, etc.
Lack of specifications and guidelines	• FHWA generic IC specifications, AASHTO IC specification (for both soils and asphalt). (See references 72, 73, 77, and 78.) • Task working groups/committees by AASHTO and ASTM, etc., to develop model specifications and guidelines.

Challenges	Solutions
Wireless network connectivity Examples from Machine Control Online:[79] Inspection “We need more bandwidth onsite to enable remote video monitoring.” “We don’t have Wi-Fi available onsite.” AMG “We are struggling with remote model downloads during machine operations because of network connectivity problems.” “The current network doesn’t have sufficient range to broadcast base station corrections across the entire jobsite.”	• Case studies at project and statewide levels. • Pilot projects to evaluate the interface between GPS rovers and 3D models. • Surveys of lead agencies/contractors.
File size for GPS rovers for inspection Existing devices do not have enough memory to handle 3D model files.	Iowa DOT, which is providing the project in smaller sections to fit the memory limitations or providing line strings that reduce the file size to something more manageable.[50]

Implementation Efforts at State Transportation Departments

As mentioned earlier in this section, maturity meters have been used to measure and log internal concrete temperature and time. They have been commonly used for two purposes: (1) recording of temperatures in mass concrete for the purpose of determining temperature gradients and (2) implementation of the maturity method for evaluating early-age strength. An example of a meter in use is shown in figure 32.

Source: FHWA.

Figure 32. Photo. Temperature and maturity monitoring with hand-held reader.

Many State transportation departments' specifications have required the internal temperature of concrete to be monitored during the early ages of strength gain. Massive concrete elements generate a large amount of heat during this time due to hydration. Transportation agencies have often limited the maximum temperature that should ever be experienced by the core (the hottest part) of the element and have often put limits on the difference in temperature that might exist between the core and any surface. These limits have been put in place because excessive heat and large temperature gradients could compromise the durability and performance of concrete.

This study found that some maturity meters were self-contained loggers that measured and stored time and temperature data, which could be downloaded into a hand-held reader whenever the data were required. Data could then be viewed in Microsoft® Excel spreadsheets or in proprietary software to evaluate the difference in temperatures between different locations within the element. The advantages of using such devices included minimized data loss (as long as the sensors were placed correctly and the wires leading out of the element were not severed) and reduced labor because data did not have to be manually recorded at specific time intervals. Maturity meters have been used for mass placement on TxDOT projects, including the Grand Avenue Parkway and DFW Connector.

A number of State transportation departments have allowed the use of the maturity method to evaluate early-age strength gain in either standard specifications, special provisions, and/or supplemental specifications. The Washington State Department of Transportation (WSDOT), UDOT, TxDOT, WisDOT, and Iowa DOT are only a few examples of State transportation departments that have included maturity in their standard specifications as an option for determining strength for opening to traffic. WSDOT is an example of an agency that has also required maturity for some projects through a special provision. This study found that MoDOT did not address maturity in its standard specifications but did do so in a supplemental specification.

It has been common for State transportation department specifications, special provisions, or supplemental specifications for maturity to provide detailed descriptions of what equipment to use, where to place maturity meters, the quantity of meters to place, how to develop and calibrate the curve, and how to validate that curve. (See figure 33 for an example of temperature sensor placement.) Not all specifications or provisions have been equal in the level of detail or content, however. For example, WisDOT specifications have required the maturity curve to include data points up to 120 percent of the required strength and required at least one sensor for every 2,000 yd^2 (1,672 m^2) of concrete pavement or 100 yd^3 (76.5 m^3) of concrete for other, non-pavement applications. MoDOT has required one sensor for every 3,750 yd^2 (3,135 m^2) of pavement, with one sensor placed within the last 50 ft (15 m) of concrete, one sensor at the end of a structural pour, and one sensor for every 10 patches; MoDOT has not required data points based on a percentage of strength gain. The variance in State requirements has usually been associated with agency and contractor comfort levels and experience, which can be very different from State to State and can be attributed to factors such as familiarity with the method, environmental conditions, and available materials.

Source: FHWA.

Figure 33. Photo. Temperature sensors placement before concrete pour.

The following documents provide more information on mass concrete and the maturity method:

- ASTM C 1074-11, *Standard Practice for Estimating Concrete Strength by the Maturity Method*.[(73)]
- AASHTO T 325, *Standard Method of Test for Estimating the Strength of Concrete in Transportation Construction by Maturity Tests*.[(78)]
- American Concrete Institute (ACI) 301, *Specifications for Structural Concrete*.[(80)]
- ACI 228.1R, *In-Place Methods to Estimate Concrete Strength*.[(81)]
- ACI 318, *Building Code Requirements for Structural Concrete and Commentary*.[(82)]
- *Use of the Maturity Method in Accelerated PCCP Construction*.[(83)]
- "Maturity Matters."[(84)]

Success Stories

The following subsections provide summaries of published reports, industry presentations, and team interviews with State transportation agencies that have implemented and used the field inspection technologies previously described in this section.

IC: MnDOT

MnDOT has been a national leader in IC for the past decade. A granular soils IC project took place at MnROAD, a pavement test track, in 2004. Since then, approximately 40 IC projects have been conducted in Minnesota. In 2014, 10 percent of MnDOT projects were to include IC and thermal profiling. MnDOT has developed a roadmap to implement IC and thermal profiling on 100 percent of MnDOT projects in 2018.

Funding for the development and enhancements of Veta, a map-based tool for viewing and analyzing data from various IC machines and MOBA® PAVE-IR™ thermal bars/scanners, has been provided by MnDOT. In addition, MnDOT has been leading a new TPF Study, *Enhancement to the Intelligent Construction Data Management System (Veda) and Implementation*.[(85)] According to the TPF study description, "MnDOT, in collaboration with local contractors and suppliers, is moving forward with full implementation of geospatial technologies such as IC and thermal profiling (infrared imaging) as QC tools on grading, reclamation, and asphalt paving projects."[(85)]

The following documents provide more details on MnDOT's IC implementation:

- 2016 Q*uality Management Special—Intelligent Compaction (IC) Method* describes the special provision.[(86)]
- MnDOT's *Advanced Materials & Tech*nology Web page includes implementation schedule and current projects.[(87)]

- MnDOT's *Advanced Materials & Technology Forms & Worksheets* Web page includes IC-related forms and aids.(88)

Concrete Temperature and Maturity Meters: WSDOT and UDOT

Typically, for State transportation department jobs, the use of the maturity method has been advantageous for fast-track paving operations, including new construction and repair work. WSDOT has embraced these benefits for more than 10 years, had confidence in the method, and trusted the results. For WSDOT, the maturity method has become common practice. Once contractors realized how easy implementation was, many chose to use maturity even when it was not required because it was beneficial to their QC process. For a 2014 repair project on I-5 for which maturity was required, data were being collected by the contractor and submitted to the engineer regularly. For this job, maturity was helping WSDOT and the contractor recognize that, as temperatures began to drop, it took longer to achieve the maturity index value that indicated enough strength gain had occurred for opening to traffic on replaced panels. Maturity was a way of knowing what was going on with the mix in the field rather than relying on breaking sample sets that were not as representative.

