Automation in Highway Construction Part II: Design Guidance and Guide Specification Manual

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Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

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 presents a description of the key automation technology areas and the associated benefits, challenges, and solutions.(1) Part II (this volume) 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.

While 3D design practices are common in State transportation departments, automation technology requires added detail in 3D design models to output data in a portable and durable format and also requires additional organization and description of the data. This report provides the accuracies needed for both survey control and topographic survey. It describes how construction specifications can incorporate practices to manage the use of automation technology in a manner to adapt to project characteristics and evolving technologies. It also describes how consistency in 3D data and survey methods provides for automated inspection tasks, especially acceptance and measurement processes, can enhance transparency, make inspectors available to observe construction, and enhance project safety. State transportation departments interested in developing 3D digital design for use in automation in highway construction would benefit from reading this volume.

Cheryl Allen Richter, P.E., Ph.D.
Director, Office of Infrastructure
Research and Development

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16. Abstract

Automation in highway construction includes an increasing 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 goal of automation in highway construction is to increase speed, efficiency, and/or safety during the construction process. This goal is in conjunction with components, processes, and software that assist in a more efficient construction system.

The primary objectives of this project were to (1) address gaps identified for implementing automation in highway construction and (2) 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 for each of the two objectives. Part I presents a description of the key automation technology areas and the associated benefits, challenges, and solutions.[1] Part II (this volume) presents an overview of enabling technologies and policies for automation in highway construction as well as implementation strategies. This volume also includes design procedures and practical guidelines to properly generate three-dimensional models for uses 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
5D	five-dimensional
AASHTO	American Association of State Highway and Transportation Officials
AMG	automated machine guidance
ASCE	American Society of Civil Engineers
ASCII	American Standard Code for Information Interchange
ATC	alternative technical concept
BIM	building information modeling
CAD	computer-aided design
CADD	computer-aided design and drafting
CIM	civil integrated management
CORS	continuously operating reference station
CPM	critical path method
DTM	digital terrain model
EDC	Every Day Counts
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FTP	File Transfer Protocol
GIS	geographic information system
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Iowa DOT	Iowa Department of Transportation
KYTC	Kentucky Transportation Cabinet
LiDAR	light detection and ranging
MDOT	Michigan Department of Transportation
MoDOT	Missouri Department of Transportation
NEPA	National Environmental Policy Act of 1969
NSRS	National Spatial Reference System
NYSDOT	New York State Department of Transportation

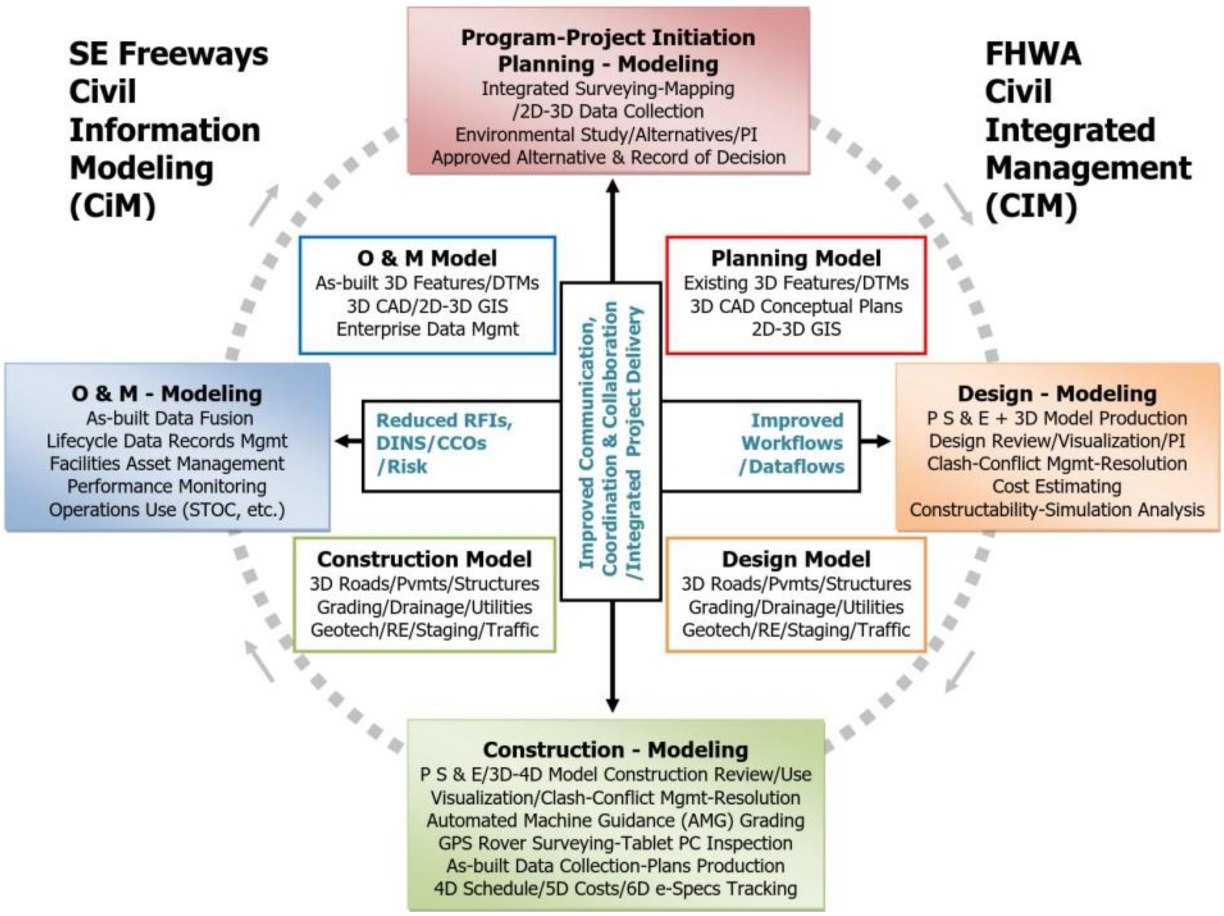
ODOT	Oregon Department of Transportation
OPUS	Online Positioning User Service (OPUS)
PDF	portable document format
QL-A	quality level A
QL-B	quality level B
QL-C	quality level C
QL-D	quality level D
QTO	quantity takeoff
RACI	Categorical scale where R stands for responsible to complete the work, A stands for accountable to ensure the task is complete, C stands for consulted before finalizing, and I stands for informed of the results
RAM	responsibility assignment matrix
RFID	radio frequency identification
ROW	right of way
RTK	real-time kinematic
RTN	real-time network
RTS	robotic total station
SHRP2	Second Strategic Highway Research Program
SUE	subsurface utility engineering
TIN	triangulated irregular network
UAV	unmanned aerial vehicle
UTM	universal transverse mercator
WBS	work breakdown structure
WisDOT	Wisconsin Department of Transportation
XML	extensive markup language

CHAPTER 1. INTRODUCTION

While no State transportation department has fully implemented an integrated automation technology solution programmatically, there are several examples of mature project-level implementations throughout the United States that form the backdrop for the guidance developed in this report. There was not an attempt to capture a nationwide perspective in this report. Instead, a collection of noteworthy practices gleaned as part of a number of in-motion parallel efforts were collected, including the Federal Highway Administration's (FHWA) Every Day Counts (EDC) technology deployment outreach, the American Association of State Highway and Transportation Officials (AASHTO) Domestic Scan Program, the National Cooperative Highway Research Program research on automated technologies, and State and regional conferences.(2) Documented sources of notable practice were sought to provide illustrative guidance and guide specifications including survey, design and computer-aided design and drafting (CADD) manuals, construction specifications, special provisions and special notes, construction manuals, training materials, conference proceedings, and implementation documents.

There are examples of projects that have taken an integrated approach to leverage a shared three-dimensional (3D) digital dataset for automating a range of highway construction applications like automated machine guidance (AMG), construction layout, and real-time field verification to accept completed work. These projects shared the cost of creating and maintaining the necessary data while realizing the full benefit of each individual automation application.

Figure 1, adapted from the Wisconsin Department of Transportation (WisDOT) Southeast Freeways civil integrated management (CIM) documentation, serves as a good example that illustrates how automation can be integrated into the various phases of the project for more efficient delivery.(3) The vision for automation in highway construction is that the necessary 3D engineered data can be shared among and across a multitude of automation technology uses that are applicable to each project. These automation technologies may include remote sensing survey techniques such as light detection and ranging (LiDAR), unmanned aerial vehicles (UAVs), 3D model-based design, four-dimensional (4D) and five-dimensional (5D) construction simulation, subsurface utility location technologies, AMG construction, electronic construction documents accessed via mobile devices (a part of e-Construction), and non-destructive methods for measuring and accepting construction (e.g., including ground-penetrating radar, paver-mounted thermal profiler, intelligent compaction, and real-time field verification with location-aware survey instruments).(4)



Source: ©Parve.
PI = Public involvement.
DTM = Digital terrain model.
GIS = Geographic information system.
CAD = Computer-aided design.
P S & E = Plans, specifications, and estimates.
RE = Resident engineer.
GPS = Global Positioning System.
SE = Southeast.
2D = Two-dimensional.
6D = Six-dimensional.
RFI = Request for information.
DINS = Design issue notices.
CCO = Contract change order.
O & M = Operations and maintenance.
STOC = State Transportation Operations Center.

Figure 1. Illustration. Integration of automation technology on the Southeast Freeways project.[3]

OBJECTIVE

The objectives of this project were to address challenges and opportunities identified for automation in highway construction from project development through construction and to develop guidance for State transportation departments to assist them in determining how best to use automation to improve effective and accelerated project delivery. Some automation applications may warrant programmatic implementation, while others may warrant use on a project-by-project basis. The study involved collecting, organizing, and analyzing data from various State transportation departments and other facility owners using automation technology.

Part I of this study relays implementation and success stories from transportation agencies on the use of automation.(1) This report, which is part II of this study, provides design guidance and accompanying guide specifications for highway agencies to successfully implement automation in highway construction. The guidance covers how to generate 3D digital design data for downstream uses in construction as well as provides information on how to manage the use of these data in construction.

SCOPE

The scope of this report does not imply a positive return on investment for implementing automation technology on all projects regardless of type, size, and range of construction activities. Further research is being conducted to make value judgements on where automation in highway construction is beneficial. This guidance is intended to be used after the decision to implement automation technology has been made. The scope is built on the premise that to be able to optimally use automation during the construction phase of a highway project, preparation begins during the planning, surveying, and design phases. The report is organized as follows:

- Chapter 2 describes the objectives and stakeholders involved in implementation, as well as affected policy areas, impacts on capital, and human resources and change instruments for implementing automation technology.
- Chapter 3 presents the various investments in enabling technologies and policies that a State transportation department needs to implement to reap the benefits of a coordinated approach to automation in highway construction.
- Chapter 4 presents implementation strategies used by agencies that have implemented mature (though not necessarily comprehensive) automation practices.
- Chapter 5 introduces the guidelines that follow in chapters 6 through 10.
- Chapter 6 describes the needs for capturing survey data prior to design.
- Chapter 7 introduces practices for subsurface utility locating.
- Chapter 8 describes design development to support the uses of 3D engineered data, including 4D and 5D models.
- Chapter 9 discusses guide specifications.
- Chapter 10 concludes the guidance with the use of 3D engineered data in construction by both the contractor and the owner.

- Chapter 11 discusses current successful automation technology integration and introduces future trends that should be planned for.

- Chapter 12 provides conclusions to the report.

GLOSSARY OF TERMS

The following glossary of terms is provided to aid in understanding the terms used in the following sections:

- **3D engineered model**: A 3D model of a roadway or related feature that is developed to the appropriate engineering precision to support construction applications.

- **3D solid primitives**: Solid 3D CAD objects that do not have any intelligence. They are based on regular 3D geometric shapes like cylinders and cubes. 3D solid primitives may be mathematically extracted from point clouds to represent pipes, bridge piers, bridge girders, utility poles, etc., in CAD objects that are easier to manipulate for clash detection or visualization.

- **4D model**: A simulation of how a facility changes over time, usually during construction. A 4D model is the product of connecting a 3D model to a schedule, introducing the fourth dimension of time.

- **5D model**: A simulation of how a facility changes over time where the related costs of those changes are included in the simulation. Usually, the changes involve construction, and the costs are incorporated in the schedule. The fifth dimension represents cost.

- **Absolute accuracy**: Also called "network accuracy," the level of accuracy in relation to a global coordinate system. In simple terms, it is the accuracy with which something can be located in the world.

- **AMG**: Use of survey-grade position sensors and on-board computers to guide an operator or control the hydraulics of construction equipment.

- **Classification**: The process by which software sorts LiDAR data points into categories based on predefined rules. Predefined categories include ground, vegetation, noise, and water.

- **Corridor model**: A method of modeling linear designs in CADD. The corridor combines horizontal and vertical alignments, super-elevation definitions, and a parametric cross-section definition with a DTM surface to create a 3D approximation of the design concept. The corridor model can output DTMs of proposed surfaces like subgrade for use in AMG.

- **Continuously Operating Reference Station (CORS)**: Continuously operating Global Navigation Satellite System (GNSS) receivers in a fixed location that compute and broadcast a position correction for use in real-time kinematic (RTK) GNSS applications.

- **DTM**: A digital topographic model of specific area of a ground surface minus objects such as trees, vegetation, and structures that can be manipulated through CAD programs. All elements of the DTM are spatially related to one another in 3D represented as a network of triangular or polygonal faces. DTMs for design and construction commonly use a triangulated irregular network (TIN).

- **Geospatial data**: 2D or 3D data that are spatially referenced by being projected onto a mapping coordinate system such as a State Plane Coordinate System.

- **GNSS**: A system of navigation that uses a global network of satellites to provide autonomous geospatial positioning. The network of satellites includes the U.S. GPS and Russia's GNSS and will include China's BeiDou and Europe's Galileo.

- **GPS**: A subset of GNSS comprising the satellites owned by the United States. It is often used colloquially to refer to GNSS as a whole.

- **LandXML**: A data exchange format based on extensive markup language (XML) for horizontal construction data that provides support for surface, alignment, cross section, pipe network, and point data types.

- **LiDAR**: A remote sensing survey method. A sensor sends a pulse of light and measures the returning beam to define the position of the remote object that reflected the beam of light. The LiDAR sensor may be mounted on a tripod (static LiDAR), mounted on a vehicle and in-motion (mobile LiDAR), or mounted on an aerial vehicle such as an airplane or helicopter (aerial LiDAR).

- **Local accuracy**: Also called "relative accuracy," the accuracy of the position of a point in relation to other points in the dataset. Local accuracy may exceed absolute (or network) accuracy for a particular dataset. Local accuracy is a consideration for measuring depths or lengths or areas, which are unrelated to the geospatial location of the features.

- **Metadata**: A description of the basis of the data, typically survey data, but may relate to any 3D data. Metadata usually includes the definition of the horizontal and vertical datums that relate 3D coordinate data to a physical location on the surface of the Earth.

- **National Spatial Reference System (NSRS)**: A consistent coordinate system used throughout the United States. NSRS defines latitude, longitude, height, scale, gravity, and orientation.

- **Point cloud**: A collection of data points, often collected with remote sensing methods like LiDAR, that is so dense as to define the whole scene. Point clouds often contain hundreds of thousands of points and may have a point density greater than 1 point/inch.

- **Point density**: The number of survey data points per unit area. This may relate to field survey points or points within a point cloud generated by remote sensing methods such as LiDAR.

- **Remote sensing**: A survey method that obtains information about the position of objects without coming into contact with the object. LiDAR and photogrammetry are examples of remote sensing methods.

- **Resolution**: The degree of detail that is provided in a 3D dataset. For a DTM, resolution is a product of point density and absolute accuracy.

- **Robotic total station (RTS)**: A total station that automatically tracks the target and is controlled from a distance by a remote control (usually the data collector attached to the target).

- **RTK**: A method of correcting systemic errors in a GNSS position created by atmospheric perturbations. An RTK unit receives both a GNSS position and a correction and applies both in real-time to determine position. The correction is calculated and broadcast by base station of known position.

- **Real-time network (RTN)**: A similar concept to RTK, but instead of receiving the position correction from a defined physical station, the correction comes from a virtual reference station. The correction from the virtual reference station is computed using position corrections from a network of physical stations.

- **Rover**: A mobile survey instrument with a data collector that allows the operator to determine position in real time. The survey instrument may be an RTK GNSS receiver, a combination RTK GNSS receiver and laser receiver, or a target for an RTS.

- **Site calibration**: Also called "site localization." A survey technique by which design grid coordinates are translated into coordinates on the ground with scaled distances. A site calibration/localization computes a rotation and scale factor for horizontal layout and creates a vertical datum.

- **Template**: A parametric CADD object that defines the cross-sectional shape of an object. The template is extruded along a line in 3D space to create a 3D model. In corridor modeling, the parametric relationships in the template are calculated at defined template drop locations. In corridor models, the density of template drops defines the resolution of the 3D model.

- **TIN**: A type of DTM created by applying an algorithm (usually the Delaunay triangulation) to connect irregularly spaced points into triangular faces. TINs are usually used to define elevation surfaces for CADD and AMG.

CHAPTER 2. DEVELOPMENT OF AUTOMATION TECHNOLOGY GUIDELINES

The rapidly evolving nature of technology advancements makes it an enormous task for implementing agencies to update standards, policies, and specifications and train their personnel to accommodate new technologies. The solution and challenge that implementing agencies must grapple with is to introduce agnostic, performance-based guidelines that are sufficiently flexible to adapt to change. This is a significant undertaking.

Developing guidelines for the specific automation technologies identified in part I requires making refinements to a broad range of policies, standards, and specifications as well as acquiring a body of knowledge that reaches far beyond any one individual or organization. There are significant enabling technologies and policies and staff training that must precede the use of automation in highway construction.

Though the magnitude has not yet been quantified by project type, delivery method, construction activities, duration, or other factors, it is anticipated that automation in highway construction provides a number of efficiency, safety, and time-saving benefits. Upfront investment may be large, but incremental progress should yield positive results. Ultimately, a coordinated, performance-based approach to agency business should provide a flexible approach to maintaining a highway system in an environment that supports innovation. This would allow the selective use of automation technologies appropriate to individual project characteristics. Figure 2 outlines the workflow for incrementally modifying guidelines to support automation.

Source: FHWA.

Figure 2. Flowchart. Developing automation technology guidelines.

OBJECTIVES

New technology is replacing less efficient technology and workflows in design as well as less safe and less efficient practices in construction. However, policies to manage due diligence and practices to equitably allocate and manage risk in the age of automation are not keeping pace with these new technologies. While there is strong hypothetical bias and optimism for the positive impact of automation in highway construction on safety, efficiency, and construction outcomes, there is not much documented return on investment or business case analysis to guide investment in any one area before another.

Construction documents have not materially changed over the years. Automation in highway construction has data needs that are not supported by paper plans or by the processes and methods to develop those paper plans. The breadth of policy and practice touched by automation implementation is broad, from detailed nuances of topographic survey accuracy thresholds, to retrieving as-built data from construction equipment, to processing 3D data with hardware and software to measure pay quantities and accept work.

The breadth of automation technology integration means that practical and actionable implementation requires some focus on deliberate objectives. There are some logical preemptive investments, identified as enabling technologies and policies, which are described in chapter 4. In terms of a comprehensive strategy for automation in highway construction, the first necessary step for an agency is to define short-, medium-, and long-term objectives for automation technology implementation.

As a leading State, Wisconsin began with a process to define the impact that delivering 3D digital design data to contractors would have on institutional and legal issues as well as determining relevant design and construction work processes. After conducting a stakeholder consultation, the objectives were broadened to 3D technologies in general.(5)

The Michigan Department of Transportation (MDOT) began with broad objectives for automation and noted anticipated benefits to using 3D engineered models and electronic data.(6) In its *Development Guide*, these benefits are noted to arise from the following:(7)

- More accuracy and data intelligence used in electronic design documents.
- More accessible visualization available during the design process.
- Enhanced ability to detect and mitigating clashes.
- Greater ease of data migration from survey to design to construction.
- Easier realization of the design intent during construction.
- Better construction quality outcomes.
- More accurate and more consumable digital as-built records.
- Digital data that are preserved in an accessible format for future use.

By contrast, Oregon Department of Transportation's (ODOT) original implementation impetus had a narrower focus. ODOT's contractors were noted to be using AMG in an effort to reduce construction costs. It was recognized that ODOT used software and processes that could produce the necessary data for AMG operations, but there was a lack of clear guidance and consistency in the timing and nature of 3D digital data provided to its contractors.(8)

STAKEHOLDERS

In order to develop practical and implementable policies and processes, agencies should consult with affected stakeholders with strong technical and institutional knowledge. One of the challenges to implementing guidelines for automation in highway construction is that the changes necessary to support automation technology often need to occur prior to the construction phase. While it can be empowering to the designers to lead the change, they need information on the requirements for construction or the changes will not be effective. Table 1 provides a list of potential stakeholders to an automation implementation and their role in the process.

Table 1. Stakeholders in automation in highway construction implementation.

Stakeholder	Consultation Role
Survey	Topographic survey and construction oversight
Design	CADD automation, 3D model reviews, design/constructability reviews, contract documents, processing survey/CADD data for construction engineering, and inspection
Contracts	Contract and bid documents
Construction	Constructability reviews, field survey methods for measurement/ inspection, and specifications
Information technology	Planning and specifying of new information technology resources to support networked, mobile field inspection tools and new computer hardware, software and storage capacity for survey, and design and contract management
Contractors	Topographic survey requirements, 3D data requirements, impact of specifications on safety and efficiency, as-built data from AMG, and field survey methods for measuring and checking work
Consultants	Impact of new guidelines on business and reasonable timeline for change and lessons learned from design-build experience
Local public agencies	Impact of new guidelines on business and reasonable timeline for change
Small businesses	Impact of new guidelines on business and reasonable timeline for change
Disadvantaged business entities	Impact of new guidelines on business and reasonable timeline for change
State licensing boards	Laws for digital signatures and digital seals

Contractor association advocacy has helped to identify contractor needs and make a case for augmenting contract documents with 3D digital design data. Many design automation departments have made changes to the way 3D data are used in design and shared prior to bid. Construction specifications have been modified or special provisions have been created to allow optional AMG construction with reduced staking and some obligations to provide equipment and training. Construction engineers and inspectors are beginning to develop digital methods for construction oversight. Some State transportation departments have created special provisions to enable contractors using AMG to provide equipment and training for inspectors. This has left most State construction departments in a reactive position for implementing automation via digital 3D data-driven workflows for measurement and acceptance. With more consultation with construction surveyors, broader usage cases may be identified for real-time field verification processes for measurement and acceptance.(9)

There has been much focus on the 3D digital design data upon which many automation technologies rely, but many automation processes also rely heavily on survey equipment and methods. While construction surveying is typically not a licensed practice, there is a very important role for surveyors to play in planning and implementing automation policies and guidelines.[10] Contractors are important partners because they have the most experience with automation and have been using automation technology at risk. Consequently, many contractors have implemented procedures internally that optimally balance the cost of data acquisition and preparation with the benefits of efficient, high-yield operations.

POLICY AREAS

A number of current policies and specifications, which are unique to each State transportation department, can be revised to accommodate automation in highway construction. These changes can be managed within the current policy framework. With two notable exceptions, the changes are within the control of the State transportation departments. The two exceptions are laws governing use of digital signatures and digital seals on engineering contract documents, both of which are usually controlled by State licensing boards.

As the primary sources of policy for digital data, States' survey, design, and CADD manuals could be modified to include provisions for creating and delivering the 3D data that automation technologies need. Many States have a construction manual that provides guidance to construction managers and inspectors in conducting their activities. Recommended modifications to manuals are shown in table 2.

Table 2. Recommended modifications to manuals.

Manual Type	Recommended Adaptation
Survey (see chapter 6)	• Considerations for establishing site control. • Inclusion of metadata. • Accuracy tolerances for topographic surveying. • Use of remote sensing. • Non-traditional survey products.
Design (see chapters 7 and 8)	• Subsurface utility locating technologies. • Potential applications of 3D models in design development. • Possible revisions to standard details. • Creation of a 3D model standard. • Creation of 4D and 5D model specifications. • Implementation of 3D data review protocols. • Processes for creating contract documents and bid reference documents.
CADD (see chapter 8)	• A 3D model guide specification that defines standards for creating and managing 3D models, in addition to standards for the outputs from 3D models. • 3D data review protocols.
Construction (see chapter 10)	• Construction data management. • Low accuracy positioning. • High accuracy positioning. • Automation processes for construction engineering and inspection.

Corridor models are an effective way to model for AMG equipment because the broad brush of a 15-ft-long blade can be replicated digitally with a corridor template. When combining implementation of automation in highway construction with a desire that design data be used directly by contractors and inspectors, there is an opportunity to revisit standard details to determine if changes could provide efficiencies in modeling and construction. Specific areas that may be affected are introduced in the Considerations for Standard Details section in chapter 8.

As construction methods change rapidly with evolving automation technology, new document and data types have been introduced that do not have contract language to manage them. Automation technology implementation provides an opportunity to review, measure, and accept work based on digital objective evidence.

There are guide specifications for accommodating automation in highway construction with modifications to the following typical sections in an agency's standard specifications:

- Controlling Work: Plans and Working Drawings.
- Controlling Work: Conformance with Plans and Specifications.
- Controlling Work: Construction Stakes, Lines, and Grades.
- Controlling Work: Inspection of Work.
- Controlling Work: Quality Control Plan.
- Measurement and Payment.
- Earthwork, Fine Grading, Base Course, and Paving.

CAPITAL AND HUMAN RESOURCES INVESTMENTS

Automation in highway construction creates a paradigm where skilled professionals execute their work in a streamlined, digital environment that replaces manual tasks with automation. Some of the benefits of automation include fewer workers exposed to heavy equipment or less time to execute inspection tasks.[10] However, automation in highway construction is not perceived as an opportunity to reduce the construction workforce. Rather, it is an opportunity to produce better construction outcomes by introducing processes that allow inspectors to document as they inspect and spend more time observing construction. This involves investing in people to create a highly skilled workforce that makes use of sophisticated hardware and software.

Hardware

Hardware may be needed in survey, design, or construction offices; however, it is less common that survey and design hardware need upgrading. Provision of equipment and training for construction field staff can be managed in a variety of ways. An agency may purchase or lease equipment, or the contractor may furnish equipment for the duration of construction.[9] The latter may be attractive because it takes procurement out of a capital budget. However, when furnishing the equipment is a line item in a bid for optional use of automation technology, contractors may consider this detrimental to their ability to be competitive and may be a disincentive to the use of automation.

Software

Investment in software goes beyond the cost of the software licenses and support agreements. Most agencies have invested in software standardization and CADD automation to provide consistency in datasets and efficient data creation. With new software comes the cost of creating new standards and new automation tools. There is also a cost associated with migrating or accessing legacy datasets.

New software may be needed for survey, design, and construction staff to support automation in highway construction. Software used to manipulate and process LiDAR data is rapidly evolving. Many agencies are in the process of evaluating or updating their CADD software for design. There may be a need for new CADD software licenses for construction staff to use onsite. Construction staff may wish to review the contractor's AMG models, create staking data, evaluate potential design revisions, or process as-built survey data to measure or accept completed work. CADD software used by the survey and design office may fulfill these purposes, or construction software may be a better fit.

Changing Job Functions

Until recently, construction surveyors set the stakes and hubs that translated information on construction plans into a format that was interpreted on the ground in a consistent manner by the contractor and inspector. Automation technology is used to perform site layout in real time using position sensors and an on-board computer or handheld data collector. This places the site layout in the hands of the equipment operators and inspectors who usually are not surveyors. It also removes physical layout markers and separates how and when the contractor and inspector interpret the plans on the ground using surveying equipment. Consequently, the adoption of automation in highway construction requires a broader understanding of survey methods.

With automation technology, construction surveyors have a changing role, from pounding stakes and hubs to providing oversight. By contrast, preconstruction job functions are not materially affected. Surveyors have new considerations for control and topographic survey accuracy. Designers need to add more detail, document designs in new digital formats and data types, and create protocols to review the digital data. Contract officers need to ensure that contract language and specifications adequately address the use of digital data in construction.

Training Needs

The goal of automation in highway construction is to develop new workflows that replace laborious manual processes. As a consequence, the training needs created by automation technology implementation are vast. The need for training is one of the most often cited barriers to implementation. There are different levels of training that are needed at different times. For example, webinars or short presentations can raise awareness by disseminating information, but they often do not advance implementation. Many agencies have found that hands-on training in new methods and processes can be delivered in the classroom or online to advance implementation of automation in highway construction.(9)

An integrated automation technology implementation affects surveyors and designers who typically are not involved in construction. Overview training of how the changes imposed upon them improve outcomes in construction can be beneficial. Some States have provided this through outreach to stakeholders at annual consultant or contractor association training conferences. The Florida Department of Transportation (FDOT) hosts an annual design expo where there have been many of such sessions; the archive of presentations is available online.[11]

Once new policies, specifications, or standards are created, they need to be implemented. Some changes may affect how people do their jobs. Practical hands-on training needs are greatest in 3D design and CADD automation, as well as in methods for performing real-time verification.[10] Just-in-time training has been found to be most effective for hands-on training in workflows or new software tools.[9] Training in survey principles and real-time verification methods can be provided to construction field staff through a special provision or specification. This option is described in the guide specifications in chapter 9.

CHAPTER 3. IMPLEMENTATION STRATEGIES

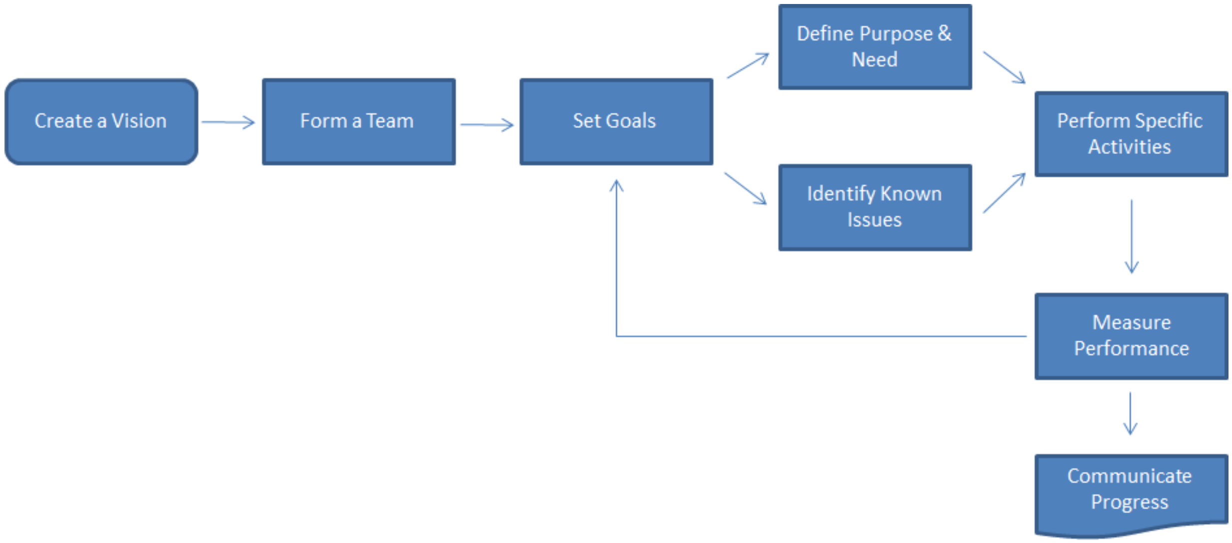
The culture at an implementing agency will affect the way in which automation in highway construction will be mainstreamed. For example, State transportation departments have different methods in implementing automation technology; some have adopted a formal, agency-wide implementation plan, while others implement it on a project-by-project basis based on resources and interest at the regional/local levels. Some agencies have successfully advanced the use of automation technologies without a formal implementation plan. The common method transportation agencies use to rapidly implement automation is through a small team with decisionmaking power and executive sponsorship.

The need to explicitly quantify the benefits of implementing 3D models and their related automation technology uses before any investments are made to change the traditional business practices would be a significant challenge. A majority of the cost overruns associated with the traditional project delivery processes are accrued in the construction phase in the form of errors, omissions, inaccurate quantities, unresolved transitions that need to be field fit, and in the perpetuation of construction methods and inspection protocols that could be made safer and more effective. However, the investments to realize the benefits of automation must be made in the project scoping and design phase through accurate survey and 3D model development that facilitates better construction. The implementation of automation in highway construction should be viewed in a holistic manner and should include costs and benefits spread across all project phases at a programmatic level to leverage the cost efficiencies associated with targeting a program of projects rather than a single project.

Implementing enabling technologies and policies to create 3D data during design is a necessary first step to achieving automation in highway construction and can be managed within a design or a design automation department. Putting the 3D data to work in the field (and post-construction) takes a coordinated effort from multiple departments. Input from the range of stakeholders identified in the Stakeholders section in chapter 2 is important to facilitate the implementation of automation technologies throughout the different phases of highway projects.

FORMAL IMPLEMENTATION PLANS

One recommendation to mainstream automation in highway construction is to create a formal implementation plan. An implementation plan recognizes the actions to consider, identifies the various internal and external stakeholders, and facilitates the broad collaboration required to achieve the end result. Writing the plan is only part of the journey; executing the plan is where the majority of the effort occurs. The implementation plan should provide a structured approach to mainstreaming automation, create a clear purpose for implementation, set goals, establish criteria for success, and provide input from people with multiple perspectives to identify opportunities for success and plan to overcome obstacles. Figure 3 is a sample flowchart for the implementation process.



Source: FHWA.

Figure 3. Flowchart. Implementation process.

As shown in figure 3, common elements of an implementation plan include the following:

- **Create a vision:** The vision for the future post-implementation should provide a broad message that unifies the organization in support of the plan.
- **Form a team:** Team members should be responsible and accountable. They should be consulted and informed of activities in the plan. Team members will do the work and will be affected by the consequences of implementation tasks.
- **Set goals:** Goals are outcomes that are intended by the implementation. They should align with the agency or organization's strategic goals.
- **Define the purpose and need:** The purpose and need establish a logical case for why change is needed. This helps to secure executive sponsorship and funding for the implementation.
- **Identify known issues**: Known issues need to be identified that may provide obstacles to the implementation.
- **Perform specific activities**: These activities should describe the steps taken to implement the plan. Activities should be specific, measurable, achievable, realistic, and time-bound.
- **Measure performance**: Performance measures track the progress of implementation. When the activities are measureable and time-bound, then tracking completion of activities provides the data necessary for performance measures.
- **Communicate progress**: Reporting performance measures communicates progress and helps to maintain momentum and support for the implementation.(12)

NOTABLE IMPLEMENTATION STRATEGIES

Over the past several years, many State transportation departments have made significant progress in building capabilities in enabling technologies and policies and extending their support for automation in highway construction. Some of them have used formal implementation planning strategies. Notable, successful practices from those plans are described in the following subsections.

Establishing a Vision

Automation in highway construction is part of the greater CIM strategy that is the subject of ongoing consideration and much research.[13] CIM represents a global shift to digital, data-centric practices in developing and managing infrastructure assets. Creating a vision that places automation in the context of other related digital advancements is a strategy that has been used by a few State transportation departments, such as WisDOT and ODOT.[14,15]

For some State highway departments, the future of many automation and enabling technologies has been communicated under the umbrella of “engineering automation,” which is a term widely used by ODOT.[15] This is consistent with the philosophy of CIM. Another approach is to focus on seamless data flows and data lifecycles.[6,14] This uses a customer-focused view of data collection and creation, keeping in mind immediate data uses and potential uses in the future.

Defining a Purpose and Need

A purpose and need statement does not have to be a business case. Instead, it can be more persuasive if it includes objective measures of the benefits and costs involved in implementing automation technology. One approach is to provide a purpose and need for individual initiatives or activities rather than supporting the whole vision statement.[14] The purpose and need for implementation should be documented to define how the proposed change solves a problem or improves outcomes.

A common starting point for implementing automation technology has been to support AMG by implementing 3D design processes, as was the case in Wisconsin, Michigan, and Oregon.[16,6,8] These implementation documents note current practices, new developments, and a description of how the proposed change solves problems or improve outcomes. The purpose and need statements vary in length, detail, and the extent to which they cite quantitative substantiation.

Identifying Known Issues

Analyzing the current state of the practice and identifying issues that may hamper implementation can be instructive for setting achievable time limits on goals, identifying members of the implementation or stakeholder teams, and developing specific activities that drive implementation forward. Issues should be brainstormed to craft actionable next steps that are achievable. Commonly known issues for different automation and enabling technologies include the following:

- Training needs.
- Need for new software or hardware.
- Need to extend, modify, or create standards or specifications.
- Policies that impede adopting new practices.
- Concerns of the impact of change on small and previously disadvantaged businesses.
- New job functions that do not fit with established job descriptions.
- A lack of clear understanding of the impact of the proposed changes.

Implementation Goals

Building on lessons learned and resources developed by other agencies significantly reduces the time needed to implement automation in highway construction. The original ODOT vision document provides a 25-year vision for implementing a variety of automation technologies.(15) The subsequent *Construction Machine Automation Six Year Plan* laid out a 6-year plan for implementation, but that proved too ambitious to meet all the stated goals.(17) Changing policies, deploying new policies, and training staff to implement new ways of working requires a significant, multiyear investment. ODOT successfully implemented 3D roadway design over a 3-year period.(8) That involved building on current practices, defining standards, producing a tech bulletin to modify policies, and introducing a 1-year implementation period before the new requirements for 3D roadway design became mandatory.(9)

WisDOT began exploring how to support AMG in 2007 and expanded to a broad 3D technologies implementation plan in 2009.(16,5) The original plan included 6 initiatives with a combined total of 26 prioritized goals between them.(5) All six initiatives were refined to reflect significant progress and were carried over to the 2013 update, where two more were added.(14) The updated plan separates goals into short-term (1–2 years) and long-term (2 or more years) horizons. There were an average of eight short-term goals and four long-term goals for each initiative.

The Utah Department of Transportation (UDOT) began their implementation planning in early 2014 and was able to build on lessons learned and resources developed by other agencies. The timeline for implementing the vision for advertising and constructing projects using electronic plan sets utilizing 3D CAD modeling software was nearly 3 years. The UDOT implementation plan was divided into a short-term plan (May–December 2014), a mid-range plan (2015 calendar year), and a long-range plan (2016 calendar year).(18) The short-term plan focused on quick wins and conducting research into capturing lessons learned. The mid-range plan activities were to create interim policies, deliver training, and conduct outreach with stakeholders. The long-range plan goals were not clearly defined but rather focused on being responsive to challenges identified in the short-term and mid-range plan activities.(18)

Establishing an Implementation Team

An implementation team should include those who determine how to implement automation in highway construction and those who are directly affected by the change. This includes surveyors, designers, construction engineers, and inspectors. Responsibility assignment matrices (RAMs) are a useful tool to clearly define responsibilities for implementation tasks. Oregon created a 3D Roadway Design Committee with six primary members, five alternates, six representatives from other committees, and seven individuals who sponsored the committee or served as advisors.(8) The RAM responsibilities for each task used the RACI categories, which is defined as follows:

- **R** = Responsible to complete the work.
- **A** = Accountable to ensure the task is completed.
- **C** = Consulted before finalizing.
- **I** = Informed of the results.

It is notable that the approach by the ODOT 3D Roadway Design Committee was to place responsibility for defining how 3D design data would be developed and delivered in the hands of roadway designers. The consumers of this data (i.e., surveyors and construction personnel) were consulted on the process, but those affected by the change in design procedures were empowered to manage it.(8)

In establishing their implementation team, UDOT identified a committee chair, an assistant chair, and five discipline leads. The five disciplines were preconstruction, construction, survey, training, and technology. Two executive sponsors were identified, and external stakeholders who were a part of the short-term plan activities included consultant and contractor associations, equipment and software vendors, and contractors and consultants with experience on specific projects.(18) UDOT also used a RAM to assign responsibilities for implementation tasks. The RAM used by UDOT assigned responsibilities using the PLANS categories, which is defined as follows:

- **P** = Primary person to complete the work.
- **L** = Learns results of task.
- **A** = Accountable to ensure task is complete.
- **N** = Needs to be consulted.
- **S** = Shared completion of work.

Specific Activities

Specific activities are performed to complete the actual implementation. These are the individual steps taken toward meeting the goals. Specific activities should be small, focused, and readily completed. The more disaggregate they are, the faster they can be completed, and the greater sense of momentum in the implementation. Specific activities make up the tasks in the rows of the RAMs (see table 3 as an example).

Usually, implementation plans are formalized after some implementation activity has been completed. It is an opportunity not only to document the changes that need to occur but also how newly implemented practices support further development. Forming a work group to undertake an initiative or complete the work for a set of related specific activities is a positive action that advances implementation and is worth of noting as a specific activity.(14) Other specific activities may represent larger tasks, like creating a manual or implementing a new policy.(8) Common specific activities for implementing automation in highway construction include the following:

- Scheduling regular meetings with stakeholder groups (e.g., contractor associations).
- Creating special notes, special provisions, or developmental specifications to pilot and develop new policies and procedures.
- Developing a legal disclaimer for 3D models.
- Implementing digital signatures for contract documents.
- Creating new content for design and construction manuals.
- Purchasing hardware and software for construction field offices.
- Creating training programs or procuring training from vendors.

Tracking Performance

Tracking the progress and effectiveness of an implementation plan can be daunting, but it is a way to maintain momentum by justifying the investments made and substantiating further investment. Tracking completed activities is the simplest way to track performance; it can be effected through the RAM or through a simple spreadsheet.(19,8)

When the specific activities include pilot projects, it is an opportunity to capture other objective and quantitative data to measure performance. In the *Geospatial Utility Infrastructure Data Exchange 2014 Pilot Initiative*, MDOT tracked the cost of capturing the data on seven pilot projects and used that data to estimate that implementation would cost between 0.75 and 2 percent of construction costs.(20) This information could be used in a cost-benefit analysis or to define the purpose and need of broader implementation.

IMPLEMENTATION PLANNING RESOURCES

Table 3 and figure 4 through figure 6 are example tools that can be used in creating implementation plans. Specifically, table 3 is a sample RAM that uses the RACI categories. It is set up to track performance related to completing tasks in according to the time limits established for the specific activities. Figure 4 through figure 6 are worksheets for creating initiatives, defining the purpose and need, setting multiyear goals, identifying known issues and strategies to manage them, and creating specific activities that are time-bound and measurable.

Table 3. Sample RAM.