When a State has provided the option for or required using maturity, it was often up to the contractor to implement it. Implementation can save the contractor time and money. Usually, savings were realized by (1) stripping forms sooner or opening to traffic quicker, thereby potentially expediting construction schedules, and (2) reducing the number of test samples that need to be broken for project QC and acceptance. Understanding there could be significant savings related to maturity testing, the UDOT Region One Materials Laboratory has implemented the use of maturity for in-house validation of concrete strength. Since the most recent economic downturn, many State transportation departments have had to tighten their belts and save money wherever they could. This was the case for UDOT in 2010. The option for using maturity to evaluate strength gain in early-age concrete for opening to traffic was written into the State specifications in 2008. However, it was not until 2010 that UDOT began to consider the maturity method as a way of reducing its own costs for validation testing. The rationale for the shift was simple: Why spend hundreds of dollars on testing multiple sets of samples when you could spend less than a hundred dollars on a maturity sensor and take multiple readings instead? Since then, maturity has been used on four major paving projects: I-84 Mountain Green to Morgan, State Road 252 in Logan, Riverdale Road in Riverdale, and 12th Street in Ogden. While it has remained an option to the contractor and has not been required for validation, the use of maturity has been continuously encouraged throughout the State. Region One Materials Laboratory engineers reported in a blog post: "Using maturity meters helps reduce risk, save money and open to traffic as soon as possible."(84)

Technology Costs and Resulting Savings

The benefits associated with the field and inspection technology were previously described and include improved materials quality, uniformity, and consistency with faster feedback and continuous and more complete coverage; elimination/reduction of coring new and existing pavements/structures and other destructive and/or labor-intensive testing methods; increased safety owing to fewer people setting up stakes and checking grades; increased efficiency and productivity; and improved communication and safety.

Cost and ROI information associated with these technologies varied widely because some of these technologies were still not used routinely by State transportation departments and continued to undergo research and development (e.g., GPR, infrared bar, and real-time smoothness profilers). More established technologies (telematics and maturity meters) were available from multiple manufacturers and were mostly used for larger projects. More research is needed to document the cost and resulting savings.

CHAPTER 4. 3D AND DIGITAL DATA MANAGEMENT

The automation in highway construction technologies presented in the previous chapters of this report involved collection, processing, analysis, and storage of large volumes of data. State transportation departments have faced challenges with the required IT infrastructure, data management, and software. Noland noted that "while there has been tremendous progress in civil and structural design software, data acquisition tools, 3D machine control and fleet monitoring, the lack of cohesive data flow accessible throughout the construction lifecycle remain." (p. 4)[(89)] Noland identifies the lack of standards as one of the major challenges for efficient and integrated digital data usage and transfer but notes that "no single company or person is responsible for the lack of standards," because such a big undertaking should be an industrywide effort.[(89)]

NCHRP Synthesis 446 examined the state of the practice for gathering, analyzing, storing, and using geospatial data in State transportation departments; however, similar issues have been encountered for most automation in highway construction technologies. The key findings (including a survey for State transportation departments) were the following:[(16)]

- The top three barriers to technology adoption, indicated by the State transportation departments, were cost, inertia, and technical expertise.

- The three key drivers of success when introducing new geospatial technology were an early adopter mindset, an internal champion, and an interest in safety.

- The top three geospatial technology research needs identified by the State transportation departments were data management, data integration, and transition from 2D to 3D workflow. Most research reports were published internally only. Reports for pilot projects were generally not made available on the Web. Failures and decisions not to use a technology were rarely documented and even more rarely made publicly available.

- State transportation departments were split between a desire for national and State standards. Service providers favored national standards, when possible. They also preferred performance-based specifications and guidelines.

- Using advanced geospatial data technology can have many benefits for transportation agencies. Change can sometimes be a slow, difficult process, but given the economic conditions that exist today, most cannot afford the luxury of waiting for development of a complete set of best practices and guidelines for new technologies. By sharing the experiences and lessons learned among transportation (and other) agencies, the learning curve can be shortened and cost efficiencies achieved.

- Geospatial service providers have been early adopters of geospatial technology, particularly 3D workflows. They indicated that the three key drivers of success when introducing new geospatial technology were an early adopter mindset, an internal champion, and an interest in safety. Similar to the State transportation departments, service providers said they believed that focused research projects, documentation, and centralized information dissemination would help overcome many barriers.

An example of State-level efforts to address digital data and management have been those of the Kansas Department of Transportation (KDOT), which recently evaluated sharing electronic/ digital data with contractors and updated its construction specifications and electronic deliverables policies.(39) Table 9 summarizes the challenges and provisional solutions for KDOT's electronic/digital processes. KDOT's findings were similar to other States that began implementation of 3D and automation technology but, owing to legal/contractual issues, still referred to the 2D plans as the controlling document.

Table 9. KDOT summary of electronic deliverables challenges and decisions.(39)

Challenge	Input	Decision
Lack of knowledge and experience	• Surveys. • Industry expert meeting. • Pilot project.	• Provide construction inspectors with GPS rover. • Provide inspector training.
Fear of releasing electronic data/legal concerns	• Literature review. • Surveys. • Industry expert meeting.	• Paper plans control. • Liability covered by specifications and disclaimer.
Source of 3D model	• Literature review. • Surveys. • Industry expert meeting.	• Provided 2D design files. • 3D files created by contractor.
Quantifying benefits	• Literature review. • Surveys. • Industry expert meeting. • Pilot project. • Interim policy.	• Not practical to obtain quantitative benefits. • Identified qualitative benefits.

CIVIL INTEGRATED MANAGEMENT

At a national level, there has been a joint initiative by FHWA and AASHTO, the American Road and Transportation Builders Association, and AGC to promote Civil Integrated Management (CIM). CIM has been defined as the collection, organization, and managed accessibility to accurate data and information related to a highway facility, which should to be applied throughout all phases of highway projects. Automation technologies, such as LiDAR, 3D design models, and AMG, have been key components of CIM.(90)

This concept was also discussed during the 2011 ICST Stakeholder Workshop/Strategic Roadmap referenced in the introduction of this report. It was concluded that there was a need to define "a work process to capture and integrate 3D modeling and electronic data throughout the project delivery process and life-cycle stages." (p. 68)[3] The ultimate goal was not only to create a database but to define a complete model, including the following aspects:

[3]Unpublished source obtained from internal communication. Torres, H. et al. (2012). Intelligent Construction Systems and Technologies Roadmap. Federal Highway Administration Contract DTFH61-08-D-00019.

- Process model (policies and procedures).
- Financial model (costs and ROI).
- Human resources model (roles and competencies).

Heikkilä and Jaakkola referred to this concept as "automation of road construction" and explained that it was achieved in large part by the use of different information models throughout a highway project as shown in figure 34.(53) Heikkilä and Jaakkola reported that 3D technologies were used broadly in Europe where agencies were also working on developing integrated work processes.(53)

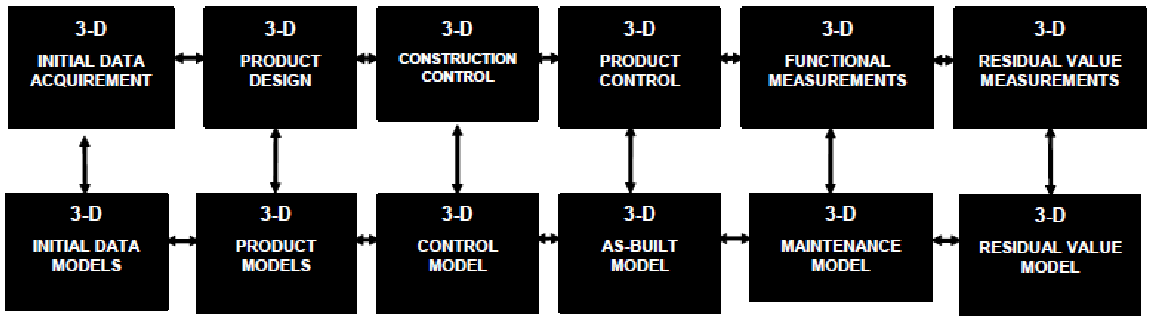


Figure 34. Diagram. 3D models for automation of road construction.(53)

More recently, Parve made a presentation on this topic and the implementation of CIM for the Southeast Freeways Program projects in Wisconsin.(91) In figure 35, Parve illustrates how the CIM concept takes 3D modeling a step further.

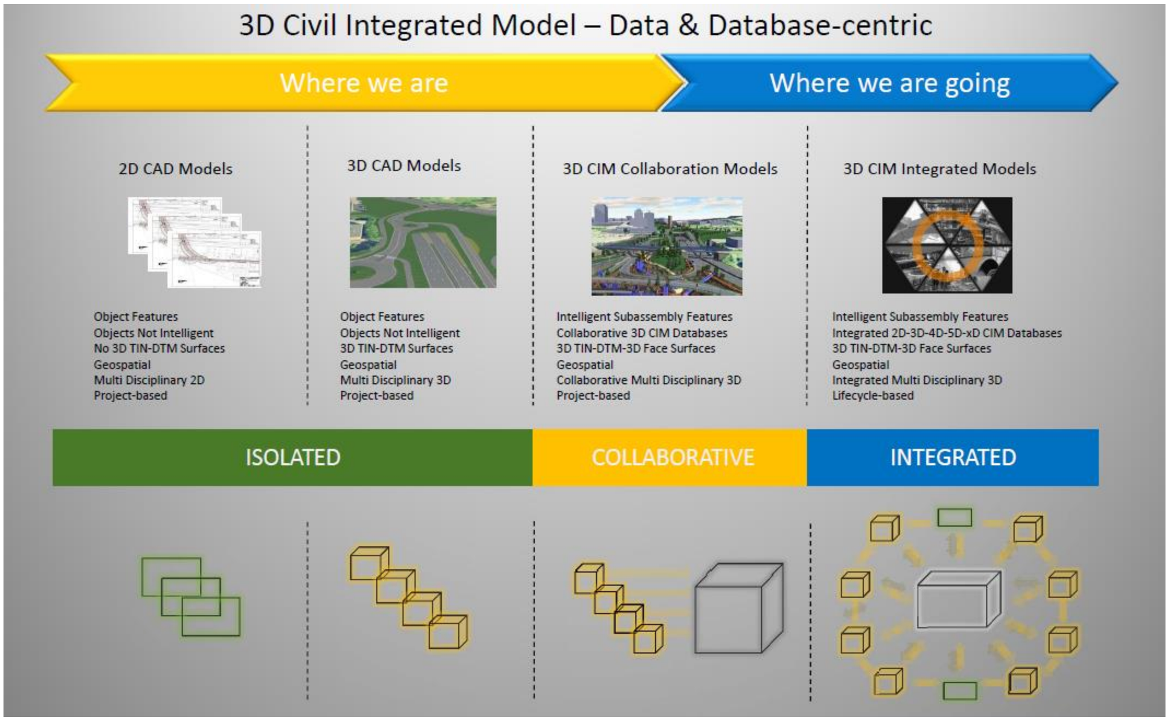


Figure 35. Diagram. 3D CIM concept illustration.[(91)]

Bañuelos and Chen reported on the benefits of the implementation of building information modeling (BIM) based on a survey of the transportation industry in the United Kingdom.[(92)] They described BIM as analogous to CIM for the transportation industry in the United States, and they found that the most significant benefit was improved coordination through collaboration and communication, which led to improved efficiency and accuracy. 3D models were found to enhance visualization, allowing better understanding of projects and earlier conflict detection and resolution. Time and cost savings were reported during the construction phases owing to clash detection and better coordination during design.[(92)]

The main barrier for implementation of this concept has been resistance to change because it represents the evolution of traditional and established workflow processes. In addition, because it was still in the concept phase of the development cycle, there was a lack of awareness of benefits, unknown cost, procedural issues, lack of specifications, legal issues, etc.