Initiative	Status	Task No.	Description	Start Date	End Date	Responsible Parties using RACI Scale									
						Sponsor	Committee Chair	Initiative 2 Leader	Initiative 3 Leader	Stakeholder Group 1	Stakeholder Group 2	Survey Staff	Design Staff	Procurement Staff	Construction Staff
Initiative 1	On time[c]	1	Coordination	1/1/15	Ongoing										
Coordination	Complete[a]	1.1	Form an implementation team	1/1/15	2/28/15	C	A	R	R	C	C	I	I	I	I
Coordination	On time[c]	1.2	Hold quarterly team meetings	3/1/15	Ongoing	I	A	R	R	R	R	I	I	I	I
Initiative 2	On time[c]	2	Implementation plan	4/15/15	10/15/15										
Implementation plan	Complete[a]	2.1	Identify known issues	4/15/15	6/15/15	I	A	R	C	C	C	C	C	C	C
Implementation plan	Complete[a]	2.2	Create goals	4/15/15	6/15/15	I	A	R	C	C	C	C	C	C	C
Implementation plan	Ahead of schedule[b]	2.3	Define purpose and need	6/15/15	8/15/15	I	A	R	C	C	C	C	C	C	C
Implementation plan	Ahead of schedule[b]	2.4	Define specific activities	6/16/15	8/15/15	I	A	R	C	C	C	C	C	C	C
Implementation plan	Not started[d]	2.5	Set performance measures	8/15/15	10/15/15	I	A	R	C	C	C	C	C	C	C
Initiative 3	On time[c]	3	Description	Start date*	End date*										
Description	Ahead of schedule[b]	3.1	Specific activity 1	Start date*	End date*	I	A	—	R	—	—	—	—	—	—
Description	Not started[d]	3.2	Specific activity 2	Start date*	End date*	I	A	—	R	—	—	—	—	—	—

*Indicates templates/examples for agencies to define their specific activities.

—Indicates that the information is not applicable to the column headings.

Note: Status color scale is as follows: [a]Dark green = Complete, [b]light green = Ahead of schedule, [c]yellow = On time, and [d]red = Not started.

Capability Description	**Purpose and Need**
Responsibility Assignment	**Baseline and Goals**
Who is Responsible to complete the work:	Baseline State of Maturity
Who is Accountable to ensure the task is completed:	Short-term Goal to be achieved within 12 months
Who should be Consulted before finalizing:	Short-term Goal to be achieved within 24 months
Who should be Informed of the results:	Medium-term Goal to be achieved within 5 years
	Long-term Goal to be achieved within 10 years

Source: FHWA.

Figure 4. Worksheet. Initiative planning worksheet, page 1.[12]

Known Issues and/or Challenges to Implementation	Strategies to Manage/Overcome Issues
Technological	
Procedural	
Change Management	

Source: FHWA.

Figure 5. Worksheet. Initiative planning worksheet, page 2.[12]

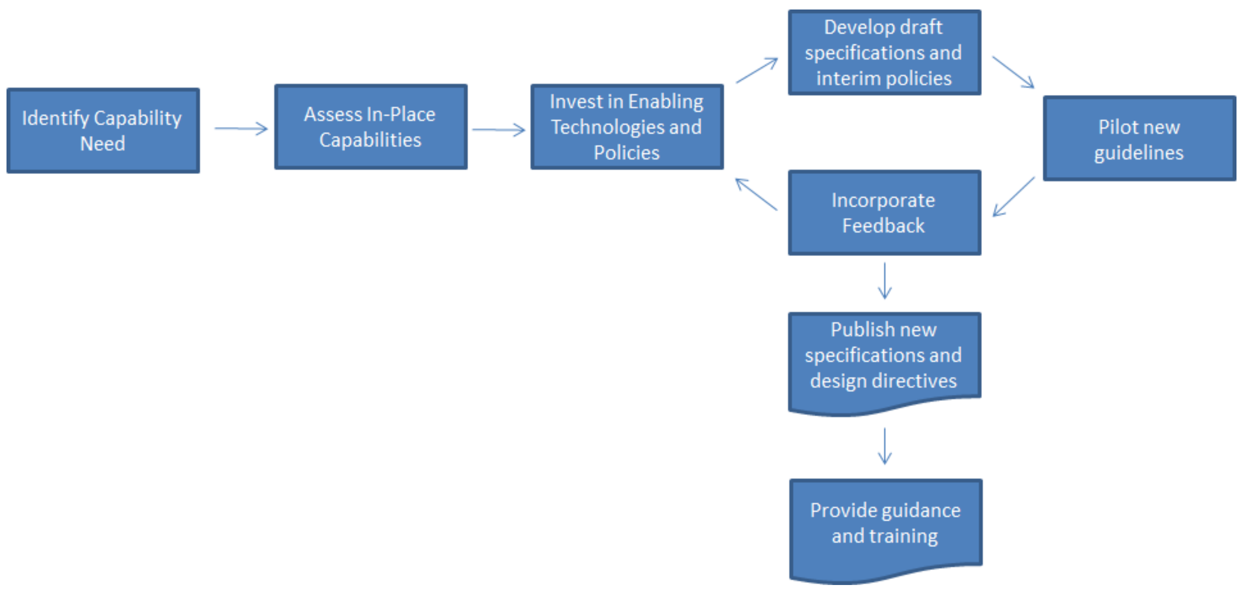
Specific Activities				
No.	**Description of Activity**	**Responsibility**	**Time Frame**	**Performance Measures**
1			Start Duration Completion	
2			Start Duration Completion	
3			Start Duration Completion	

Source: FHWA.

Figure 6. Worksheet. Initiative planning worksheet, page 3.[12]

CHAPTER 4. ENABLING TECHNOLOGIES AND POLICIES

Enabling technologies and policies build the framework for a coordinated approach to supporting automation in highway construction. Those may include hardware, software, or skills needed to create the 3D data upon which automation technologies depends; modifications to the specifications to enable the use of evolving automation technology; or guidance for implementing both the technology and policies. Figure 7 is a workflow for building capacity with enabling technologies and policies to drive forward implementation of automation guidelines.



Source: FHWA.

Figure 7. Flowchart. Increasing capacity with enabling technologies and policies.

Table 4 lists a range of enabling technologies and policies that are needed to support automation in highway construction. The table presents a range of different maturity levels at which the technologies and policies can be implemented. Advanced maturity is not necessarily a prerequisite to supporting automation. Each implementing agency will need to consider the optimal level of maturity to support the agency's unique goals for supporting automation in highway construction.

Table 4. Capability/maturity matrix for enabling infrastructure.[12]

Enabling Infrastructure	Maturity Level				
	1: Initial	**2: Evolving**	**3: Defined**	**4: Managed**	**5: Enhanced**
Statewide CORS network	Limited access to a CORS network	Statewide CORS network that is asset/ GIS grade only	Limited access to survey-grade CORS network	Statewide CORS network that is survey grade	Publically owned statewide survey-grade CORS network
RTN GNSS	Single-based RTK; requires site localization	Commercial RTN solution; requires site localization	Commercial RTN solution; tied to the NSRS	Statewide CORS RTN solution; tied to the NSRS; limited access	Statewide CORS RTN solution; tied to the NSRS with statewide access
Coordinate reference system	State plane coordinate system used on all projects	Modified State plane coordinate system used on all projects	Some projects use custom coordinate systems	Low distortion projections used for some projects	Standardized low distortion projections used for all projects
Computer hardware for design	All staff have computers	All staff have networked computers	All staff have networked computers that are less than 3 years old	Some staff have mobile tablets	All staff have access to desktop and mobile computers
Computer software for design	Email, Internet, portable document format (PDF), and other general office software only	CADD design software for designers and technicians	CADD design software for all and limited access to design review software	All design staff have CADD design and design review software	Desktop and mobile CADD design and design review software for all staff
CADD standard	A CADD manual outlines minimum requirements for 2D electronic plans	CADD Manual outlines minimum requirements for 3D model used to generate 2D plans	Standardized 3D model format and outputs including standard file naming convention	Standardized 3D model format and outputs including file and object naming convention	Standardized 3D model with data density tied to construction tolerance
Design review procedure	Plans review processes only	3D data are visually reviewed with no formal process	There is a formal process for a visual review of specific 3D data	There is a formal process for visual and software review for 3D data	There is a rigorous, formal process to review 3D data at all milestones
Document management system	Files released on CD-ROM or universal serial bus key	Files posted online on a File Transfer Protocol (FTP) site for unmanaged download	Files posted online on a secure FTP site for password-protected download	Secure, managed file sharing environment	Common data environment for all stakeholders

Enabling Infrastructure	Maturity Level				
	1: Initial	**2: Evolving**	**3: Defined**	**4: Managed**	**5: Enhanced**
Electronic signing and sealing	Electronic files are for information only	Digital sign and seal on PDF documents	Pilot initiatives to digitally sign 3D models	Digital sign and seal on any electronic documents	All deliverables are electronic with digital sign and seal
Construction specification	Method specification may inhibit the use of new technology	Special provisions developed to facilitate and manage construction with AMG	Draft AMG specification developed and being piloted	AMG specification incorporated in standard specifications	Quality assurance specification enables use of evolving technology
Computer hardware for construction	Limited access to computers on some sites	Field offices have computers but limited network access	Field offices have computers and full network access	Field offices have networked computers and some mobile tablets	Networked computers and mobile tablets on all construction sites
Computer software for construction	Email, Internet, PDFs, and other office software only	Some access to construction software	Desktop computers have construction software	Desktop and mobile computers have construction software	All applications are cloud-based and can be accessed from multiple desktop and mobile devices
Field equipment for construction managers and inspectors	Specification allows using the contractor's rovers and RTSs	Specification requires contractor to furnish rovers, RTSs and training	Limited agency-owned rovers and RTSs	Agency-owned rovers and RTSs available to all construction sites	All construction staff have access to rovers and RTS and are trained to use them
A construction manual	Provides guidance to implement AMG specification	As for level 1 plus provides guidance on AMG methods and equipment limitations	As for level 2 plus provides guidance on capturing independent field survey observations for real-time verification	As for level 3 plus provides guidance on using CADD systems to measure quantities and check tolerances	As for level 4 plus guidance on survey methods for site localization and verifying control

IN-PLACE CAPABILITIES

Surveyors have generally adopted new tools that enable more accurate remote sensing, rapidly collecting a large number of data points and more safely executing field surveys. There are challenges associated with managing large datasets in general and, more specifically, in extracting meaningful data from these datasets. Software tools are rapidly evolving to classify point clouds, remove noise, filter to an optimum number of data points for performing design, and produce the CADD graphics needed for plans development. Surveyors are able to consolidate datasets generated from multiple different methods of data capture to produce base mapping products that meet the needs of modern construction.

Geometric design computations are relatively simple. Rules-based CADD tools that compute 3D coordinates have been in use since the late 1980s. These tools evolved to be able to display 3D graphics, but other than 3D surface models, the 3D graphics were not widely used. Instead, designers used the tools with sophisticated automation to create 2D plans efficiently. This supported historic processes for design and constructability review that were reliant upon plans.

Continued CADD software development provided for more design automation and more accessible 3D graphics. Policies for design review and bidding did not change, however. Therefore, despite rich 3D data being available at the conclusion of design, it usually remained there. In the 1990s, advances in survey equipment including RTK GNSSs, mobile data collectors, and total stations enabled surveyors to use mobile location-aware tools. This provided efficiencies and safety gains in horizontal construction stake-out. In the late 1990s, AMG systems began to emerge, which led to contractors reverse-engineering 3D models from plans for use with AMG.

CAPABILITIES REQUIRING DEVELOPMENT

From a technological standpoint, the enabling infrastructure is largely in place (see table 4). The biggest hurdles are implementing policies, making investments in equipment and software, and training the workforce in using these new processes and policies. The following subsections describe the changes and developments that agencies need to consider in the areas of surveying, SUE, design, bidding, and construction.

Survey

Survey needs include construction tolerance accuracy on any tie-ins to existing hard surfaces (e.g., pavements, bridges, etc.) and better accuracy in general to avoid drainage issues and to generate accurate earthwork and materials quantity estimates.

Previously, with a paper-based delivery of design data to construction, survey computations remained in the hands of the construction surveyor. The construction surveyor had control of converting the design grid coordinates to ground stake-out coordinates. Rather than performing manual calculations, design data are now recreated in CADD to process computations and export to survey data collectors for field stake-out. These tools and survey methods form the foundation of AMG construction and real-time verification.

Subsurface Utility Engineering (SUE)

The state of the practice with regard to SUE has been evolving over the past two decades.[21] Since 1991, FHWA has been encouraging the use of SUE on Federal aid and Federal Lands Highway projects.[21] In 2009, responding to a challenge from FHWA's administrator to identify ways to shorten project delivery, a joint committee representing AASHTO, the Associated General Contractors, and the American Road and Transportation Builders Association identified that improved processes for utility location and relocation is an important step in expediting the completion of transportation infrastructure projects.[22]

As a follow up to this recognition, FHWA's EDC round 1 included a nationally canvassed initiative that highlighted existing flexibilities currently in place under Federal law and regulations and described techniques that foster effective utility coordination during project development which warrant more widespread use.[23] FHWA is currently completing a study to investigate issues associated with State transportation departments asserting their responsibility for managing utility installations within the highway right-of-way, with a focus on the use of 3D techniques to assist in that management.[24] The Second Strategic Highway Research Program (SHRP2) includes several important projects that are aimed at providing additional guidance on utility location, data storage, mapping and conflict management. The most relevant studies for this work include the following:

- ***Technologies to Support Storage, Retrieval, and Use of 3-D Utility Location Data***: This project developed a data storage and retrieval model to accommodate large volumes of utility data, interface with existing design software (e.g., CAD software), and provide a method for organizing the data so that it can reliably be used throughout the project design phase, during construction, and on future projects.[25,26] The model data store has provisions for including horizontal and vertical location of the utilities as well as attribute data that is needed to effectively coordinate with utility owners. A number of agencies including California, Ohio, Kentucky, and Texas are participating in proof-of-concept studies that are piloting the data repository.

- ***Utility-Locating Technology Development Using Multisensor Platforms***: This project developed two functional automation prototypes to improve the detection and accurate determination of positions of buried utilities for use in detailed project design and construction work.[27] The specific technologies packaged in the prototypes included a multichannel ground-penetrating radar system to locate utilities in one pass and a new multisensor platform that combines electromagnetic induction and 3D ground-penetrating radar to produce utility location data.

- ***Innovations to Locate Stacked or Deep Utilities***: This project developed prototype devices that extended the locatable zone for deeply buried and stacked utilities beyond the surface-based detection approaches considered in utility investigation technologies.[28] Long-range radio frequency identification (RFID) tags and active acoustic locating devices were selected for final prototype development and testing. Although it was concluded that both technologies needed further development to bring them to a commercially ready state, the RFID technology was judged to be closer to commercial readiness. The RFID prototype developed in this research overcame the traditional depth limitations (approximately 6 ft) associated with this technology by incorporating an internal, long-life (50 years) battery on the active tag. The long-range RFID active tag technology has also been identified as promising utility location technology in the previously cited FHWA work.[(24)]

Finally, the American Society of Civil Engineers (ASCE) developed an important standard of care guideline, *Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data*.[(29)] This standard is the foundational reference for much of the in-motion work described in this section.

Design

For roadway design, historic CADD tools have evolved to become natively 3D within the design environment. This allows designers to interact with their designs in 3D without additional effort to produce 3D graphics. Perhaps the biggest leap for designers is conceptualizing the 3D graphics to be the design rather than the plans. The process of creating plans focuses effort on a subset of the overall project, for instance 50-ft interval cross sections. The areas between the cross sections may contain transitions between typical sections.

When the 3D model is conceived of as the design, there is a shift of effort to design these transitions rather than having them managed in the field. This results in fewer field issues, more accurate quantity estimates, and constructed facilities that better reflect the design intent. The most efficient and valuable way to communicate the design intent is to provide the 3D CADD data itself, which requires new policies, processes, and, in some cases, technology to be able to review, certify, sign, and manage the digital data contractually.

During the transition phase from designing for plans to designing 3D engineered models for construction, designers are hesitant to allow 3D data to supersede plans in the order of precedence of contract documents defined by construction specifications. While 3D data are beginning to flow to construction, the mechanisms that allow that data to flow currently are legal disclaimers and “hold harmless” agreements, which are intended to limit the agency’s liability for errors and omissions in the 3D data. These transfer all risk associated with the accuracy of the data to the contractor, which is neither equitable nor efficient risk allocation. Furthermore, it leaves the owner’s representative without a reliable or independent source of 3D data to use for real-time verification. Giving 3D data contractual standing requires revising the construction specification to change the precedence of 3D CADD data and contract plans and limiting authorized uses of the data to the specific activities for which it has suitable resolution.

Bidding

The infrastructure to transfer 3D data to a format and resolution necessary for construction requires the development of document management systems. Existing systems for managing construction contract documents provide a foundation that can be extended. Policies and standards are important to ensure that the 3D data are consistent in quality and presentation and contain all the necessary information for both the contractor and owner. This requires standards related to the 3D data type, the density or level of detail in that data, the format of the data, the horizontal and vertical coordinate datums, and authorized use of the data.

Construction

Most changes needed in construction are to manage 3D data and support real-time verification by the engineers and inspectors onsite. AMG and real-time verification take construction layout and surveying out of the control of the surveyor and place it into the hands of equipment operators and inspectors. To ensure that construction continues to be performed and measured within the appropriate tolerances, policies and procedures need to be implemented to provide the appropriate construction survey oversight to these activities.

Of paramount importance is a process and policy by which the original project control is verified and the method is agreed for projecting design grid coordinates into ground coordinates with scaled distances. If the contractor and inspector do not use consistent approaches, then differences in survey techniques could erroneously be interpreted as construction errors. These processes and policies can be built into the construction specification.

A work plan requirement can also be included in the construction specifications. The work plan provides notice and agreement over how the contractor will be using 3D data for layout and AMG as well as which AMG systems will be used for each construction activity, 3D data sources, and processes for keeping data current when design or field changes occur. Another element that can be built into a construction specification are provisions for the contractor to furnish equipment for the owner’s independent use.

Protocols for real-time verification need to be developed. Equipment and software are rapidly changing to make data capture and management more efficient. Protocols should be flexible to accommodate evolving technology and should focus on methods to ensure proper construction survey oversight while capturing the right data to measure and accept completed work with independence.

There are hardware, software, and training investments that are necessary to migrate to data-driven processes for construction engineering and inspection. The need extends beyond the field and back to the region or head office where data may need to be processed during construction and must be managed and archived after construction is complete.

IMPLEMENTATION MATURITY

There are various levels of implementation maturity for each of the enabling infrastructure and policy elements. The adoption of technology in highway construction to date has led to highly refined and siloed processes. Highway professionals and agencies have adopted distinct datasets, data formats, and software applications to meet the objectives of the individual asset lifecycle phase. Within phases and disciplines, technology is mature and efficient. However, single phase optimization is not an efficient way to manage data about highway assets throughout their lifecycle. Transferring data throughout the different highway project delivery phases (planning, surveying, design, construction, and operations and maintenance) remains largely paper-based, and there is often duplication of data creation and management.

The first step toward implementing paperless project delivery has been to replace a paper page with an electronic page. One of the limitations of using an electronic page is that the data are static. Database-driven systems allow data to be queried and reused, but portability beyond the construction phase is enabled by a geospatial component to the database. To realize the vision for lifecycle highway asset data, there must be a geospatial component to the data, which references the 3D data to a mapping projection and geoid model. The use of geospatial data is well entrenched in 3D design and AMG construction. However, current procedures for construction engineering and inspection use project-specific linear referencing. Implementing geospatial field technology to perform real-time verification and capture post-construction as-built survey data is a significant change, but there are efficiency gains that can contribute to better safety outcomes by reducing the exposure of inspectors to equipment movements.(30)

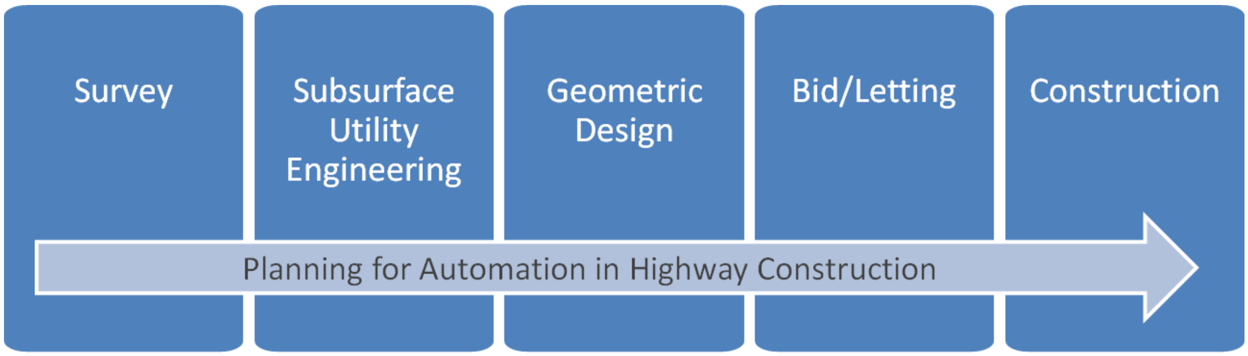
While the enabling infrastructure and policies identified are wholly in the control of State transportation departments, the policies for digital signatures and digital seals are not. Each State engineering board must implement a policy before its transportation department can begin to digitally sign and seal contract documents. Digital signatures are an essential means of authenticating digital contract documents. In a digital page level of implementation, the technology is mature to support digitally signed PDF documents, which can be 2D or 3D documents. FDOT has developed software to review and digitally sign LandXML files using a public/private key encrypted digital signature.(11) The technology to digitally sign CADD files needs further development at this time. Though the FDOT software digitally signs or validates a digital signature on any electronic file type, it is not possible to simultaneously view that file and validate the signature. In the interim, if 3D data are to have contractual standing, then a document management system is needed to protect the contractual version and provide universal access to it.