Relevant efforts related to CIM for transportation agencies include the following:

- NCHRP Project 20-64 (completed in 2006), which developed partial TransXML schemas in the areas of surveying/design, construction/materials, bridges, and safety.[(93)]
- NCHRP 20-07/Task 295 (completed in 2011), which conducted a survey of existing XML schemas for incorporation into TransXML.[(94)]
- NCHRP Project 10-96 entitled *Guide for Civil Integrated Management (CIM) in Departments of Transportation* (which was to begin in 2014).

CHAPTER 5. AUTOMATION TECHNOLOGY IMPLEMENTATION PLANNING

As State transportation departments in the United States have transitioned from 2D to 3D design and implemented the automation technology described throughout this report, lead States have been outlining statewide 3D technology implementation plans to be able to produce robust engineered models and effective 3D workflows that could be used for design, construction, material fabrication/procurement, visualization, scheduling, estimating, quantity tracking, and as-built documentation. The implementation plans/documents for Wisconsin and Oregon are summarized in this chapter. Part II of this report presents more information on enabling technologies and policies, along with implementation strategies for State transportation departments.(1)

WisDOT

WisDOT has been one of the few State transportation departments that has thoroughly documented and publicly published its efforts to implement 3D technologies. In 2009, WisDOT created its plan, *WisDOT Implementation Plan: 3D Technologies and Methods for Design and Construction*, which consisted of six major initiatives as summarized in table 10.(17)

Table 10. Summary of initiatives, goals, efforts, priorities, and lead sections.(17)

Initiative	Goal	Effort	Priority
Height Modernization and CORS—Lead: BTS (Surveying and Mapping)	Internal/external support groups secure funding.	High	High
	Implement 5-year completion plan (2009–2013).	High	High
DTM Data Collection and Analysis—Lead: BTS (Surveying and Mapping)	Fill survey data coordinator positions.	Moderate	High
	Determine map-check frequency.	Low	Medium
	Revise FDM and business practice for map checks.	Moderate	Medium
	Develop standards and procedures.	High	High
	Pilot standards and procedures.	Moderate	High
	Implement standards, procedures, and training on DTM data collection.	Moderate	High
	Implement DTM-to-DTM for earthwork.	Moderate	High
	Evaluate technologies (e.g., LiDAR, airborne GPS).	Low	High
3D Design Process—Lead: BPD (Roadway Standards and Methods)	Existing Civil 3D® pre-deployment plan.	Moderate	High
	Civil 3D® new user training.	High	High
	Develop and execute extended deployment plan.	Moderate	Medium
	Annual users conference process.	High	Low
	3D model content and format standards.	High	High
	Establish date for 3D models for PS&E.	Low	High
	Evaluate 3D models as construction contract documents.	High	Medium

Initiative	Goal	Effort	Priority
Automated Machine Guidance—Lead: BPD (Project Services)	Monitor and refine grading specification.	Low	High
	Develop, pilot, and implement base course specification.	Moderate	High
	Investigate and evaluate need for paving specification.	Moderate	High
	Study bridges and utilities and make recommendation.	Low	Medium
Field Technology and Inspection—Lead: BPD (Project Services)	**Rovers-for-Construction Group**		
	Investigate scenarios and feasibility.	Moderate	High
	Pilot, evaluate, and develop implementation plan.	High	TBD[1]
	Execute implementation plan.	High	TBD[1]
	Inspection Automation Group		
	Investigate feasibility.	Moderate	High
	Develop implementation plan.	High	TBD[1]
	Execute implementation plan.	High	TBD[1]
Infrastructure Lifecycle Uses of 3D Data—Lead: 3D Technologies Management Group	To be developed.	N/A	N/A

[1]To be determined by preceding feasibility study.
TBD = to be determined; N/A = not applicable.

For all the initiatives, WisDOT defined short (1- to 2-year) and long (beyond 2-year) goals. Also, WisDOT identified the relationships and dependencies among initiatives as shown in figure 36, which was key for efficient and successful implementation of 3D technologies.

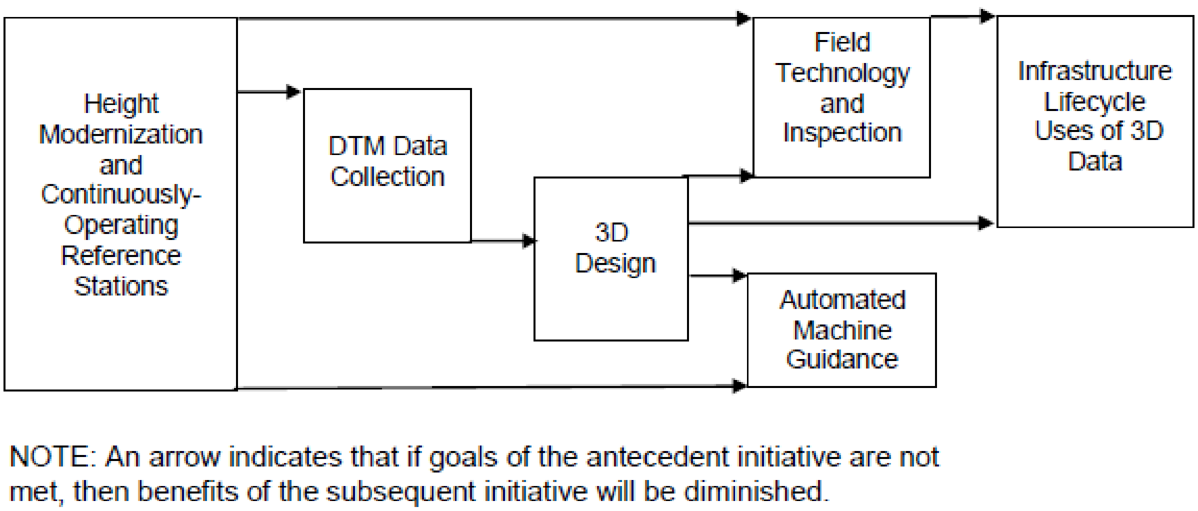


Figure 36. Flowchart. WisDOT 3D initiatives dependency diagram.[17]

WisDOT's 3D technologies implementation plan was updated/extended in 2013 based on the progress made since 2009. The updated plan consisted of the following eight initiatives, which included LiDAR, utilities, 3D design, inspection for WisDOT's megaprojects (Southeast Freeways Program), and IT infrastructure:

- Height Modernization Program (Passive and Active Networks).
- LiDAR and Digital Mapping Data Acquisition.
- Statewide 3D Design Process.
  - Southeast Freeways 3D Design Process.
- AMG.
- Southeast Freeways Field Technology and Inspection.
- Utilities.
- Roadway Lifecycle Uses of LiDAR Data.
- Information Technology Infrastructure.