Regardless of whether 3D digital data can be used for construction with automation technology, there are considerations that should be addressed contractually.(31) The means of authenticating contributors, like with digital signatures or document management systems, is one consideration. Ownership and responsibilities for controlling the data on Web-based or other collaboration platforms should be identified. Responsibility for errors introduced by data exchange or using the data in software is another important issue to manage contractually. Finally, the extent to which the owner warrants the data or terms of use needs to be managed contractually. In vertical construction, a building information modeling (BIM) project execution plan is usually annexed to the contract documents that manages these issues and others associated with multidisciplinary coordination and collaboration.(32)

CHAPTER 5. INTRODUCTION TO AUTOMATION TECHNOLOGY APPLICATIONS AND GUIDELINES

There is a need for interdepartmental coordination between district, design, survey, and construction departments to determine agency-wide objectives for automation in highway construction. This chapter illustrates how this interdepartmental coordination supports effective use of automation on individual construction projects.

Effective and integrated use of automation technology starts at project scoping, as shown in figure 8, with tailored survey mapping products. These survey products form the basis of 3D design data that are ready for use in construction. The 3D design models can form the necessary data for automation technology used in construction layout, AMG, quantity measuring, the capture of 3D digital as-built records, and real-time field verification to accept completed work.



Source: FHWA.

Figure 8. Flowchart. Planning for automation technology integration.

The various construction uses require open, portable, and durable data formats. Robust review protocols check that the design intent is preserved when 3D design data have been reformatted or translated. Standard specifications can accommodate the use of evolving technology by establishing performance-based outcomes. Construction inspection manuals describe technology-neutral processes for capturing data to measure and accept work with independence.

Table 5 shows a capability/maturity matrix showing different levels of implementation of the processes and policies at the project or organization level to prepare and use 3D data for automation in highway construction. There is synergy between mature practices in some areas (e.g., providing 3D contract models that supersede plans and in using automation for construction engineering and inspection). In other areas the practices may be unrelated (e.g., using 3D models to visualize right-of-way impacts and capturing digital as-built data).

Chapters 6–10 describe and reference workflows, business practices, standards, and specifications that have been adopted by State transportation departments. Note that the published examples referenced in the remainder of this report may not yet reflect the full maturity that is possible or conceivable at this time.

Table 5. Capability/maturity matrix for applications of automation in highway construction.[12]

Application of 3D Models	Maturity Level				
	1: Initial	**2: Evolving**	**3: Defined**	**4: Managed**	**5: Enhanced**
Survey methods	Aerial and field survey to create 2D line work and 3D DTMs	Aerial remote sensing combined with field survey to create 2D line work and high-density 3D DTMs	Predesign survey deliverable from multiple datasets and survey methods	Survey manual identifies activities/ areas requiring enhanced vertical accuracy	Predesign survey deliverable from multiple datasets with accuracy tied to construction tolerance
Survey metadata	Survey metadata including coordinate system, datum, and projection is noted on the control sheet	Coordinate system, datum, and projection are shared with digital files and are not embedded	Some CADD files have the projection, datum, and coordinate system embedded digitally	CADD with spatial data have the projection, datum, and coordinate system embedded digitally	Seed/template files have standard projection, datum, and coordinate system embedded
Visualization	Occasional use for isolated projects and uses	Some projects have a 3D model that is reused for multiple applications	Many projects use a 3D model during planning for multiple applications	Many projects use a 3D model for multiple applications during all phases	Need for visualization is assessed for all project types and phases
Road design	3D CADD to create 2D plans with manual edits. 3D models for information only; inconsistent with plans	3D CADD to create 2D plans. 3D models for information only but are consistent with plans	3D CADD to create 2D plans. 3D models for information only but are consistent with plans	3D model takes legal precedence over plans for earthworks and paving	3D model with earthworks, paving, existing, and proposed utilities and structures
Utility design	Hydraulic analysis output linked to 2D plans	Hydraulic analysis output disconnected from 3D CADD for plans production	A single 2D CADD model for hydraulic analysis and plans production	A single 3D CADD model for hydraulic analysis and plans production	A single 3D model for hydraulic analysis, plans production, and clash detection

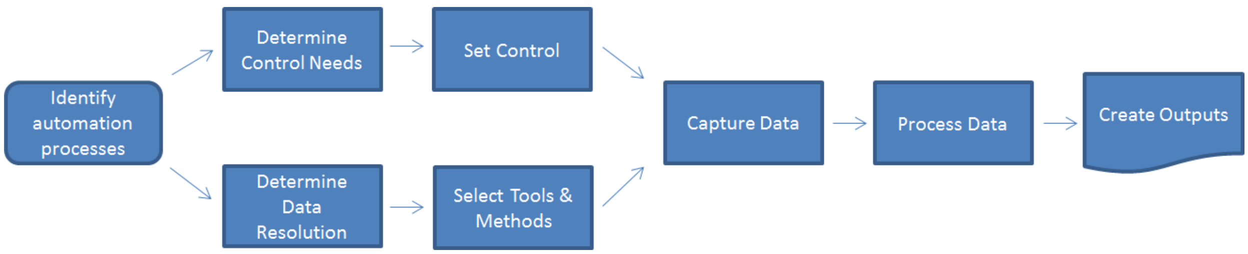
Application of 3D Models	Maturity Level				
	1: Initial	**2: Evolving**	**3: Defined**	**4: Managed**	**5: Enhanced**
Bridge design	Limited 3D structural analysis	Structural analysis output linked to 2D plans	3D structural analysis imports roadway geometrics and ground to spatially orient the model	A single 3D model for structural analysis, plans production, and constructability for standard bridges	A single 3D model for structural analysis, plans production, and constructability for all bridges
Other structural design	Limited 3D structural analysis	Structural analysis output linked to 2D plans	3D CADD model identifies structure limits, structures not accurately modeled	3D structural analysis based on a common data environment with roadway geometrics for standard structures	3D structural analysis based on a common data environment with roadway geometrics for all structures
Right-of-way engineering visualization	2D diagrams created from the 2D CADD line work are used to consult stakeholders	2D diagrams and images from 3D visualization models when these are available	2D diagrams and 3D images from the design models are used on isolated projects	Images of the 3D design overlaid on an aerial image draped over a 3D surface	3D model on a mobile tablet to navigate from multiple angles with stakeholders
Right-of-way engineering data management	2D line work for proposed right-of-way limits exported to land information database	Existing right-of-way (ROW) information includes links to right-of-way maps and documents	Standard process updates land information database during ROW acquisition	Existing and proposed ROW information is linked to the land information database	Survey-grade land information database with map interface to interact with current data
Clash detection	2D CADD files overlaid on a common spatial projection for manual comparison	3D CADD files overlaid on a common spatial projection for manual comparison	Design review software used to perform 3D clash detection digitally during design	Subsurface utility locations updated during construction for ongoing 3D clash detection	Subsurface utility locations are incorporated into AMG models to alert operators
Maintenance and protection of traffic	Temporary roadways are modeled in 3D during design to validate staging	Images from 3D model used to communicate MPT to stakeholders during design	3D model updated during construction to produce images for public outreach	Videos rendered out of 3D model to communicate MPT to stakeholders	4D model used to plan for holiday traffic and create videos for stakeholders

Application of 3D Models	Maturity Level				
	1: Initial	**2: Evolving**	**3: Defined**	**4: Managed**	**5: Enhanced**
Constructability review	Designers review 3D models, but review process is not documented	There is a draft design review process for surface models and clash detection	There is a standard 3D model review process for surface models and clash detection	The standard review process includes 3D clash detection and 4D staging review	The contractor maintains a 3D model connected to their resource-loaded schedule (5D model)
Staging	2D staging plans with static 3D images of each stage for information only	2D staging plans with static 3D images of each stage as contract documents	High-level 4D model to communicate staging for information only	High-level 4D model replaces 2D staging plans as contract document	4D model used to resolve staging issues across multiple contracts
Construction scheduling	3D models for earthworks quantity takeoffs (QTOs) and staging and locating borrow/spoil pits	3D models are used for earthworks and structure QTO and staging	3D models are used for 4D simulation to review the critical path	4D model with space/time clash detection is used to optimize the critical path	4D model queries a resource-loaded schedule to visualize cost and/or risk data (5D model)
Contract models	Contractors create 3D models from 2D plans	3D line strings and surfaces provided for information only	3D models that reflect the design intent provided for information only	Pilot initiatives to provide 3D models that supersede 2D plans for some construction activities	3D models supersede 2D plans for some construction activities
Construction via AMG	AMG systems for activities that require up to 0.1-ft vertical accuracy (e.g., rough grading)	AMG systems for activities that require up to 0.5-inch accuracy (e.g., fine grading)	AMG systems for activities that require up to 0.25-inch accuracy (e.g., paving)	AMG systems for a wide range of activities (e.g., profile milling, paving, and slip forming)	AMG systems used to achieve good material yields and smoothness regardless of tolerance
Construction layout	Agency owns site layout and sets stakes	Agency owns site layout and sets stakes; contractors perform a GPS/GNSS site localization that is not reviewed	Contractor's site localization for AMG operations reviewed by agency	Contractor and agency use a common site localization for layout with rovers	Contractor and agency agree on a common site localization that is documented in an automation technology work plan

Application of 3D Models	Maturity Level				
	1: Initial	**2: Evolving**	**3: Defined**	**4: Managed**	**5: Enhanced**
Source of construction 3D data	Contractors creates and reviews 3D data used in construction	Contractor's 3D data reviewed by agency prior to construction	Contractor and agency agree on a common set of 3D data for construction and quality assurance	Agency provides models for construction, measurement, and quality assurance	Agency provides models for construction, and contractor provides as-built models
Quality assurance tolerance checks	Staff are aware of stakeless methods but lack equipment and training	Use contractor's Rover, but no site localization or 3D model review	Contractor's site localization and 3D model are reviewed to use contractor's Rover independently	Contractor's site localization and 3D model are reviewed, tolerance methods agreed	Independent, 3D model-based tolerance checks with survey equipment and minimal stakes
Measurement tools	Traditional survey instruments supplement analog tools	Digital levels supplement traditional survey instruments	Survey instruments with data collectors and spreadsheets for calculating areas and volumes	Survey instruments with data collectors and CADD for calculating areas and volumes	Survey data processed with CADD for measuring and calculating lengths, areas, and volumes
As-built data	Paper plans are redlined and archived	PDF plans are redlined and archived electronically	CADD files are updated based on paper/PDF redlines	As-built data are captured and delivered digitally if requested	The format for capturing as-built data is standardized and required on projects

CHAPTER 6. SURVEYING

AMG, which is a primary mode of automation in highway construction, uses real-time survey instruments. This prominent role of survey equipment in construction has implications that need to be supported during the original control and topographic survey. A workflow for developing topographic and control survey products that support automation in highway construction is shown in figure 9.



Source: FHWA

Figure 9. Flowchart. Producing survey products to support automation in highway construction.

This chapter covers the following topics:

- Establishment of a site control.
- Survey metadata.
- Accuracy tolerances for topographic survey.
- Use of remote sensing.
- Non-traditional survey products.

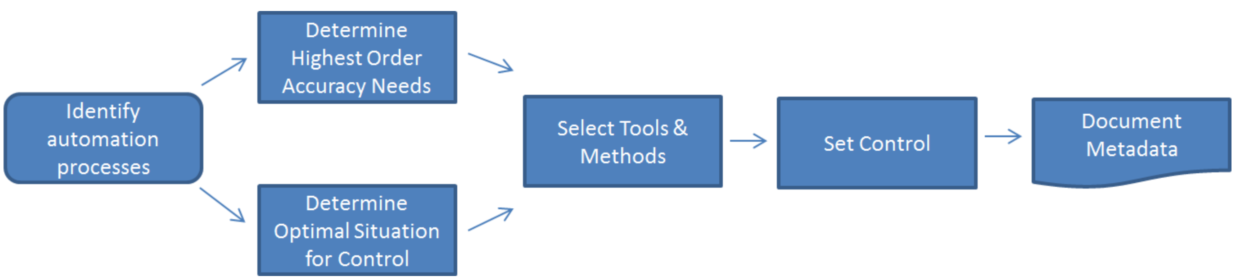
Location, density, and durability of project survey control are important considerations to establish project control for successful use of automation in construction. While not an issue limited to construction with automation technology, consistently employing quality control affects the accuracy with which a project is constructed. Using the original mapping control in construction is the best way to build the project in accordance with the design intent.(6) Automation for construction engineering and inspection is most easily implemented when both the contractor and inspector work off the same control network and basis to translate the plans to build the project. Otherwise, there can be differences in observations due to different survey methods rather than construction errors.

Implementing automation in highway construction relies on 3D digital data that have the necessary accuracy to meet the tolerances in the construction specifications. This means that the survey information upon which the design is based must be accurate to the same tolerances. These tolerances are documented in an agency’s construction specification. While there is no industry standard, there should be consistency. In many cases, the accuracies and densities needed from the original topographic survey are much higher than what has been typically collected.

Newer survey methods like LiDAR reduce the time for capturing data with the necessary spatial accuracy and point density. However, they are less cost effective than traditional remote sensing applications. Agencies have to balance the probability of the automation technology being used with the cost of producing the necessary survey data. Nevertheless, existing low-accuracy ground survey data are a very commonly cited challenge for construction regardless of automation use. Contractors report checking tie-ins to existing facilities to identify any redesign that may be needed to fit to field conditions and spot-checking the existing ground survey during bidding to determine accurate quantities. While accuracy greater than 3-inch is not always needed at all locations, this level of accuracy can avoid earthwork change orders or redesign at tie-ins to hard surfaces.

ESTABLISHING SITE CONTROL

The original project survey control is the source of ground truth for construction, setting the parameters that relate the design on the plans to locations on the ground. The original control accuracy can be selected to support the highest order use in design, construction, and asset management. The quality of the control has a direct impact on the network accuracy of as-built record data integrated into an asset management system. If the control is geospatially referenced to the NSRS, then the mapping products can be projected onto different mapping projections that may be needed for design, construction, and asset management. For example, design documents may use a State plane coordinate system, construction documents may use site localization, and asset management documents may use a universal transverse mercator (UTM) coordinate system. Figure 10 illustrates the process to successfully establish site control to support the use of automation processes and equipment in a project.



Source: FHWA.

Figure 10. Flowchart. Setting site control to support automation in highway construction.

Control Accuracy

The investment in mapping control affects the network accuracy of all the data captured and created relative to that control. This includes the original base mapping, construction layout, and construction as-built surveys. Modern survey instruments make establishing control with high orders of accuracy more cost effective than in the past. Investing in durable, accurate control supports automation in highway construction and use of as-built record data for asset management and in future maintenance or construction activities.

To produce a design that ties seamlessly into existing features, the base mapping must have a high order of network accuracy for those features. The accuracy of the control is a limiting factor. Horizontal tie-ins are simpler to transition and field fit than vertical tie-ins. For design and construction, horizontal control can be of a lower order than vertical control. The value of higher accuracy horizontal control than that indicated in table 6 may materialize in asset management uses of the data, such as subsurface utility locations.

Table 6. Minimum positional accuracies for mapping control to support automation technology.

Control Type	Network Accuracy (ft)
Horizontal	0.10
Vertical	0.02

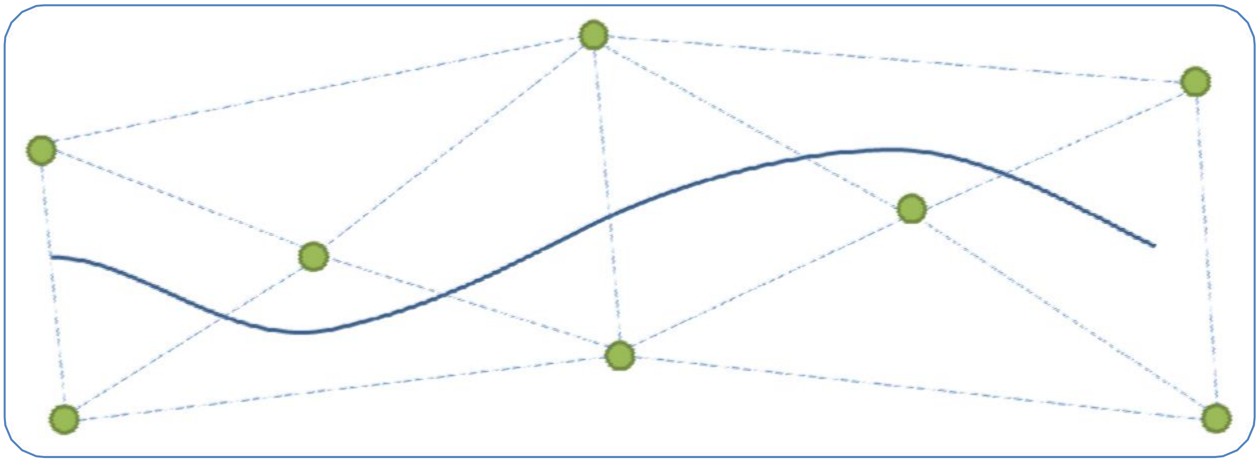
Situating Control

Effective site control situating practices are unchanged from long-standing practices. The original mapping control is what ties the ground to the projected grid upon which the design is developed. Durable control that has been well documented with complete metadata aids in preserving the design intent when mapping the design grid back onto the ground in construction.

AMG systems work effectively with site localization, which computes a rotation and scale factor for horizontal layout and creates a vertical datum. Using a site localization approach will result in tight vertical closure and good horizontal closure if the control is sited appropriately. AMG systems are able to replicate the surveyor’s workflow and work off a mapping projection and a geoid model when the base station is set up over a known point. However, this is not easy to do without a skilled surveyor. Many contractors prefer the site localization approach, which has specific control location needs.

When using site localization, RTK correction may be provided by an independent base station, a CORS, or an RTN. Site localization includes a map projection, a horizontal adjustment, and a vertical adjustment. The control is used to determine the horizontal and vertical adjustments. The horizontal adjustment consists of a rotation, translation, and scale factor. A minimum of two control points are required for computing a horizontal adjustment, a minimum of three control points are required to compute a vertical adjustment, and a minimum of five points are recommended for both.[(33)] The control needs to enclose the project area in order to produce a good site localization with low residuals. More than one site localization may be used on a project to keep the horizontal and vertical closures small.

On linear projects where the vertical control is located too close to the linear axis, the vertical plane computed by the site localization may result in large errors transverse to that axis, which increase with distance from the axis.[(33)] Secondary control can be placed near the alignment during construction. In figure 11, green circles indicate the preferred primary control distribution for a linear project (alignment shown in solid blue) to support a site localization. The dashed lines represent the control network diagrams.



Source: FHWA.

Figure 11. Illustration. Effective control siting to support site localization for a linear project.

Site localization resides in the data collector and is used with various survey instruments. Where total station is used for AMG operations or automated inspection, secondary control within the line of sight is required. The secondary control can be set during construction and tied to the primary control established during the original base mapping. Since the secondary control will not be used to establish the site localization, it can be located along the linear axis situated to aid in visibility and durability.

SURVEY METADATA

Given the importance of the original project control in construction, it is necessary to preserve the survey metadata, which describes the basis for the horizontal coordinate system projection and vertical datum upon which the original survey mapping is based. The metadata for control must be preserved so that surveyors can locate and, if necessary, replace the original survey control monuments during construction or for future maintenance or construction activities. Table 7 provides a sample of survey metadata needed to reconstruct the original mapping if needed during construction.

Table 7. Sample survey metadata.

Metadata Element	Example
Horizontal datum	• UTM North Zone 11 referenced to North American Datum of 1983 • Adjustment: NSRS 2007
Vertical datum	• North American Vertical Datum of 1988 • Geoid Model: Geoid 12A (CONUS)
Coordinate system	Nevada Central 2702
Projection	• Transverse mercator • Central latitude: 34° 45' 00.00" N • Central longitude: 116° 40' 00.00" W • False northing: 6,000,000 ft • False easting: 500,000 ft • South azimuth: No • Positive direction: North/east
Grid scale factor	0.9999912
Units of measure	U.S. survey feet (ft)

In the event that the original control is disturbed prior to or during construction, the construction surveyor will need to establish it. It is common to include a control plan in the construction plans. At a minimum, the control plan should contain the metadata as well as the northing, easting, elevation, and description for each control point. It may be useful to include the station and offset of the control relative to the design baseline in the contract documents.(34) The Nevada Department of Transportation maintains a database of survey monuments, including construction control that is publicly available through a Web-based GIS.(35)

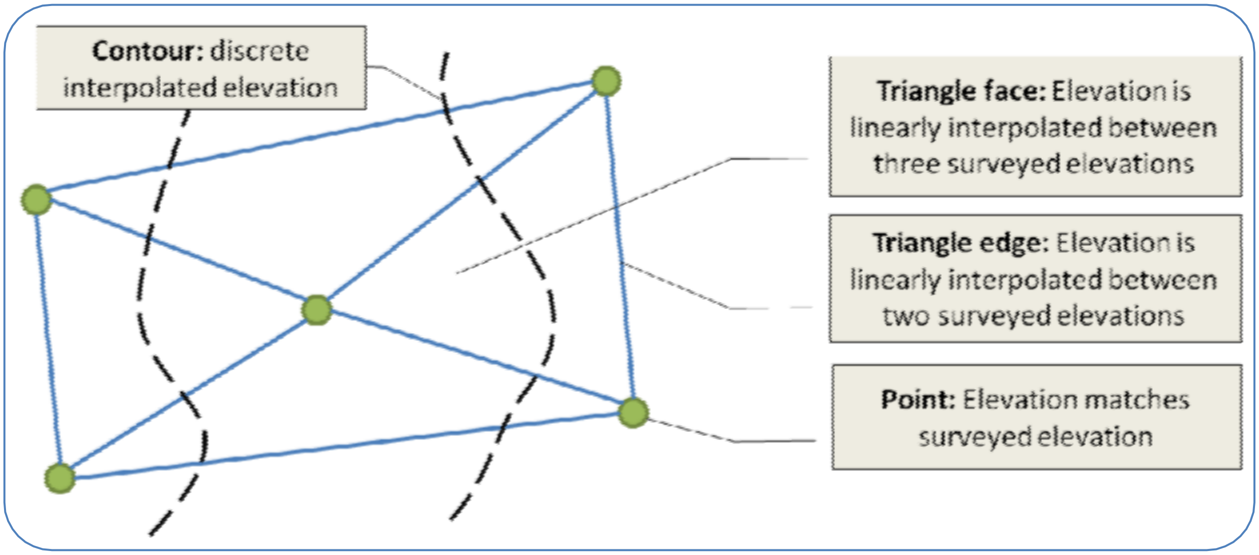
The survey report provides information to surveyors who may need to recreate the workflow, either to locate control or reestablish it. The report should include the metadata as described in table 7, the list of controls, network diagrams, minimally constrained report, fully constrained report, means and methods of conducting the observations, and any issues or concerns arising from the field work.(36) The survey report does not need to be included in the contract documents, but it should be available if there are an issues with the control during construction.