ODOT

ODOT's automation technology implementation plan was presented by Singh in *Engineering Automation: Key Concepts for a 25-Year Time Horizon.*[(35)] This document discussed the development of long- and short-term plans for engineering automation at ODOT. Key concepts for engineering automation throughout highway project phases (surveying, design, and construction) and their connectivity were discussed. The document proposed short-term implementation plans for the different concepts. One of the 24 key concepts discussed was construction automation, which was essentially the same concept addressed throughout this report—automation in highway construction. Singh illustrated how construction automation and other concepts, such as remote sensing, 3D design, and underground utilities, were interconnected and how this interconnection should be considered for their successful implementation.[(35)]

Another key publication by ODOT was *Construction Machine Automation—Six Year Plan.*[(95)] This very concise plan outlined the following ODOT implementation steps (2009–2015) defined by the ODOT Machine Control Standards Committee:

2009–2011

1. Digitally signed Contract Plans and related documents.

2. Continued 2.5D design data—standardized and formatted to support this period's machine control and survey stakeout goals.

3. Digital "Engineering Data" available to contractor in stages as needed by their schedule.

4. Machine Control focused on roadway excavation and grading, and trench excavation for pipe installation.

5. Continue the concept of Contract Plans as "Primary" and Engineering Data Packet as "Secondary."

6. Construction surveyors available for high-precision positioning checks, stakeout, and Post-Construction Surveys.

7. Inspectors utilizing mobile devices to manage construction documentation—they would not have access to high-precision positioning tools.

8. Post-Construction Surveys (short list).

9. Designers, Drafters, Surveyors, and Inspectors trained to accomplish these goals.

2011–2013

1. True 3D design data (short list).

2. Design data should be on the new low-distortion Oregon Coordinate Reference System.

3. Digital "Engineering Data Packet" available to contractor upon Invitation to Bid (short list).

4. Redefine Engineering Data Packet as "Primary" and Contract Plans as "Secondary."

5. Revise Specifications to reflect changes.

6. Post-Construction Surveys (complete).

7. Designers, Drafters, Surveyors, and Inspectors trained to accomplish these goals.

2013–2015

1. 4D design data (3D design coupled with construction schedule).

2. Digital Engineering Data Packet to include all elements of construction.

3. Inspectors utilizing hand-held high-precision positioning tools with onboard design data for field verification.

4. Project Connected Site—wireless data hub.

5. Designers, Drafters, Surveyors, and Inspectors trained to accomplish these goals. (p. 2)[95]

CHAPTER 6. SUMMARY AND CONCLUSIONS

For this project, the team conducted an extensive, thorough literature search. The team also held a face-to-face meeting with WisDOT, followed by a series of conference calls and correspondence with Iowa DOT, MoDOT, and ODOT, which were lead State transportation departments for automation and 3D technologies. ALDOT and GDOT were at the beginning stages with automation and 3D technologies; nevertheless, they also shared information on some of their implementation efforts. The following bullets summarize the key findings:

- A number of automation technologies were reviewed, and the following list includes the key technologies that were being investigated and/or implemented by State transportation departments:
    - Remote Sensing.
        - LiDAR and 3D laser scanning systems.
    - Underground Utility Location Technology.
    - 3D Design.
    - Machine Control and Automation.
    - Field Technology and Inspection.
        - IC, GPR, infrared thermal profilers, real-time smoothness profilers, and concrete temperature and maturity meters.
        - Inspection tools: telematics, smartphones, tablets, etc.

- The main benefits provided by automation throughout the different highway project phases included time and cost savings and increased productivity, quality, and safety.

- The main challenges for implementation of automation included cost; lack of standards, specifications, and guidelines; need for specialized training; large volumes of data; and lack of data management tools.

- In general, most automation technologies were considered “disruptive” technologies that required training and revision of standards, specifications, and workflows. In addition, the different automation technologies required large investments/purchases, and strong cases must be made for procurement and implementation. Documentation of benefits, ROI, case studies, and draft specifications and guidelines were needed to assist with this task.(18)

- In addition, and as stated by Vonderohe and Hintz, “3D design, AMG, and other 3D technologies (LiDAR, RTK GPS, etc.) have individual merit that could be used to make cases for individual adoption. However, synergistic benefits and broader support for agency mission and goals can be expected if they are viewed as interrelated components of a larger whole that needs not only understanding but also advocacy at multiple levels in multiple business areas.” (pp. 57–58)(38)

The following bullets summarize the general experiences of State transportation departments when implementing automation technology at an agency level:

- In most agencies, automation and 3D technologies implementation started with contractors using AMG and approaching senior management at State transportation departments for support. Some of these efforts dated back to 2000–2004. The majority of the transportation agencies began working with chapters of the AGC to address this topic.

- Upper management support was critical for successful implementation. One of the lead State transportation departments, WisDOT, reported that a key for its success has been that its upper management has understood the difficulty in quantifying the costs and benefits of 3D technologies and has been willing to consider implementation of 3D technologies on a qualitative basis.

- Some State transportation departments have begun automation and 3D technologies implementation without following a formal written implementation plan. For example, action teams have been created internally at the agencies for the different areas/ technologies. Those teams also worked with industry representatives to determine the needs and solutions.

- Performance-based specifications facilitated the implementation of automation and 3D technologies because the desired outcome was specified and not the technology to be used.

The following bullets are the lessons learned from early adopter State transportation departments and recommendations to agencies now starting to evaluate and implement automation and 3D technologies:

- **Review the agency's existing workflows and determine how those need to be transformed to implement automation and 3D technologies instead of trying to outline new ones.** For example, work with industry representatives (e.g., AGC) to determine whether providing digital/3D data currently available at the agency, not necessarily the complete 3D model, would be useful for contractors.

- **Staff training is one of the main challenges, especially for 3D design and field inspection.** How training would be done would depend on whether the design process was centralized at the agency headquarter offices or decentralized at the district level. If centralized, transition to new methods and technologies could be handled by specific projects. In the case of a decentralized process, the transition could be staged per district. In both cases, the organization should start training small groups and then move to the entire office/district. In addition, the organization should set policies after training is completed (e.g., "after 20XX letting date, all projects will use X automation technology," or "X type projects").

- **Draft at least a brief implementation plan identifying the main initiatives and corresponding steps, champions (which translates into accountability), and deadlines.** The implementation plan needs to be updated/reviewed continuously.

- **Work with industry and equipment manufacturers/vendors and conduct periodic meetings to keep up with new technologies, applications, software, etc.**

Part II of this report presents design procedures and guidelines to properly generate 3D models for downstream uses in construction and other phases of highway project delivery.[(1)] In addition, Part II presents information on enabling technologies, policies, and implementation strategies for State transportation departments evaluating automation and 3D technologies.

APPENDIX. CASE STUDY: WISDOT SOUTHEAST FREEWAYS PROGRAM ZOO INTERCHANGE

As State transportation departments in the United States transition from 2D to 3D for design and construction, lead States have been outlining statewide automation and 3D technologies implementation plans to be able to produce robust 3D engineered models and effective 3D workflows that could be used for planning, design, construction, material fabrication/ procurement, visualization, scheduling, estimating, quantity tracking, as-built documentation, maintenance, and operations. This case study by WisDOT Southeast Freeways Program provides an overview of the functional use of automation and 3D technologies throughout the different milestones of the Zoo Interchange project in Milwaukee, WI.

BACKGROUND: 3D EFFORTS IN WISCONSIN

Similar to other State transportation departments, WisDOT began the transition from 2D to 3D design driven by design-construction needs for reduced costs, improved schedules, increased plan sets quality, and increased collaboration with consultants and contractors using 3D models by reengineering 3D surfaces from 2D plans in conjunction with AMG. WisDOT has been one of the few transportation agencies that has thoroughly documented and publicly published its efforts to implement automation and 3D technologies throughout the design, construction, and entire project lifecycle process.

From 2007 to 2009, WisDOT, including Roadway Design, Utilities, Bureau of Structures, Bureau of Traffic Operations, Real Estate, and Management, created its statewide plan for 3D technologies and methods for design and construction implementation.(17) In this statewide plan, WisDOT illustrated that 3D design was only part of a bigger picture in which 3D technologies are deployed from the planning/surveying phases through design to construction and to operations/maintenance. For all the 3D initiatives, WisDOT defined short- (1- to 2-year) and long- (3- to 5-year) term goals. Also importantly, WisDOT identified the relationships and dependencies among 3D initiatives as shown in figure 37, which were key for efficient and successful implementation of 3D technologies.

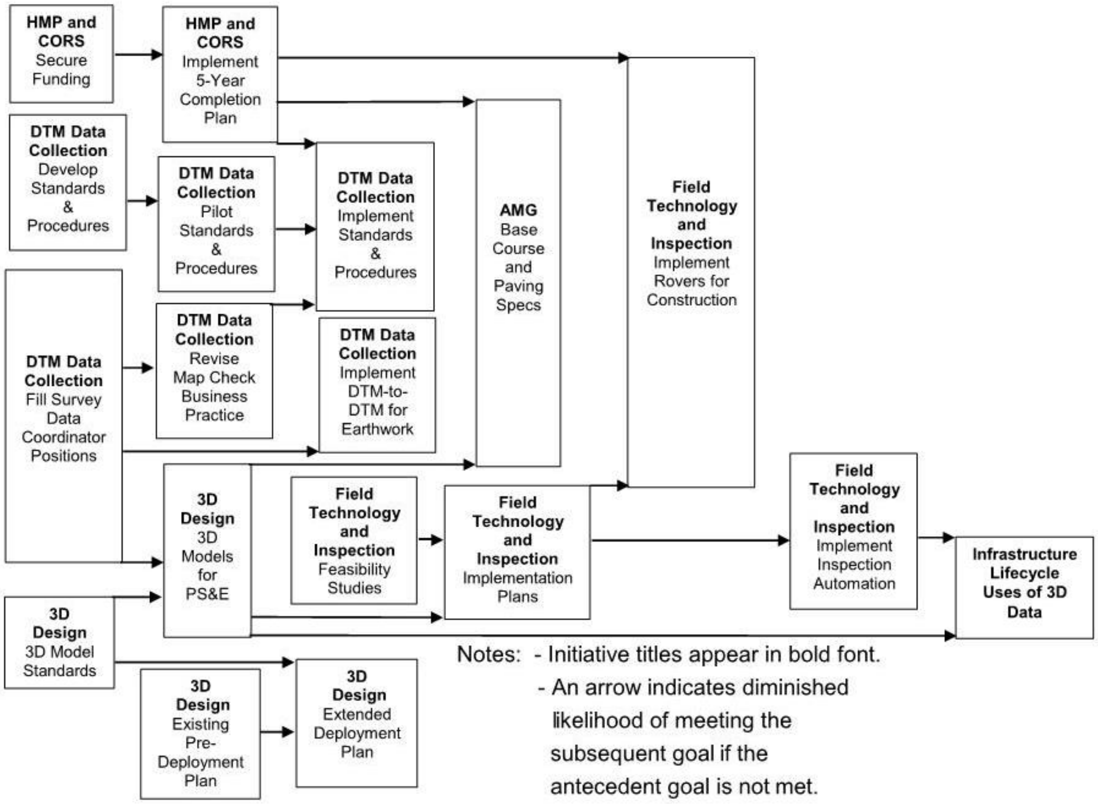


Figure 37. Flowchart. WisDOT summary of 3D initiatives.[17]

WisDOT's 3D Technologies Implementation Plan was updated in 2013 based on the progress made since 2009.[18] The updated plan consisted of the following eight initiatives:

- Survey Height Modernization Program (Passive and Active Networks).
- LiDAR and Digital Mapping Data Acquisition.
- 3D Design Process (Statewide and Southeast Freeways).
- AMG.
- Field Technology and Inspection (Southeast Freeways).
- Utilities.
- Roadway Lifecycle Uses of LiDAR Data.
- IT Infrastructure.