ACCURACY TOLERANCES FOR TOPOGRAPHIC SURVEY

Traditional survey products include right-of-way and adjacent property legal descriptions, an existing ground DTM, CADD line work and point symbols, digital photography, control description, and metadata describing the map projection, vertical datum, horizontal scale factor, and rotation.(36) These deliverables are a streamlined set of data that are sufficient to perform design, right-of-way acquisition, and construction layout. These survey products are also sufficient for construction with automation technology.

With automation in highway construction, there is a desire that the original 3D design data be used in construction. For that to be possible, the topographic survey needs to provide sufficient accuracy so that the design data matches the field conditions at locations where the design is constrained by fixed features. Design issues requiring field fits in construction are usually the result of insufficient vertical accuracy in either the survey control or the topographic mapping.

The accuracy of DTM surfaces and break lines depends on two components: the accuracy of the data points and the distance between them. As shown in figure 12, the larger the distance between survey points, the greater the area of interpolation in DTM elevations.



Source: FHWA.

Figure 12. Illustration. Relationship between survey observations and elevations computed for a DTM.

For the data points, unnecessary network accuracy can be costly to collect, but not enough network accuracy of certain constraining features can lead to redesign and change orders. Tie-ins to hard surfaces are often constraints on the design (e.g., existing pavements, existing bridge structures, or existing curbs and gutters). CADD software interpolates between points. Much like accuracy, unnecessary point density increases cost, but too little point density can miss necessary details. For example, super-elevation at a tie-in may be miscalculated if the distance between points is greater than the lane width.

High accuracy survey is able to extend the application of automation technology into newer areas like full-depth recovery or asphalt resurfacing projects where there is a need for drainage improvements, super-elevation corrections, or profile improvements. These operations require survey of the existing feature with a high network accuracy to develop milling or reconstruction profiles that improve the roadway geometrics while optimizing material yields.

Topographic accuracy needs can be differentiated based on whether the feature is a constraint, a design feature, a location feature, or a planning feature. A constraint should be a fixed feature that the constructed facility must tie into exactly. A design feature should be a feature whose location or physical characteristics (e.g., slope or depth) affect design decisions, a location feature would be a feature that influences the design, but it can be modified or relocated (e.g. a grass-lined ditch or a natural slope). A planning feature would be a feature that needs to be depicted on the plans but does not significantly influence the design (e.g. a woods line or wetland beyond the limits of the right-of-way). Table 8 is a guide to minimum horizontal and vertical accuracies for constraint, design, location, and planning features.

Survey instruments are constantly evolving. If a survey specification describes the outcomes of the topographic mapping, the surveyor can select appropriate tools to capture the necessary data efficiently and safely depending on the site conditions.

Table 8. Minimum network accuracies for different feature types.

Feature Type	Description	Minimum Network Accuracy (ft)	Maximum Distance Between Points (ft)	Example Features
Constraint	The precise location or physical characteristics constrains the design and cannot be modified or relocated cost effectively	H = 0.04 V = 0.02	5	Tie-ins to existing sewers, curbs, culverts, pavements, utility covers, and bridge elements
Design	The location or physical characteristics affect design or constructability	H = 0.10 V = 0.04	10	Minimum grades on pavements or ditches, stream thalwegs, or existing pavements that will be modified
Location	Feature can be modified or relocated, or its precise location does not affect design or constructability	H = 0.25 V = 0.10	25	Stream banks, tops and toes of slopes, ditches, natural ground, retaining walls, and storm/sanitary sewer inverts (not tie-ins)
Planning	Feature will be shown on plans, but location does not affect design or constructability.	H = 0.50 V = 0.50	50	Utility poles, landscaping, woods lines, wetland limits, fences, and features to be demolished.

H = Horizontal.
V = Vertical.

Table 9 provides an example of how the features in table 8 apply to different AMG construction activities and includes minimum point densities for DTM surfaces.

Table 9. Survey resolution required to support AMG operations.

Project Type	Applicable AMG Methods	Constraint Features	Design Features
Asphalt mill and pave with ride improvements	2D sonic averaging for milling and paving	No survey required	No survey required
Asphalt mill and pave with cross slope or drainage correction (hard tie-ins only at start and end)	2D sonic averaging for milling and paving	No survey required	No survey required
Asphalt mill and pave with cross slope or drainage correction (tie to hard surface or curb and gutter)	3D profile milling with constant depth or 2D paving. Alternately, constant depth milling and 3D paving	• **Breaklines**: Crown and edges of pavement • **DTM**: Pavement 100 ft either side of tie-ins at start and end and areas with minimum grade	**DTM**: Pavement between constraint features, ditches, and drainage features
Concrete overlay with or without ride and drainage corrections	3D paving	• **Breaklines**: Crown and edges of pavement • **DTM**: Pavement 100 ft either side of tie-ins at start and end and areas with minimum grade	**DTM**: Pavement between constraint features, ditches, and drainage features
Reclamation	Grading, fine grading, base, and paving	**DTM**: Pavement 100 ft either side of tie-ins at start and end and areas with minimum grade	**DTM**: Pavement between constraint features, ditches, and drainage features
Shoulder and side slope widening or improvements	Grading, fine grading, base, and paving	• **Breaklines**: Saw cut line • **DTM**: Pavement 100 ft either side of tie-ins at start and end and areas with minimum grade	**Breaklines**: Edge of shoulder, slope break points, toe of slope, ditches, and drainage features
Lane widening	Grading, fine grading, base, and paving	• **Breaklines**: Saw cut line • **DTM**: Pavement 100 ft either side of tie-ins at start and end and areas with minimum grade	**Breaklines**: Edge of shoulder, slope break points, toe of slope, ditches, and drainage features
Reconstruction	Grading, fine grading, base, and paving; possibly 3D profile milling and excavation	**DTM**: Pavement 100 ft either side of tie-ins at start and end	**DTM**: Driveways, utility covers, ditches, and drainage features
New construction	Excavation, grading, fine grading, base, and paving	**DTM**: Pavement 100 ft either side of tie-ins at start and end	**DTM**: Driveways, utility covers, ditches, and drainage features

Topographic mapping for the original ground DTM may merge the datasets arising from a variety of survey instruments.[37] It is possible to differentiate between survey shots captured with different methods in CADD files. Hard shots taken with total stations or GNSS rovers have higher accuracy than remotely sensed shots taken with aerial photogrammetry or LiDAR. DTMs can also be separated according to accuracy, but they would need to be consolidated for 3D design to target corridor model end conditions and for computing earthwork volume quantities in design and construction. Differentiating between sources communicates to the designer and contractor the confidence with which they can hold the observation and whether supplemental survey is needed.

USE OF REMOTE SENSING

Remote sensing has its benefits among a range of survey data acquisition tools. As a remote sensing application, LiDAR is vulnerable to gaps in data acquisition from shadowing and visual occlusions. It cannot be relied on as the sole data source for mapping data acquisition. Rather, it can be part of a suite of tools at the surveyor's disposal to deliver topographic mapping products.

The four primary types of remote sensing currently in use are as follows:

- Aerial photogrammetry.
- Aerial LiDAR.
- Mobile LiDAR.
- Static LiDAR.

Aerial remote sensing is able to cover a wide area in a relatively short amount of time. However, processing times are long, and the network accuracy is limited to 0.25 to 0.5 ft. Mobile LiDAR has notable safety benefits, especially in high-volume and/or high-speed roadways, but it is costly to mobilize. Processing times for mobile LiDAR are long, and point density is high, leading to large datasets. Network accuracy from terrestrial mobile LiDAR is about 0.17 ft. Static LiDAR has long setup times, capturing vast datasets of relatively high network accuracy, up to 0.02 ft close to the sensor, but eroding with distance from the sensor.[38]

Table 10 relates the different LiDAR data acquisition methods to their suitability for capturing data in the accuracy bands identified in table 8. Aerial LiDAR may not be able to achieve the higher accuracy needs. Mobile LiDAR may need extensive control to achieve higher accuracies and may not be able to achieve the highest accuracy category. Static LiDAR may not be cost effective for wider area mapping. LiDAR hardware and software continue to evolve, and the suitability of different methods may change. Table 10 is a guide based on current technology. Tool selection is best left to the mapping surveyor, who is the licensed professional responsible for means, methods, and outcomes of the mapping survey.

Table 10. Suitability of LiDAR methods by topographic mapping accuracy ranges.

Feature Type	Aerial LiDAR	Mobile LiDAR	Static LiDAR
Constraint	Not appropriate	Not appropriate	Suitable
Design	Not appropriate	Consider	Suitable
Location	Consider	Suitable	Consider
Planning	Suitable	Suitable	Consider

Certain project characteristics are predisposed toward the use of different types of LiDAR for data acquisition. These include the extent of the area to be mapped, the type of project, the terrain, and time sensitivity.(39) Other factors that may influence the choice of LiDAR method include traffic conditions, whether there is a need to capture roadside features in addition to terrain, and whether there are opportunities to consolidate data acquisition for multiple uses. Table 11 reflects suitability of different LiDAR methods for different project characteristics.

Table 11. LiDAR method suitability for different project characteristics.

Project Characteristics	Aerial LiDAR	Mobile LiDAR	Static LiDAR
Green fields	Suitable	Not appropriate	Not appropriate
Existing roadway	Consider	Suitable	Consider
Large area	Suitable	Suitable	Not appropriate
Time sensitive	Consider	Consider	Suitable
Variable terrain	Suitable	Consider	Not appropriate
High traffic volumes	Suitable	Suitable	Consider
High traffic speeds	Suitable	Suitable	Consider
Urban area	Consider	Suitable	Suitable

As LiDAR hardware and software technology evolves, thresholds for different methods will change. For example, setup speeds, effective ranges, and other limiting factors will improve, while data filtering and processing times will decline. Table 12 lists project characteristics favorable for data collection using aerial LiDAR, mobile LiDAR, and static LiDAR.(39,36) Individual LiDAR methods may become more broadly applicable than those shown in table 12. In many circumstances, field survey methods may be more efficient than LiDAR, particularly smaller projects. Field survey will usually be necessary for setting control, collecting subsurface utility locations and inverts, and collecting positions of constraint features (as defined in table 8).

Table 12. Project characteristics favorable for different LiDAR methods.

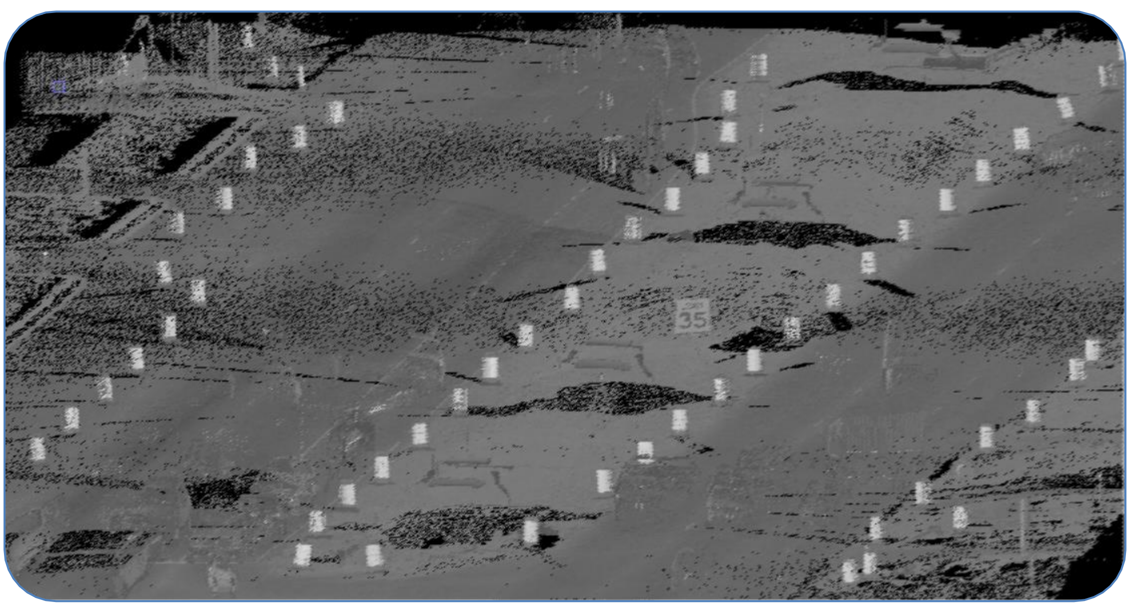
Aerial LiDAR	Mobile LiDAR	Static LiDAR
• Mainline lengths > 1,300 ft • Large areas and wide corridors • Large bridge replacements • Variable terrain • Rural reconstructions • Areas with limited foliage	• Long, rural corridors • High-speed corridors • Corridors with high volumes • Multilevel interchanges • Resurfacing projects with cross-slope or super-elevation corrections • Data collection time constraints	• Mainline lengths < 1,300 ft • Small areas • At-grade intersections • Low-volume and low-speed roadways • Flat terrain • Small bridge replacements • Urban resurfacing projects with drainage or cross-slope repairs • Interstate widening

Regardless of the method of collection, LiDAR acquires vast amounts of data.(2) It is prone to collecting “noise” (i.e., observations that are artefacts of collection or mobile obstructions like passing vehicles, birds, survey setups, tripods holding temporary control, and even surveyors themselves). The effort to perform quality control, filter, register, classify, and extract topographic mapping products from LiDAR data is non-trivial, as is the challenge of managing the large datasets. The benefits of mobile LiDAR in particular are best realized where the datasets are shared between many applications.(2)

In addition to topographic mapping deliverables, it is desirable that the surveyor provide detailed metadata, a survey narrative report that includes the quality control details, the registered point cloud, the raw point files in E57 format (developed by the ASTM E57.04 Data Interoperability Subcommittee), and, if available, digital photo mosaic files.(36,40)

NON-TRADITIONAL SURVEY PRODUCTS

New methods of survey data capture (i.e., LiDAR) enable surveyors to capture a vast collection of survey points in a short period. These points can be collected in such a dense collection, called a “point cloud,” as to depict the full scene within the sensor’s line of sight. The density of points is such that a full scene can often be understood and interpreted. Point clouds have been used to check clearances for construction equipment, plan construction activities in constrained areas, and view complex existing structures and features like bridges and historic buildings that would otherwise be challenging to model. In figure 13, the striping, traffic control barrels, and a speed limit sign are evident amid “noise” from scan setups and passing vehicles.



Source: FHWA.

Figure 13. Illustration. Unfiltered point cloud.

For many applications, LiDAR captures too many points, and the data need extensive filtering and processing to produce a workable dataset. While not useful for normal design, right-of-way, and construction processes, the unprocessed datasets can be useful for other functions. Software tools are emerging to extract 3D solid primitives from the point cloud to better use computer clash detection algorithms or for 4D or 5D modeling.

CHAPTER 7. SUBSURFACE UTILITY LOCATION

Subsurface utility location and relocation within the right-of-way constitute leading causes for delays for highway and bridge construction projects. Several aspects of utility location, including identification of the type of utilities and the format, accuracy, and sources of their positional and other attribute data, are often problematic to identify from existing records and are flagged as project risks. Consequently, design cannot progress without expensive location identification investigations during construction. This chapter covers the following topics:

- Purpose of SUE.
- Data quality levels and applications.
- Data quality levels and applications in project delivery.
- How to use 3D subsurface utility location information.

At the time of mapping, it is not always clear which subsurface utilities need to be located with high accuracy. Traditional locating methods result in low quality data that is often only 2D. As the design matures, subsurface utility location information should be reviewed, and supplemental information of higher accuracy should be obtained where warranted.

PURPOSE OF SUE

Ownership of the utility location data is a source of risk. Even though the utilities of concern are located with the highway right-of-way, the data regarding the utilities are often owned and updated by utility companies and not coordinated with the enterprise data stores of State transportation departments. Predominantly, the main repository for geospatial data describing subsurface utilities is typically each individual utility owner's GIS. These records often do not specify the spatial integrity of the data (i.e., the vertical and horizontal positional accuracy), making it difficult to rely on them for accurate 3D model development. Moreover, these data are slow to update or seldom updated when routine maintenance, repair, or rehabilitation work is performed on the utilities. This means that users of the data (e.g., highway designers and construction personnel and their contractors) must assume the lowest accuracy level associated with the survey data, resulting in uncertainty in decisionmaking and potential for costly investigations or rework. Conversely, there are many benefits to well-documented utility information, including the following:[41]

- Unnecessary utility relocations are avoided. Accurate utility information is available to the highway designers early enough in the development of a project to design around many potential conflicts. This significantly reduces the following:
    - Costly relocations normally necessitated by highway construction projects.
    - Delays to the project caused by waiting for utility work to be completed so highway construction can begin.

- Unexpected conflicts with utilities are eliminated. The exact location of virtually all utilities can be determined and accurately shown on the construction plans. As a result, the following are reduced:
    - Delays caused by redesign when utility conflicts prevent construction from following the original design.
    - Construction delays caused by cutting, damaging, or discovering unidentified utility lines.
    - Contractor claims for delays resulting from unexpected encounters with utilities.
- Safety is enhanced. When excavation or grading work is shifted away from existing utilities, there is less possibility of damage to a utility that might result in personal injury, property damage, or release of harmful products into the environment.

DATA QUALITY LEVELS AND APPLICATIONS

The use of the ASCE 38-02 quality levels in the SUE process allows designers to certify a certain level of accuracy and comprehensiveness on their plans.(28,29) There are four quality levels described in ASCE 38-02 (levels A through D), which are described as follows:(29.41)

- **Quality level A (QL-A)**: Also known as "locating," QL-A is the highest level of accuracy presently available and involves the full use of the SUE services. It provides information for the precise plan and profile mapping of underground utilities through the nondestructive exposure of underground utilities and also provides the type, size, condition, material, and other characteristics of underground features.
- **Quality level B (QL-B)**: QL-B involves the application of appropriate surface geophysical methods to determine the existence and horizontal position of virtually all utilities within the project limits. This activity is called "designating." The information obtained in this manner is surveyed to project control. It addresses problems caused by inaccurate utility records, abandoned or unrecorded facilities, and lost references. The proper selection and application of surface geophysical techniques for achieving QL-B data is critical. Information provided by QL-B can enable the accomplishment of preliminary engineering goals. Decisions regarding location of storm drainage systems, footers, foundations, and other design features can be made to successfully avoid conflicts with existing utilities. Slight adjustments in design can produce substantial cost savings by eliminating utility relocations.
- **Quality level C (QL-C)**: QL-C is probably the most commonly used level of information. It involves surveying visible utility facilities (e.g., manholes, valve boxes, etc.) and correlating this information with existing utility records (quality level D (QL-D) information). When using this information, it is not unusual to find that many underground utilities have been either omitted or erroneously plotted. Its usefulness, therefore, is primarily

on rural projects where utilities are not prevalent or are not too expensive to repair or relocate.

- **QL-D**: QL-D is the most basic level of information for utility locations. It may provide an overall feel for the congestion of utilities, but it is often highly limited in terms of comprehensiveness and accuracy. QL-D is useful primarily for project planning and route selection activities.

Table 13 summarizes applicable locating technologies and the resulting data by quality level.

Table 13. Locating technologies and resulting data for different quality levels.

Quality Level	Applicable Locating Technologies	Resulting Data
QL-A	Vacuum excavator and potholing	Precise horizontal and vertical position at discrete locations (discontinuous)
QL-B	• **Subsurface geophysics**: Ground penetrating radar • **Electromagnetic**: Inductive, conductive, active, and passive pipe and cable locators	Designated horizontal and vertical location
QL-C	Surveying visible presence of utilities (e.g., valve boxes, manhole covers, etc.)	Positive indicator of presence of a utility; inferred horizontal location
QL-D	Existing utility records and verbal sources	Inferred presence of a utility

DATA QUALITY LEVELS AND APPLICATIONS IN PROJECT DELIVERY

There is a trade-off between data quality levels and project costs. While QL-A provides the highest data quality, the precise nature of subsurface utility location and utility attribution associated with it make this quality level the most expensive to achieve. Conversely, QL-D is less accurate and hence can be achieved at a lower cost. Therefore, data collection at a given quality level needs to be selected in the context of the adjacent construction activities and the maturity of the design. Utilities located in close proximity to excavation or foundation construction warrant collection of higher accuracy subsurface utility location information. Figure 14 is a workflow for selecting appropriate subsurface utility locating technologies at each design milestone, from project scoping to preparation of bid documents.