WisDOT functional areas created work plans to detail implementation tasks and steering teams to monitor and coordinate each 3D initiative.

WisDOT SOUTHEAST FREEWAYS PROGRAM AND AUTOMATION/3D TECHNOLOGIES

The Southeast Region of WisDOT has had some of the busiest highways in the State and, consequently, some of the largest and most complex megaprojects and major projects. The Southeast Freeways Program has included megaprojects such as the Zoo Interchange, I-94 North-South Corridor, and the I-94 E-W Stadium projects.

The implementation of automation technology, including all the 3D technologies referenced above, has been instrumental to meet the design and construction demands for the Southeast Freeways Program megaprojects. Challenges for deploying automation and 3D technologies at State transportation agencies have included cost, training, IT, and workforce functional areas acceptance; however, in this case, the separate budget for the Southeast Freeways Program megaprojects has facilitated the deployment. Collocation of design consultants within WisDOT Southeast Regional offices has allowed increased collaboration involving 3D technology workflows. This "regional" implementation of automation and 3D technologies by the Southeast Freeways Program on a project level has become standard operating procedure for all Southeast Freeways Program projects as statewide implementation efforts have continued for increased 3D technologies deployment.

ZOO INTERCHANGE PROJECT

Parve described the Zoo Interchange Project as follows: "The Zoo Interchange, located west of Milwaukee, forms the junction of I-94, I-894, and US 45. The Zoo Interchange is the busiest corridor in Wisconsin, with traffic volumes averaging 350,000 vehicles per day. The $1.7 billion project, which began in 2007 and is scheduled for completion in 2018, will implement operational, safety, and capacity improvements and reduce congestion throughout the corridor." (p. 3)[(47)]

This megaproject has involved work and reconstruction along 12 mi (19 km) of I-94, I-894, and US 45; 68 bridges and railroad structures; more than 100 retaining walls; noise walls; box culverts; and numerous sign structures and utilities.

SURVEYING

The use of automation technology for the Zoo Interchange began at the survey phase with 3D data collection using various survey methods, including LiDAR technology. Traditional WisDOT projects have involved photogrammetric surveys to create the existing surface DTM. However, for the Zoo Interchange megaproject, WisDOT used an integrated survey approach combining stationary and MLSs, aerial photogrammetry, and conventional methods (total station and GPS) to get increased accuracies and coverage for the existing surface and features. In addition, the use of static and MLS technology for roadways and structures provided significant time savings, reducing field data collection time from an estimated 9 months to approximately 3 months (i.e., 1 month for field data collection and 2 months for office data/digital map processing).

As shown in figure 38, the entire project was surveyed using fixed-wing aerial photogrammetry; MLS scanning was conducted along the main freeways, I-94, I-894, and US 45; stationary LiDAR scanning was conducted for most of the local streets and structures; and conventional surveying with total station and GPS was conducted at selected locations for supplemental purposes.

Figure 38. Illustration. Zoo Interchange integrated survey.(96)

WisDOT developed a specification to conduct the integrated survey work. The document covered survey control requirements, including high-accuracy targets (spaced at a minimum of 1,000 ft (304 m), desirable 500 ft (152 m)) to geometrically adjust the MLS data to project coordinates. Also, independent QA/QC checks were specified. Guidelines were provided for the LiDAR, supplemental conventional surveys, and associated deliverables, which included design-grade DTMs, 3D point clouds, georeferenced aligned imaging, and 3D feature lines to be extracted.

WisDOT has been working to address some of the challenges inherent to LiDAR technology. One of them has been disseminating the large volumes of LiDAR data, which, for now, has required shipping external hard drives. Another challenge has been data fusion for combining the different survey data methods, which has required expertise and different software tools to provide useful information to designers.

3D DESIGN/MODELING

WisDOT has been implementing comprehensive 3D designs for its Southeast Freeways region megaprojects. For the Zoo Interchange project, WisDOT has been developing robust multidisciplinary 3D models not only to support AMG but also to conduct clash detection analysis during design, produce design documents (2D plans), and create renderings and animations for public information and other construction applications.

The Zoo Interchange has been designed using a combination of Autodesk®'s Civil 3D® (internal WisDOT designers) and Bentley®'s MicroStation®/InRoads® (external consultants) with ultimate 3D model delivery in DWG and LandXML. WisDOT has completed the transition from MicroStation®/InRoads® and CAiCE™ (drafting and roadway design) to Civil 3D®, and MicroStation®/InRoads® files by consultants have been converted to Autodesk® DWG 3D and LandXML surfaces. Currently, all new projects designed by WisDOT (in-house and consultant) since 2014 have been completed using Civil 3D®. Such transitions have represented a major undertaking by State transportation departments, and WisDOT attributed its success to its commitment to cultural change and buy-in from management. Also, the development of the *Wisconsin Department of Transportation 3D Technologies Implementation Plan* helped trigger this transition to 3D.[18]

Parve explained that a methodology and workflow for sharing, editing, and validating 3D model files was critical to project success.[47] For the Zoo Interchange project, WisDOT developed CIM 3D requirements and a 3D project execution plan (PxP) for all 3D models supplementing the project PS&E. Also, a composite model of all stages was required, stage by stage, to illustrate separate stages of construction.

In the Zoo Interchange CIM requirements, WisDOT also specified 2D/3D Utility files providing information regarding existing/proposed/abandoned utilities. Because this information has come from a variety of sources (i.e., plans, hotlines, surveys, pot holing, GPR/SPAR, as-builts, etc.), WisDOT has provided the utilities data to contractors for information purposes only and has required them to confirm with the digger's hotline and utility providers.