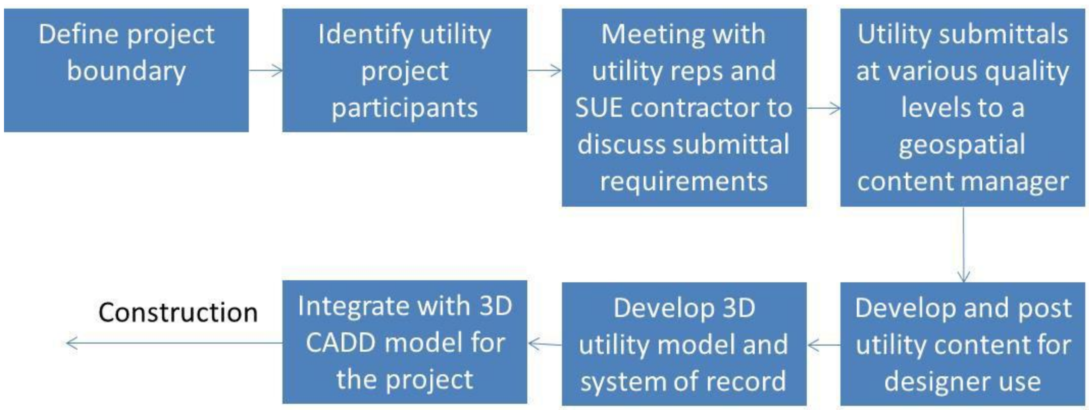
Source: FHWA.

Figure 14. Flowchart. Selecting subsurface utility locating techniques.

The need for different quality levels changes through design and construction. In construction, QL-A information is necessary for any utilities that are near excavation activities. Often, the responsibility for collecting QL-A information is left to the contractor, who bears all risk for utility strikes. The quality of subsurface utility records should be reevaluated at design milestones so that more accurate location information can be acquired where warranted.

USING 3D SUBSURFACE UTILITY LOCATION INFORMATION

While subsurface utility information is 3D in nature, using the 3D information can provide a false sense of security if the quality of the 3D data is not clear. As noted previously, there is inherent uncertainty in utility locations at all quality levels. Data with the highest level of accuracy (QL-A) can be useful for clash detection. QL-B data can also be used in clash detection if the utility location is buffered sufficiently to represent the location uncertainty. Figure 15 presents a workflow for integrating 3D subsurface utility data with CADD software to develop either 3D models or 2D project plans for final design and construction purposes.



Source: FHWA.

Figure 15. Flowchart. Integrating 3D utility data into 3D model or project plans.

The 3D models of subsurface utilities should be organized to distinguish the different quality levels for plans production and clash detection. Two effective strategies for doing so are separating CADD data into separate files or data layers for each quality level and using color on plans to distinguish between different quality levels. Separate CADD files support the seamless generating rules for clash detection algorithms that apply a buffer to utilities of different quality levels (e.g., 6 inches on QL-A and larger on other quality levels).

The most laborious and expensive part of the workflow is utility submittals and their certification in the content manager for design use. This workflow is recommended to be used on major projects where utility conflicts are identified as a substantial risk. However, it is encouraged that all projects using automation technology consider capturing as-built utilities for newly constructed, located, or relocated utility features within the right-of-way while the project is still under construction. If performed well, this effort has the real ability to augment and refine the design-level SUE mapping of the utilities and further reduce uncertainty for future projects or excavation in the same area. An ASCE committee is currently developing a standard for utility as-built records, as reported by FHWA.(42)

There is substantial long-term value in capturing accurate subsurface utility location information during construction as existing or new utilities are exposed during excavation, relocation, or installation. When survey equipment is nearby, the cost of capturing this information is low in comparison to collecting the information once the utilities are buried.

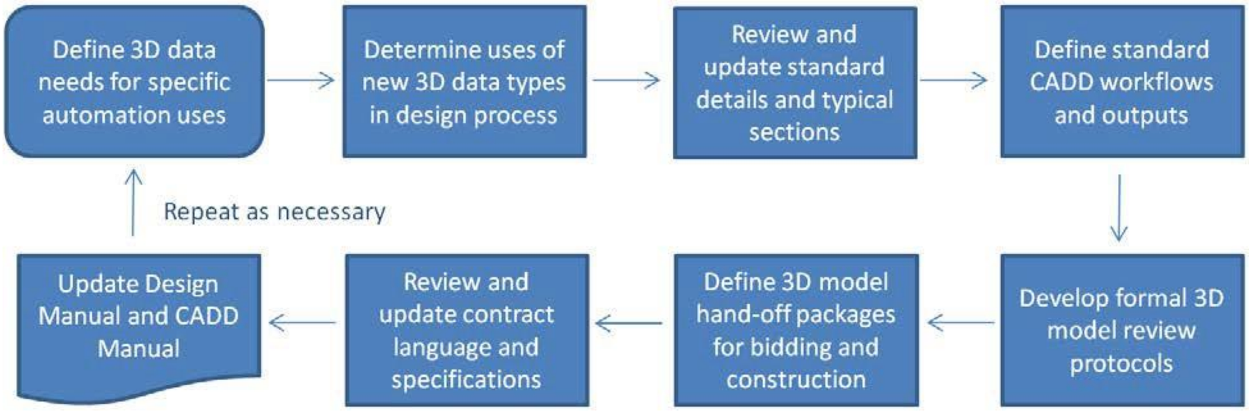
CHAPTER 8. DESIGN

The completeness and reliability of 3D design data is within the designer's control. Designers need to understand how 3D data will be used in order to create 3D design data that meets the needs of the specific automation technology and share it with confidence. The 3D design can be a dense model that depicts the design intent with sufficient accuracy to be used in construction for both AMG and real-time verification. Other uses of 3D design data (e.g., SUE and 4D modeling) do not usually need such high levels of detail or accuracy in the 3D models. This chapter covers the following topics:

- Applications in design development.
- Considerations for standard details.
- CADD data types and 3D modeling approaches.
- Guide 3D model standard.
- Guide 4D and 5D model specification.
- Guide 3D data review protocols.
- Contract documents.

Designers can adjust the level of effort invested in creating 3D design data to meet the expected uses of that data. There is less value in a detailed 3D model if the underlying survey data are of low accuracy. The designer can acquire topographic survey data at the needed accuracy, invest in subsurface utility mapping and subsurface utility locating, and take time to model out design intent in detail. At the project level, it is helpful if this flexibility is customer-focused on the specific automation technology needs. However, in design-bid-build delivery, it can be difficult to know how automation will be used in construction. Some degree of standardization is useful in the design process and is valuable once construction begins. During design, standardization provides flexibility in resourcing design production and consistency in design review. During construction, it provides predictability and repeatability to contractors and inspectors who use the data.

There is more to implementing 3D design than just getting more accurate survey data and adding additional detail in CADD. There are opportunities to use the 3D design models to develop more refined designs and compute quantities more accurately or more efficiently. Some standard details can be modified to add design and construction efficiencies. Design model standardization and quality control protocols lead to consistent, reliable data for automation in highway construction. There may be a desire for 3D models to supersede plans for automation, and other specification language can be modified to manage automation in highway construction. Figure 16 is a workflow for updating design policies to produce 3D data for automation.

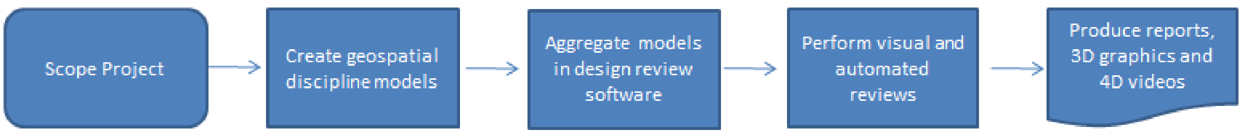


Source: FHWA.

Figure 16. Flowchart. Updating design policy documents to produce 3D data for automation in highway construction.

APPLICATIONS IN DESIGN DEVELOPMENT

The 3D models created during the process of developing and documenting designs can be used to inform the decisions made during the development of the designs. Furthermore, the design development process has several design review and public involvement milestones that can be enhanced by formal processes for using the 3D design models in those reviews. Figure 17 is a workflow for using 3D models during design development.



Source: FHWA.

Figure 17. Flowchart. Using 3D models in design development.

Table 14 lists potential applications of 3D models at milestones during design development.

Table 14. Applications of 3D models during design development.[12]

Design Stage	3D Design Model Elements	3D Design Model Uses
National Environmental Policy Act of 1969 (NEPA) (15 percent)[43]	• Existing conditions surface • Low-density proposed surfaces • Proposed roadway corridor models • Proposed structures (extent, type, etc.) • Existing and proposed utilities	• Quantify impacts on sensitive environments • Minimize ROW impacts • Compute preliminary quantities • Review proof-of-concept constructability • Minimize utility relocations (clash avoidance) • Plan surface drainage systems

Design Stage	3D Design Model Elements	3D Design Model Uses
Preliminary (30 percent)	• Existing conditions surface • Low-density proposed surfaces • Proposed roadway corridor models • Proposed structures (external faces) • Existing and proposed utilities • Storm drainage systems	• Check site distance • Perform visual impact analyses • Minimize ROW impacts • Optimize earthwork quantities • Coordinate interdisciplinary design • Perform staging and constructability reviews • Minimize utility relocations (clash avoidance) • Create preliminary plans and estimates
Final NEPA (70 percent)	• Existing conditions surface • Medium-density proposed surfaces • Proposed roadway corridor models • Proposed structures (external faces) • Existing and proposed utilities • Storm drainage systems	• Check site distance • Perform visual impact analyses • Review surface drainage • Coordinate interdisciplinary design • Create 3D graphics and 4D videos for ROW acquisition and public involvement • Compute quantities • Perform staging and constructability reviews • Conduct maintenance of traffic conceptual planning • Create ROW and utility relocation plans
Final plans (90 percent)	• Existing conditions surface • High-density proposed surfaces • Proposed roadway corridor models • Proposed structures (major systems) • Existing and proposed utilities • Storm drainage systems	• Design validation and interdisciplinary review • Create 3D graphics for public involvement • Create 4D videos for public involvement • Compute final quantities • Perform staging and constructability reviews • Conduct maintenance of traffic review • Create contract plans and final estimate
Certify (95 percent)	• Existing conditions surface • Very high-density proposed surfaces • Proposed roadway corridor models • Proposed structures (major systems) • Existing and proposed utilities • Storm drainage systems	• Create bid documents • Create 3D model reference data

Design Stage	3D Design Model Elements	3D Design Model Uses
Award (100 percent)	• Existing conditions surface • Very high-density proposed surfaces • Proposed roadway corridor models • Proposed structures (major systems) • Existing and proposed utilities • Storm drainage systems	• Create contract documents • Create staking/layout data • Create AMG/real-time verification models

CONSIDERATIONS FOR STANDARD DETAILS

If something is hard to model, it is often also hard to construct. Some standard details are historic and inefficient for newer construction methods. A 3D modeling implementation is an opportunity to review standard details and consider their relevance to construction with automation technology.

Some considerations for reviewing standard details include estimating quantities and constructability in the context of modern methods with automation in highway construction. Some examples include the following:

- **Concrete pavements with integrated curbs**: Modern pavers can pave a lane with an integrated curb in a single pass. Typical sections can be modified to reflect the most commonly supported shapes.

- **Bridge abutment slopes and culvert headwall grading**: AMG systems are being installed on a wider range of construction equipment, even as small as a skid steer. Modifications to the abutment and headwall standards may make these easier to model and easier to construct.

- **Superelevation**: Superelevation attainment usually happens at a constant rate, but some agencies allow a variable rate from one super-elevation critical station to another. These variations in superelevation attainment rate will be constructed as designed by precise AMG systems, which will create a noticeable change in the roadway.

CADD DATA TYPES AND 3D MODELING APPROACHES

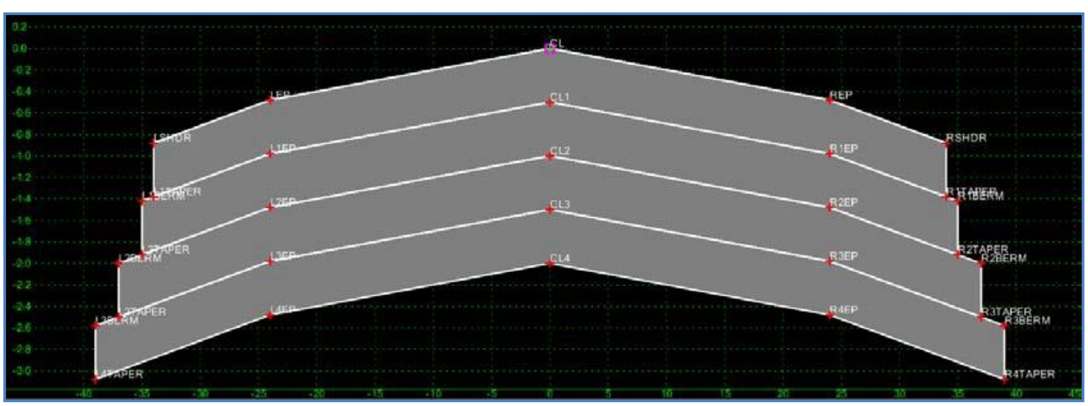
CADD software provides flexible and efficient 3D modeling tools that incorporate roadway geometrics and rules-based layout to create the roadway in 3D. The primary tool for creating 3D models of linear features like roadways is the corridor model. String models are growing in popularity, given their flexibility for modeling elements that are not parallel to the alignment. It is sometimes useful to manually edit features (e.g., manually grade small areas or to tidy up the interface between corridor and/or string models). Given the differences in data types and outputs from these different modeling methods, it is useful for an agency to standardize methods for modeling different design elements.

Many State transportation departments provide the building blocks for modeling common roadway design elements with corridor and string models as part of their standard CADD resource files. Especially for visualization, 3D solids modeling still has its place. Table 15 describes four common methods of creating 3D models and provides examples for each method.

Table 15. CADD design methods and their uses.

Design Method	Description
Corridor model	Corridor models compute the parametric rules of the typical section (also called a “template”) at defined stations (also called “template drops”). This is the most common tool for modeling linear elements that are generally regular in shape parallel to the alignment. Standard uses of corridor models include roadways and ditches. Advanced uses of corridor models include retaining walls, bridge abutments, and intersections.
String model	String models use rules to offset linear features horizontally and vertically. This is a common tool for modeling non-linear features that follow consistent rules perpendicular to the base feature. Standard uses of string models are drainage basins and parking lots. Advanced uses include intersections and lane transitions.
Feature modeling	Features are 3D line strings. Features can be created manually or output from corridor or string models. This is a common tool for manually grading small areas like around headwalls. Features need to be added to surfaces as break lines.
3D solid modeling	3D solids modeling does not follow roadway geometric rules and is usually a manual process. It is possible to create a library of 3D solid model elements like standard headwalls, light standards, and sign posts.

Figure 18 shows a template for a two-lane road with shoulders and four pavement layers. The template consists of points that have defined locations relative to the insertion point. The insertion point lies on the alignment and profile in 3D space. Each point on the template has a point name (e.g., centerline (CL) on the crown in figure 18). Points with like names are connected from one template drop to another to create 3D features that are generally parallel to the alignment. Corridors can output 3D components that are created by extruding the enclosed shapes of the typical section between two template drops. Surfaces can also be produced directly from corridor models by triangulating points with defined names between template drops.

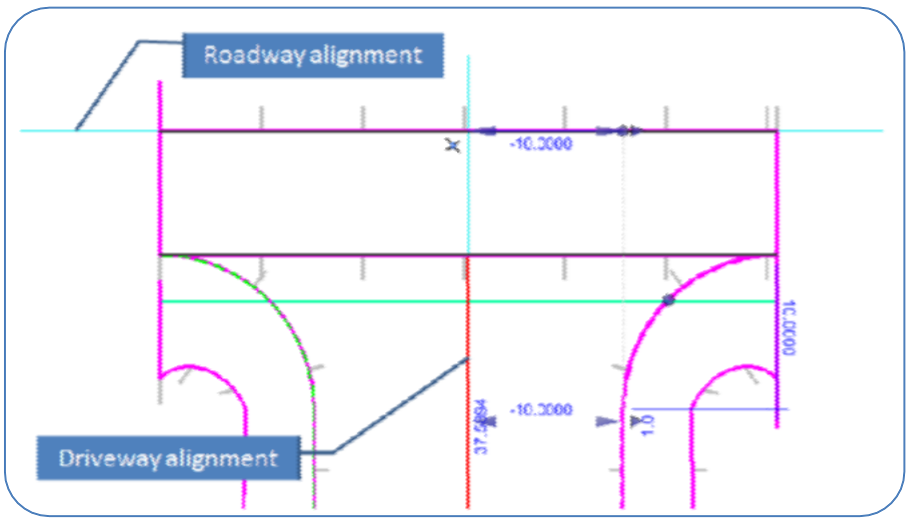


Source: FHWA.

Figure 18. Illustration. CADD template representing a two-lane road with shoulders.

As the basis of corridor models, a standard template library is an important part of a CADD standard. Point and feature names are needed for stake out, AMG and automation processes for inspection. The point and feature names are used to select data on the data collector. In figure 18, the finished ground surface was created by triangulating points labeled "LSHDR (left shoulder)," "LEP (left edge of pavement)," "CL," "REP (right edge of pavement)," and "RSHDR (right shoulder)." The subgrade surface was created by triangulating points named "4LTAPER" (left taper), "L4EP" (left edge of pavement for layer 4/subgrade), "CL4" (centerline for layer 4/subgrade), "R4EP" (right edge of pavement for layer 4/subgrade), and "R4TAPER" (right taper). A 3D feature for the left edge of pavement was created by connecting the LEP points.

String models also output 3D features and surfaces. String models should use the same standard point or feature names to provide consistent 3D line strings that are connected where corridor and string models interface. Figure 19 shows the rules embedded in a string model to create a 20-ft-wide driveway connection with a 10-ft-radius curb return to the edge of lane for the primary road.



Source: FHWA.

Figure 19. Illustration. String model that uses rules to offset the baseline horizontally and vertically.

Surfaces and features are output from corridor and string models. They can be manually adjusted by editing the features or creating new features and writing them to the surface definition. Care should be taken in considering which features to include in a surface definition. In urban areas with curb and gutter and median islands, it should be considered what value is added by incorporating these features into the surface. TIN surfaces cannot include vertical faces; curbs and retaining walls can be challenging to incorporate into a surface model. These elements may be better represented as 3D solids (also called components), which can be output from the corridor model in addition to 3D features.

Many design elements can be modeled in different ways. For instance, intersections can be modeled with corridor or string models. Some site conditions may favor one tool over another, or one CADD software product may be stronger in one method over another. Table 16 relates specific 3D model content to the CADD design methods that can generate that content and the CADD data format that is needed for automation in highway construction.

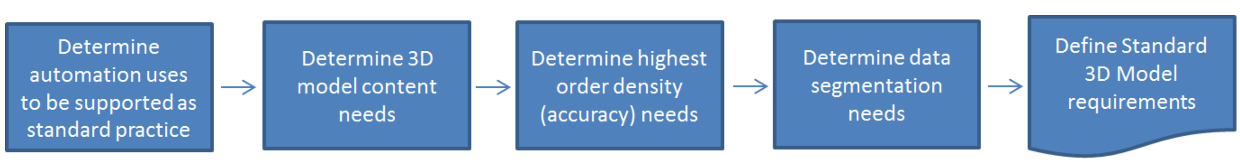
Table 16. 3D Model content by CADD data type.

Feature	CADD Design Method	CADD Data Type
Roadways	Corridor model	Alignment, surface, and 3D line strings
Side slopes	Corridor or string model	Surface and 3D line strings
Gore areas	Corridor, string or feature modeling	Surface and 3D line strings
Intersections	Corridor or string model	Alignment, surface, and 3D line strings
Interchanges	Corridor or string model	Alignment, surface, and 3D line strings
Sidewalks and paths	Corridor or string model	Surface and 3D line strings
Lane width transitions	Corridor or string model	Surface and 3D line strings
Culvert headwall grading	String model or feature modeling	Surface and 3D line strings
Guardrail berm transitions	Corridor, string, or feature modeling	Surface and 3D line strings
Benching transitions	Corridor, string, or feature modeling	Surface and 3D line strings
Bridge abutments	Corridor or string model	Surface and 3D line strings
Storm water ponds	String or feature modeling	Surface and 3D line strings
Ditches and swales	Corridor, string, or feature modeling	Surface and 3D line strings
Pavement markings	Corridor, string, or feature modeling	3D line strings
Curbs and gutters	Corridor, string, or feature modeling	3D line string (flow line) 3D line string (top of curb)
Retaining walls	Corridor, string, or feature modeling	3D line strings

GUIDE 3D MODEL STANDARD

There are three components to defining a 3D model standard. A 3D model standard must define what to model and how much detail to model it in.[12] The first component is the density of the data in the corridor and surface models. Density in this case is a proxy for accuracy. The second component is a description of what features or elements to include in the model. The third component is the segmentation of the data.

Corridor and surface models are usually aggregate (e.g., representing the entire completed facility). It can be helpful to segment the data into construction stages, and it is necessary to do so for 4D modeling. Data segmentation can also be beneficial to the designers, allowing different parts of the design to progress concurrently. Figure 20 shows the workflow to create a standard 3D model specification.



Source: FHWA.

Figure 20. Flowchart. Creating a standard 3D model specification.

The descriptions of content, density, and data segmentation that follow are not universally applicable to all project types. It can be helpful to define global inclusion or exclusion criteria for creating 3D models.[44,7]

3D Model Content

As shown in figure 20, automation uses provide the requirements of the 3D model in terms of data content, data density, and data segmentation. An implementing agency needs to consider which automation technology uses it is worth supporting and the impact of creating the data on design processes relative to the value the agency will realize from using this data. The data needs for construction are often simple. A 3D line string for the bottom of the trench can suffice for excavation. Much of the needed data is already created in the process of creating plans. The effort is in isolating that data and presenting it in an organized, easily consumable format.

The challenge of preempting automation in highway construction is not unique to designers; preempting construction uses is necessary to capture survey data with the needed resolution as was shown in figure 10. Table 17 uses the same project type organization and AMG methods provided in table 9 to present 3D model content needs. Table 17 also provides inclusion criteria by more specific project characteristics based on the likelihood of using the data for AMG.

Table 17. 3D Model content by project type and applicable AMG methods.

Project Type	Applicable AMG Method	3D Design Data Content
Asphalt mill and pave with ride improvements	2D sonic averaging for milling and paving	No design data required
Asphalt mill and pave with cross slope or drainage correction (hard tie-ins only at start and end)	2D sonic averaging for milling and paving	No design data required
Asphalt mill and pave with cross slope or drainage correction (tie to hard surface or curb and gutter)	3D profile milling with constant depth or 2D paving Alternately: constant depth milling and 3D paving	• **DTM**: Finished grade surface • **Alignment**: Primary horizontal and vertical geometrics and super-elevation • **3D line strings**: Crown, edges of pavement, grade breaks, top of curb, and flow lines
Concrete overlay with or without ride and drainage corrections	3D paving	• **DTM**: Finished grade surface • **Alignment**: Primary horizontal and vertical geometrics and super-elevation • **3D line strings**: Crown, edges of pavement, grade breaks, top of curb, and flow lines
Reclamation	Grading, fine grading, base, and paving	• **DTM**: Finished grade surface • **Alignment**: Primary horizontal and vertical geometrics and super-elevation • **3D line strings**: Crown, edges of pavement, edges of shoulder, grade breaks, and ditch flow lines

Shoulder and side slope widening or improvements	Grading, fine grading, base, and paving	• **DTM**: Finished grade surface • **Alignment**: Primary horizontal and vertical geometrics and super-elevation • **3D line strings**: Saw cut line, edge of shoulder, grade breaks, and ditch flow lines
Lane widening	Grading, fine grading, base, and paving	• **DTM**: Finished grade surface • **Alignment**: Primary horizontal and vertical geometrics and super-elevation • **3D line strings**: Saw cut line, edge of pavement, edge of shoulder, grade breaks, ditch flow lines, or top of curb and gutter flow line
Reconstruction	Grading, fine grading, base, and paving; possibly 3D profile milling and excavation	• **DTM**: Finished grade and subgrade surfaces • **Alignment**: Primary horizontal and vertical geometrics and super-elevation • **3D line strings**: Crown, edges of pavement, edges of shoulder, grade breaks, ditch flow lines, or top of curb and gutter flow line
New construction	Grading, fine grading, base; and paving; excavation	• **DTM**: Finished grade and subgrade surfaces • **Alignment**: All horizontal and vertical geometrics and super-elevation • **3D line strings**: Crown, edges of pavement, edges of shoulder, grade breaks, ditch flow lines, or top of curb and gutter flow lines

New AMG methods will continue to emerge or become more common. Automation for construction engineering and inspection may have 3D model uses regardless of what method the contractor employs. In addition to the AMG methods listed in table 9 and table 17, AMG is also used for excavation, striping, and slip forming concrete medians and curbs, among other activities. These methods may all be appropriate on a variety of projects. The flexibility to provide this data when warranted comes in establishing the CADD resource files to produce it.

The design process is iterative, and some design elements are not refined until later in the process when the roadway geometrics and other constraints have been determined. Table 18 lists the design elements needed for automation in highway construction and the optimum time to invest in modeling them during the design process. Table 18 is adapted from design manuals from Michigan, Oregon, Missouri, and Iowa. (See references 7 and 44–46.)

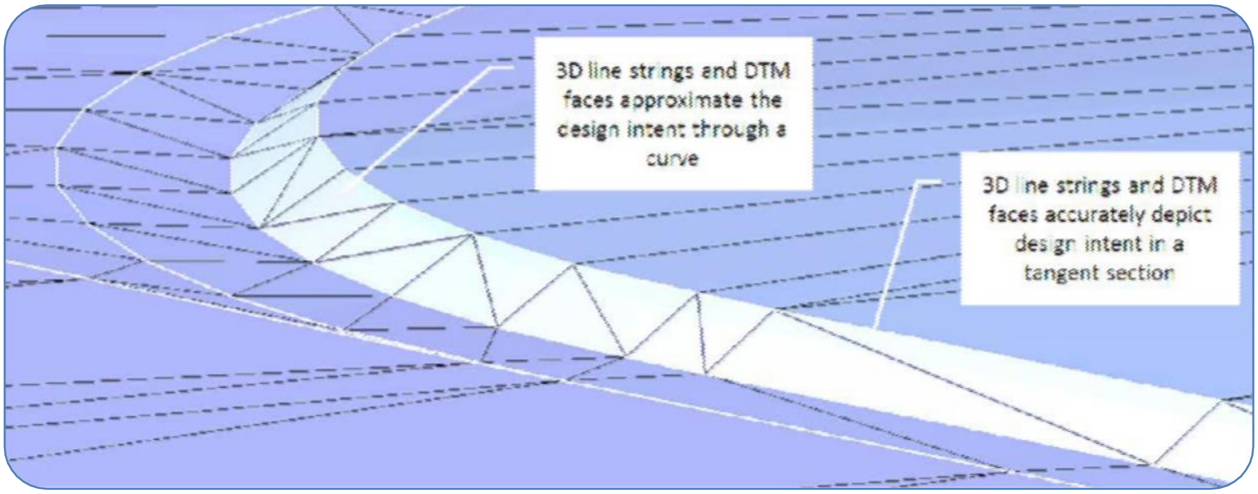
Table 18. 3D Model content by design milestone.

Features	Design Stage		
	Preliminary (30 Percent)	**Final NEPA (70 Percent)**	**Final Plans (90 Percent)**
Roadways—top surfaces	Yes	Yes	Yes
Roadways—interim surfaces	No	No	Yes
Roadways—subgrade surface	Yes	Yes	Yes
Side slopes	Yes	Yes	Yes
Gore areas	Yes	Yes	Yes
Intersections	Yes	Yes	Yes
Interchanges	Yes	Yes	Yes
Medians and cross-overs	No	Yes	Yes
Sidewalks and paths	No	Yes	Yes
Lane width transitions	Yes	Yes	Yes
Culvert headwall grading	No	No	Yes
Guardrail berm transitions	No	No	Yes
Benching transitions	No	Yes	Yes
Bridge abutments	No	Yes	Yes
Storm water ponds	Yes	Yes	Yes
Ditches and swales	Yes	Yes	Yes
Pavement markings	Yes	Yes	Yes
Curbs and gutters	Yes	Yes	Yes
Retaining walls	Yes	Yes	Yes

Interim roadway surfaces noted in table 18 may include excavation below subgrade (undercut), subbase, and base surfaces.(47) The design elements listed in table 16 and table 18 are by no means exhaustive. There may be uses for other design elements either during design or construction. Some of these elements are relatively easy to incorporate into corridor templates and can aid in creating plans, visualizations, or stake-out information. These elements include concrete median barriers, raised median islands, and guardrails.

3D Model Density

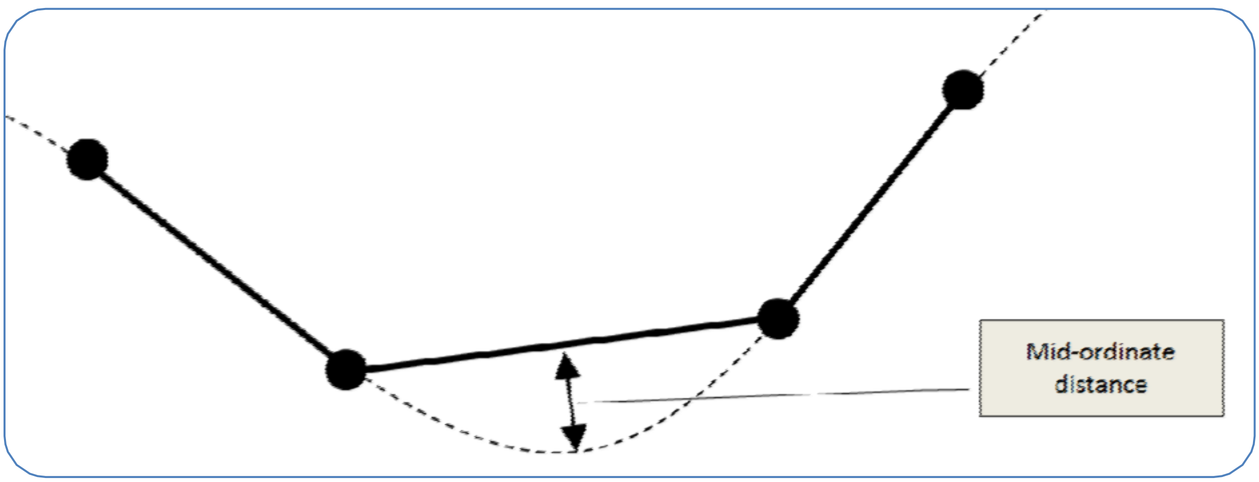
Designers know that CADD data are incomplete and imperfect. Surface models (DTMs) and 3D line strings are approximations. They are exact through horizontal and vertical tangents and other areas of constant grade. Once horizontal or vertical curvature is introduced, the DTM or 3D line string is an approximation, as in figure 21, which shows the DTM approximation of a curb and gutter around a curb return.



Source: FHWA.

Figure 21. Illustration. Approximation of curved objects in DTMs and 3D line strings.

As figure 22 shows, the 3D line string or DTM is as accurate as the mid-ordinate distance, which is the distance between the chord and the true arc or between the TIN face and the curved surface. The mid-ordinate distance (also called the "chord height") is proportional to the chord length, which is a function of the point density in the surface. The mid-ordinate distance represents the accuracy with which the model represents the design. Some CADD software can automatically densify the surface to keep the mid-ordinate distance to a maximum value.



Source: FHWA.

Figure 22. Illustration. Mid-ordinate distance.

AMG and field survey equipment measures with high accuracy relative to the model that formed the basis of AMG operations. This is an important distinction, because relative to the idealized design, the inherent error in the AMG and real-time verification hardware is compounded with the error within the model. However, this is immaterial to acceptable construction outcomes. Staking accuracy and AMG tolerance are not the same. AMG and real-time verification require 3D models with network accuracy that matches the staking tolerance. Much like for surveying, increased accuracy in design increases effort and there is a limit at which more value can be realized.

Some AMG systems can construct to within 0.02 ft tolerance of the 3D model that is loaded in the onboard computer. That does not mean that the design needs a mid-ordinate distance of 0.02 ft or less. The high vertical accuracy on the AMG equipment and the inspector's equipment ensures that there is consistent depth for good compaction and yields, not for ride quality or safety. Indeed, staking tolerance is typically lower than the nominal accuracy of AMG systems.

Corridor and string modeling methods have settings to control density. For corridor modeling, the setting is the template drop interval, which is set for each template or defined station range in the corridor. Different intervals can be established for horizontal and vertical tangents and curves. It is often useful to manually insert an additional template drop immediately before or after an abrupt change in template.(44) Template drops can be placed automatically at key stations that are defined by horizontal, vertical, or offset geometrics. The design manuals for the Iowa Department of Transportation (Iowa DOT), ODOT, and WisDOT recommend the following key stations:(46,44,47)

- Horizontal geometry points (e.g., begin/end points of curve and spiral).
- Vertical geometry points (e.g., high/low points and begin/end of vertical curve).
- Superelevation stations (e.g., reverse crown and begin full super-elevation).
- Offset horizontal geometry points (e.g., begin/end of lane tapers and curb return points).
- Drainage facilities (e.g., inlets and culvert inverts).
- Guardrail and barrier limits.

The density of the 3D model affects performance of the software and can take time to insert, particularly at the interfaces between corridor and/or string models where manual edits might be needed. As described previously, some design elements are not refined until later in the process when the roadway geometrics and other constraints have been determined. Table 19 describes the density recommended at each of the design milestones. The table is adapted from design manuals from Iowa DOT, MDOT, ODOT, and WisDOT. (See references 46, 7, 44, and 47.)

Table 19. 3D Model density by design milestone.

Features	Design Stage: Preliminary (30 Percent)	Design Stage: Final NEPA (70 Percent)	Design Stage: Final Plans (90 Percent)
Roadways	25 ft in curves; 100 ft in tangents	10 ft in curves; 25 ft in tangents	1 ft in curves; 5 ft in tangents
Side slopes	25 ft in curves; 100 ft in tangents	10 ft in curves; 25 ft in tangents	1 ft in curves; 5 ft in tangents
Gore areas	10 ft	5 ft	1 ft
Intersections	5 ft	5 ft	1 ft
Interchanges	25 ft	10 ft	1 ft in curves; 5 ft in tangents
Medians and cross-overs	Not required	5 ft	1 ft in curves; 5 ft in tangents
Sidewalks and paths	Not required	10 ft in curves; 25 ft in tangents	1 ft in curves; 5 ft in tangents
Lane width transitions	25 ft	10 ft	1 ft in curves; 5 ft in tangents
Culvert headwall grading	Not required	5 ft	1 ft
Guardrail berm transitions	Not required	5 ft	1 ft
Benching transitions	Not required	5 ft	1 ft
Bridge abutments	Not required	5 ft	1 ft
Storm water ponds	25 ft	10 ft	1 ft in curves; 5 ft in tangents
Ditches and swales	25 ft	10 ft	1 ft in curves; 5 ft in tangents
Pavement markings	25 ft	10 ft	1 ft in curves; 5 ft in tangents
Curbs and gutters	25 ft	10 ft	1 ft in curves; 5 ft in tangents
Retaining walls	25 ft	10 ft	1 ft in curves; 5 ft in tangents

3D Model Segmentation

Many State transportation departments already use data segmentation to manage CADD data during design development. There are design productivity reasons why this is helpful, including the following:[(7)]

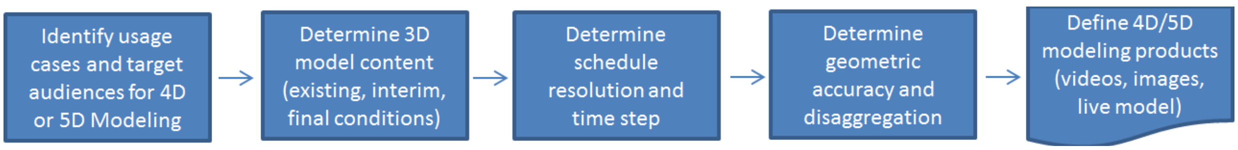
- Limiting file size to maintain software performance.
- Allowing multiple designers to progress different portions of the design concurrently.
- Allowing different disciplines to advance the design concurrently.

Document management is important, especially for interdisciplinary coordination. If possible, geographic segments should be defined in horizontal and vertical tangents.

Contractors can segment aggregate design data for their specific phasing during construction. Other than the design productivity reasons noted above, there may be a need to segment design data for 4D modeling.

GUIDE 4D AND 5D MODEL SPECIFICATION

A 4D model results from segmenting a 3D model and connecting discrete pieces of 3D geometry to tasks in a critical path method (CPM) schedule. When that CPM schedule is resource-loaded (usually with costs for each task), then the model is called a "5D model." How the 4D or 5D model is used defines the extent to which the 3D data need to be segmented and the need for supporting contextual models. Figure 23 is a workflow for creating a project-specific plan to use 4D or 5D modeling.



Source: FHWA.

Figure 23. Flowchart. Developing a 4D/5D modeling plan.

4D and 5D Model Usage Cases

Contractors and State transportation departments may choose to invest in 4D modeling for a variety of reasons. Common usage cases for 4D modeling during design development are still emerging.[48] Some usage cases may be to resolve technical issues related to particular design complexity or constructability constraints. These may require high 3D spatial accuracy and/or fine detail in the schedule to resolve. Other usage cases for 4D models have involved communicating with the public. These 4D models frequently do not need geometric accuracy or detailed schedules. Some of the reasons for creating a 4D or 5D model are indicated in table 20.

Table 20. Usage cases for 4D and 5D models.

Type of Analysis	Example Usage Case
Enhanced visualization	• Analyze impacts of different alternatives • Develop and communicate alternative technical concepts (ATCs) • Evaluate constructability • Illustrate complex traffic staging and detours • Manage public information
Estimate and resource optimization	• Optimize the critical path • Allocate resources • Accelerate/decelerate activities • Plan staging and equipment movements
Risk mitigation	• Accelerate bridge construction • Communicate risky activities for safety • Validate maintenance of traffic plans • Manage the interface between contracts
Construction progress and payment tracking	• Resolve or validate claims • Track progress • Track impact of contracting methods

The different usage cases shown in table 20 warrant the creation of a 4D or 5D model at a different time in the planning-design-construction process. Enhanced visualization usages may be warranted in the planning phase to engage the public on alternatives being studied, whereas tracking construction progress does not need to be started until after the preconstruction meeting.

4D and 5D Model Target Audiences

Before initiating the 4D or 5D modeling process, the last consideration is the target audience for the analysis products. The target audience determines the extent to which visualization is needed in creating the outputs. Whereas technical audiences can use rudimentary graphics, construction workers and the public may need rendered, textured models with surrounding context to provide landmarks and scale. CADD models can apply textures through predetermined styles that are also used for automating plan production. Example usage cases and the associated target audiences are shown in table 21.

Table 21. Target audiences for 4D and 5D models.

Target Audience	Example Usage Case
General public	• Communicate the impacts of different alternatives • Illustrate complex traffic staging and detours • Communicate ongoing construction activities • Illustrate the need for lane closures and detours
Technical professionals	• Analyze the impacts of different alternatives • Develop and communicate ATCs • Optimize the critical path • Plan accelerated bridge construction staging • Allocate resources • Evaluate constructability • Test means and methods • Assess the impact of accelerating/decelerating activities • Plan staging and equipment movements • Validate maintenance of traffic plans • Resolve or validate claims • Track progress • Track financial impact of different contracting methods (5D model) • Manage the interface between contracts
Construction workers	• Communicate risky activities for safety. • Communicate maintenance of traffic plans. • Communicate staging and equipment movements.

Steps in Creating 4D and 5D Models

4D and 5D models require careful planning to ensure that there is corresponding detail and organization between the 3D model and the CPM schedule and that the outputs have the right level of visual quality to resonate with the target audience.

Once the usage case, timing for initiation, and target audience have been determined, the following decisions need to be taken to scope the 4D or 5D mode to provide the necessary information to someone who will be tasked with preparing the 3D model and the CPM schedule:

- Define the 3D model in terms of scope (i.e., whole project or a limited area), accuracy, detail, disaggregation, and textures.

- Define the schedule in terms of scope (i.e., whole project or a limited time period), work breakdown structure (WBS) organization and detail (i.e., time step and disaggregation of tasks).

- Identify the responsibilities for data creation and sharing.

- Identify the need for maintaining and updating the 4D or 5D model.

Viewing 4D and 5D Models

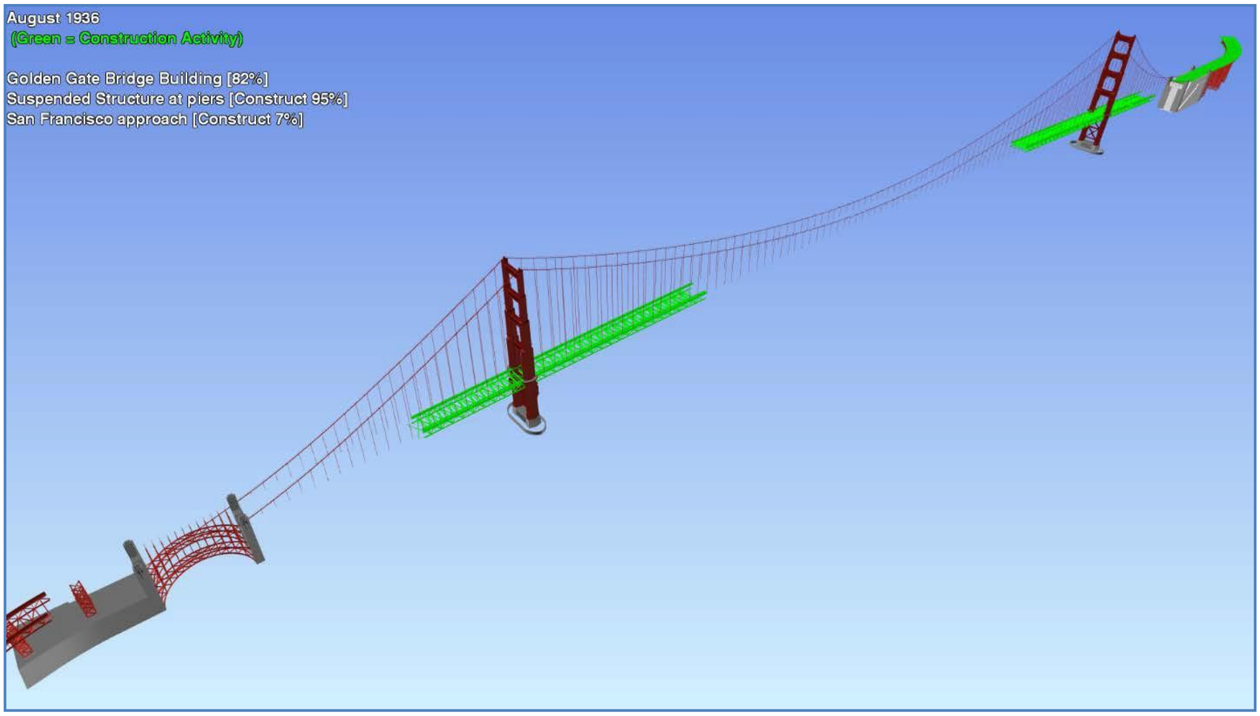
Technical audiences may be able to interact with the master 4D or 5D model in the model aggregation software. Within the software, the model can be navigated in 3D at any calendar date within the start and end date in the schedule. Simulations can be viewed coloring the existing, under construction, under demolition, and constructed elements according to a defined key. This key can be expanded (e.g., to include a color depicting cure times for concrete). (This cure period would need to be included in the WBS.)