The CIM requirements detailed in the Project Modeling Matrix (PMM) specified format, level of accuracy, level of development, staging, etc., for the 3D model components. A portion of the CIM PMM is shown in table 11 (adapted from a table on page 41 of the PMM).[97]

Table 11. A portion of the Zoo Interchange CIM project modeling matrix.[97]

Element	Format	LOA-CD	LOD-CD	Temporary	By Stage
R/W and Environmental Areas					
R/W-Proposed	DGN/DWG	0.01 ft	2D	N/A	N/A
Easements-Proposed	DGN/DWG	0.01 ft	2D	N/A	N/A
Fences-Proposed	DGN/DWG	<0.06 ft	2D	2D	N/A
Wetlands-Located/Surveyed-Existing	DGN/DWG	<0.06 ft	2D	N/A	N/A
Non-Roadway Surfaces					
Surfaces-Existing	DGN/DWG/XML	<0.06 ft	3D	N/A	N/A
Grading/Non-roadway Surfaces-Proposed	DGN/DWG/XML	<0.06 ft	3D	3D	Yes
Cut/Fill Areas-Isopachs-Proposed	DGN/DWG	<0.06 ft	2D	N/A	N/A
Longitudinal Breaklines/Surface Points	DGN/DWG	<0.06 ft	3D	N/A	N/A
Slope Intercepts/Surface Limits	DGN/DWG	<0.06 ft	2D	N/A	N/A
Roadways/Roadway Features Surfaces-Proposed					
Roadway Pavement-Top Surfaces-Proposed	DGN/DWG/XML	<0.02 ft	3D	3D	Yes
Roadway Pavement-Base Course Surfaces-Proposed	DGN/DWG/XML	<0.06 ft	3D	3D	Yes

R/W = right of way; LOA-CD = level of accuracy–contract documents; LOD–CD = level of development–contract documents; N/A = not applicable.

A PxP has been included as well as an outline of 3D model delivery milestones and 3D model specifications, including naming conventions, density, tolerances, line frequencies, file formats (LandXML v 1.2 and AutoCAD® Civil 3D® DWG), etc. The PxP is shown in figure 39, identifying project milestones for the design disciplines for 3D model deliveries.

Project Phases

Design Disciplines

Design Disciplines	30%/Functional	60%/Preliminary	90%/Final
Existing Ground	X		
Existing Utilities	X		
Existing Structures	X		
Proposed Roadway		X	
Proposed Bridges		X	
Proposed Retaining Walls		X	
Proposed Drainage		X	
Proposed Sign Structures			X
Proposed Lighting			X
Proposed Signals			X
Proposed FTMS			X
Proposed Utilities			X

Figure 39. Chart. Zoo Interchange PxP 3D model delivery schedule.[4]

WisDOT is creating 3D models of all bridges and structures, providing geometrics for the Zoo Interchange project, which has been useful for clash detection analysis. As one of its tools, WisDOT has used Bentley®'s LEAP® Bridge to create the 3D model of the bridge and then has imported a LandXML file into MicroStation® to combine with the rest of the 3D design model. Similar challenges may be faced when incorporating 3D standard details into the 3D design model.

DESIGN-CONSTRUCTION REVIEWS

For the Southeast Freeways Program megaprojects, including the Zoo Interchange, WisDOT has conducted periodic design-construction reviews in which construction and technical services staff have provided valuable feedback to designers. WisDOT has also met with industry representatives to get their feedback as well.

A critical part of the design-construction review process has consisted of clash detection review meetings following the 60- and 90-percent project submittals. Disciplines have provided their designs weekly in 3D, which have been incorporated into the 3D design model, and clash detection has been conducted twice—following 60 percent design after proposed utilities are entered and then at draft PS&E (90 percent design). A 3D file has been prepared to link/merge

[4]From unpublished presentation by C. Johnson, CH2M HILL, *Automation/Clash Detection*, FHWA Intelligent Construction System and Technologies Meeting at WisDOT, February 18, 2014, Milwaukee, WI.

plans for the different disciplines: utilities, roadway, structures (bridges, retaining walls, drainage), etc. Figure 39 shows when scheduling for clash detection is optimal according to the different disciplines. WisDOT staff explained that the key was not only to identify potential conflicts but to work to resolve them during the design phase and avoid conflicts during construction that would result in significant cost and time delays.

Parve reported ROI data involving 3D modeling for WisDOT Mitchell Interchange and Zoo Interchange megaprojects were promising based on the opportunity to reduce contract change orders.(47) A reduction in construction contract change orders could be realized using robust 3D models and, as of the date of this report (because the Zoo Interchange construction was still in progress), up to a 35-percent reduction has been observed in contract change orders. Parve also reported that opportunities for potential savings using robust comprehensive 3D models have occurred across the board, including drainage-wet utilities, dry utilities, roadways, structures, etc., in addition to grading and earthworks typically observed from use of AMG.(46)

3D CONSTRUCTION/MODELING

The use of automation and 3D technologies for the Zoo Interchange has continued through the construction phase with the use of AMG, GPS rovers and tablet PCs for construction inspection, and e-Construction.

WisDOT has developed AMG and associated 3D specifications for subgrade and base course construction following a very collaborative process involving contractors, advisory groups and stakeholder workshops, pilot projects, etc. 3D proposed models and existing 3D models are provided pre-bid to contractors for all Southeast Freeways Program projects with improved AMG utilization corresponding with available 3D surfaces. WisDOT is also developing AMG specifications for paving work with 3D models for contractors.

As for inspection, WisDOT has been employing tools such as GPS rovers and tablet PCs to use 3D models in the field and connect construction managers and field personnel with design information and 3D surfaces and features. Construction inspectors have been better able to verify that contractors were complying with plans and specifications, performing image capture for issues tracking, and keeping project records. For the Zoo Interchange, WisDOT has been implementing the use of tablet PCs to access surface models supplementing 2D paper plans, sharing electronic records to supplement paper forms, and using GPS survey equipment to check grades, etc. WisDOT has been providing Wi-Fi-enabled Internet devices to enable wireless access in the field to support automation and 3D technologies.

CONCLUSIONS

This case study of the Zoo Interchange reconstruction megaproject illustrates the benefits of WisDOT Southeast Freeway Program’s implementation of automation and 3D technologies for design and construction, including improved visualization, plan reviews, constructability analysis, multidisciplinary analysis, and virtual clash detection resolution. WisDOT has acquired and been using robust automation and 3D technologies involving planning, surveying, design, and construction for the Zoo Interchange. Implementation of automation in challenging megaprojects such as the Zoo Interchange is a good example of the realization of significant automation and 3D technologies benefits.

The use of these technologies has provided time and cost savings and improved ROI, resulting in reduced contract change orders during construction of the Zoo Interchange. The WisDOT Southeast Freeways Program has also been developing guidelines, specifications, and best practices involving 3D technologies to assist other WisDOT regions and State agencies investigating the use of automation and 3D technologies. WisDOT, as a lead State transportation department involved in 3D technologies implementation, has also assisted FHWA in its nationwide EDC2 3D modeling initiatives.

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