Most 4D or 5D model authoring software is also capable of performing 3D clash detection not only for the overall project but also for schedule-based clashes that analyze clashes at each interval of the schedule time step (e.g., each week based on current existing, constructed, and under construction elements). Clash reports can be generated to document the identified issues and manage their resolution.

A range of outputs can be produced from 4D and 5D models. All of these outputs can either be textured (to be photorealistic) or untextured, depending on the needs of the target audience. These outputs include the following:

- 3D still images from a range of camera angles.
- 3D model images merged with photographs (via photo editing software).
- Sequential 3D still images from a single camera angle.
- Construction simulation videos.
- Drive-through videos from any calendar date (via visualization software).

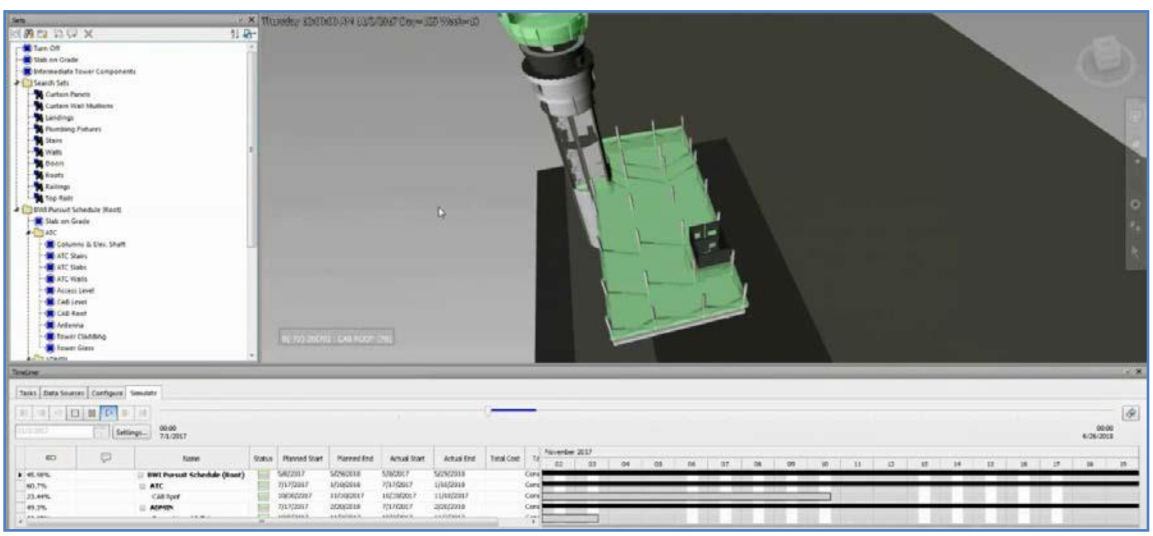
Figure 24 shows an example of a 3D still image intended for a technical audience. There is no context and no photorealistic textures applied to the 3D model elements. Colors depict constructed concrete (gray), steel (red), and elements under construction (green).



Source: FHWA.

Figure 24. Illustration. Example of a 3D still image from a 4D model for a technical audience.

Figure 25 shows a schedule simulation viewed within the 4D modeling software. On the left are the disaggregated 3D model selection sets representing collections of 3D geometry that match a task in the schedule. Below is the CPM schedule with task completion, name, planned and actual start and end dates, and a Gantt chart view. The blue slider between the 3D model and the Gantt chart allows users to select a calendar date along the construction timeline.



Source: FHWA.

Figure 25. Screenshot. Example of a construction sequence viewed in the 4D modeling software.

When detailed visualizations are needed, it is often necessary to separate the visualization models entirely from the design production CADD models. Rendering textured models can be processor-intensive, and highly detailed TIN models are inefficient. Visualization software can use polygon-based meshes, which are more efficient for rendering. However, polygon-based models are less accurate than the TIN models that are needed for AMG and real-time verification.

GUIDE 3D DATA REVIEW PROTOCOLS

Regardless of whether 3D data supersedes plans as the contract document or is supplemental to plans and subject to a hold-harmless agreement, there is a need for comprehensive review. This review is separate from design and constructability reviews but rather performs quality control on the data itself to ensure the following:

- It is consistent with plans and other contract documents.
- It accurately depicts the design intent.
- It meets the content, density, and segmentation requirements.
- It meets the needs of the intended construction uses.

Few organizations have formalized 3D data review protocols at the time this report was published. Some notable practices from Florida, Michigan, and Oregon include the following:(49,7,44)

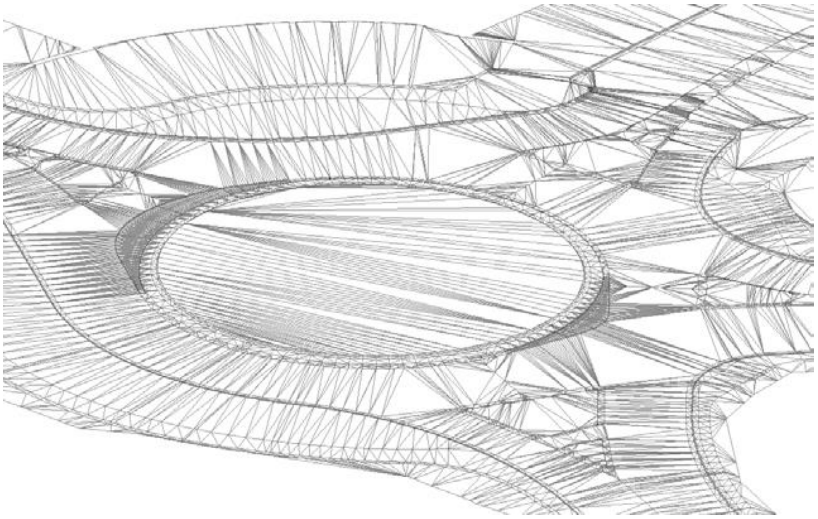
- Performing an independent 3D model review at normal plans review milestones.
- Having a person highly experienced in 3D modeling perform the review.
- Having a person with construction survey experience perform a review.
- Consolidating comments from each milestone into a single document.
- Reimporting translated data formats into the original design software to review.

Clash detection algorithms are effective at identifying and reporting physical conflicts that are unintended, but they are of little benefit where consistency is the intent, as with comparing plan lines with surface triangles. Most methods for reviewing 3D models currently rely on visual inspection. As a consequence, CADD standards need to be enforced with strong document management. Strategies for reviewing 3D data include the following:

- Checking compliance with CADD standards.
- Checking compliance with document management protocols.
- Checking consistency between the contract documents and reference documents.

- Overlaying 2D lines and 3D surfaces in the XY plane with the surface set to display triangles.
- Overlaying 3D solids (also called “components”) with surfaces and viewing from multiple angles in 3D space.
- Paying careful attention to intersections and areas where the cross section changes.
- Paying careful attention to vertical elements like curbs and retaining walls.
- Using shading and thematic coloring to highlight sudden elevation and/or slope changes.
- Displaying contours at 0.1 ft or less to identify issues that may cause blade shudder in AMG.
- Changing the vertical scale to exaggerate triangulation issues.
- Being customer-focused: not every triangulation issue needs to be fixed, and not every transition needs to be smooth.
- Using the “drive-through” feature to review the roadway from the driver’s eye.
- Using software to compute the International Roughness Index.
- Using software algorithms to flag triangulation issues.
- Using clash detection algorithms with 3D solid geometry (e.g., between structural concrete and subsurface utilities).

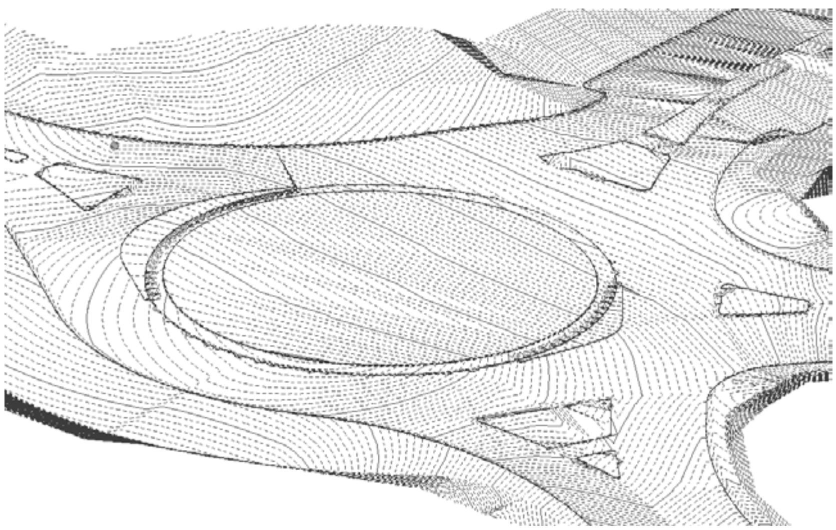
Figure 26 through figure 31 provide an illustration of the results of using a selection of data review strategies on a roadway surface for a roundabout intersection with median islands. The captions state the review strategies and describe how each highlight different issues in the surface.



Source: FHWA.

Figure 26. Illustration. Roadway surface for a roundabout intersection with visually inspected triangles with no apparent issues.

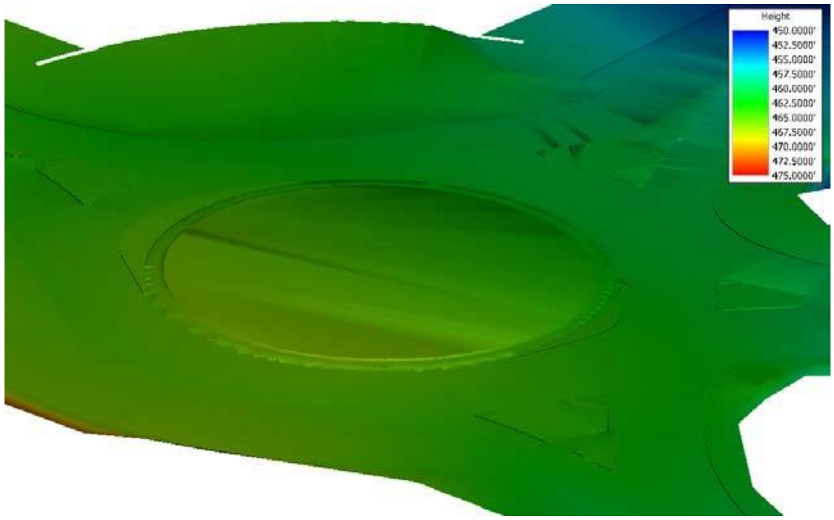
Figure 27 shows that there are issues with the curbs on the median islands on each approach. There is also a spike off the roundabout in the top center that could be an issue.



Source: FHWA.

Figure 27. Illustration. Roadway surface for a roundabout intersection with visually inspected contours.

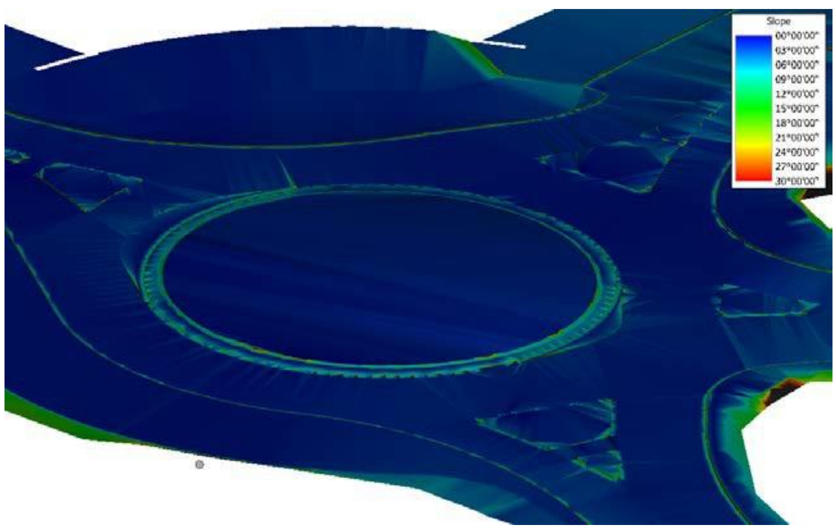
In figure 28, coloration does not show unexpected spikes, but shadows identify changes in slope. The median island in the top right could have issues.



Source: FHWA.

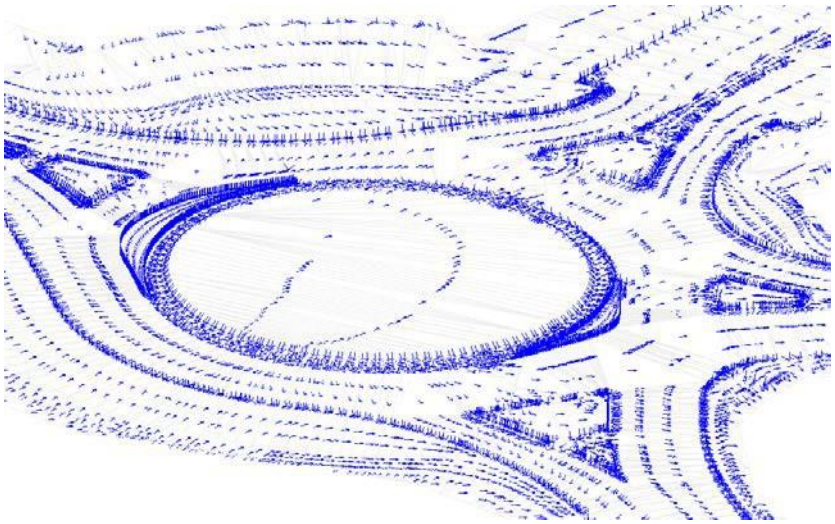
Figure 28. Illustration. Roadway surface for a roundabout intersection with color triangles by elevation.

In figure 29, there are issues with the curbs on the median islands on each approach. The spike off the roundabout in the top center is also an issue.



Source: FHWA.

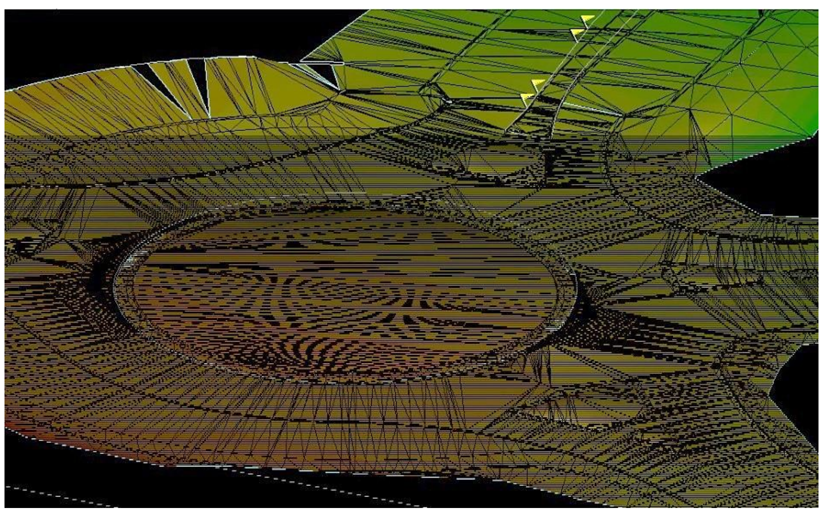
Figure 29. Illustration. Roadway surface for a roundabout intersection with color triangles by slope.



Source: FHWA.

Figure 30. Illustration. Roadway surface for a roundabout intersection with display drainage arrows with no apparent issues.

In figure 31, triangles are flagged on the median island in the approach at the top. The issues identified in visual analyses are not flagged.

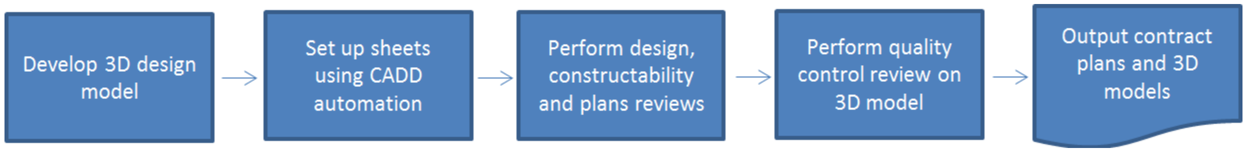


Source: FHWA.

Figure 31. Illustration. Roadway surface for a roundabout intersection using algorithms to flag issues.

CONTRACT DOCUMENTS

This chapter does not make assumptions about the order of precedence of 3D models in the contract documents or whether the 3D models are contract documents at all. Rather, it describes notable practices for using 3D models to create plans and output 3D data that are useful for automation in highway construction. Figure 32 illustrates a workflow for producing contract plans and models that are consistent and reviewing them efficiently.



Source: FHWA.

Figure 32. Flowchart. Producing contract documents and models.

The Guide 3D Model Standard section in this chapter provides detail into creating the 3D models. Processes for using model outputs to create plans are well described in an array of design and CADD manuals, including those previously referenced. Processes for CADD automation are embedded in design delivery. Manual plan edits used to be a significant time saver, but that is not the case with newer CADD software. With newer CADD software, changes to the foundation alignments, profiles, templates, corridor models, string models, or surfaces propagate dynamically to update plan graphics and annotations. Design, constructability, and plans review processes are also well established. Protocols to review 3D models were previously introduced in the previous subsection, Guide 3D Data Review Protocols.

Contract Plans

A fundamental consideration for producing contract documents is that there must be consistency between 3D models and the plans. This is extremely difficult to verify if there are manual edits on plan sheets. Table 15 shows how manual modeling processes can be written into surface definitions. Writing manual edits into surface objects is critical; manual design processes are sometimes warranted, but CADD automation should be used to create contract plan graphics and annotations. Otherwise, the risk of inconsistency is hard to mitigate with laborious review processes, both for the owner and the contractor.

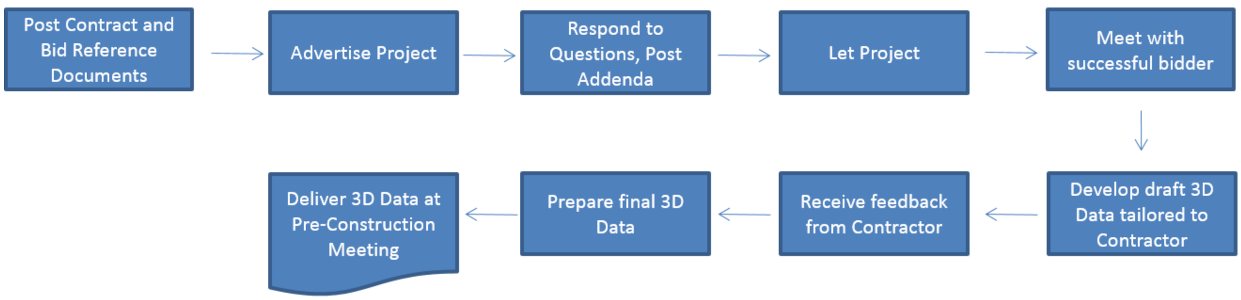
Other notable practices for the creation of contract plans from 3D models are shown in table 22. These practices are adapted from the design manuals from the Connecticut Department of Transportation, FDOT, and Iowa DOT.[50,49,46]

Table 22. Notable practices for creating contract plans.

Consideration	Description	Use
Vector PDF	Vector graphics are clear, can be scaled and measured, and do not scale when the document is zoomed. The vector graphics can be extracted by software and converted to CADD. The batch plotting tool in CADD software can be used to create vector PDFs.	• Compare 3D models and plans. • View plans on mobile device.
Digital signatures	Digital signatures use a public/private key to authenticate the signer. They can be applied to any file type and validated independently. A digital signature is invalidated if a file is modified.	Identify and authenticate contract documents.
Color graphics	The simple and selective use of color on plans can aid in the understanding and interpretation of contract plans on computers and mobile devices. Color choice should consider use in the field on mobile devices.	• Distinguish existing and proposed elements. • Emphasize important elements.
Hyperlinks	Hyperlinks can aid navigation through a set of plans by providing a shortcut from one sheet to another. Hyperlinks can also point to links external to the PDF.	• Connect plan view elements to profile or cross section sheets. • Connect detail call outs to detail sheets. • Connect quantities to quantity calculation sheets.

Contract 3D Models

There are a number of reasons for providing 3D models with bid documents, and many State transportation departments have recently implemented policies to do so, while others provide 3D data post-award or not at all.(12) Automation implementation to date has been market-driven, so there is not consistency in how contractors use 3D models to prepare bids and execute construction. A notable practice adopted by ODOT is to provide 3D models at two milestones: a generic set as bid reference documents followed by a tailored package for the successful bidder post-award (see figure 33).(44) This practice is reflected in the workflow shown in figure 33, which defines a role for the designer post-award.



Source: FHWA.

Figure 33. Flowchart. Providing contract models.(44)

There are a variety of software products that are used for automation in highway construction. Proprietary design formats are not universally supported. The challenge of using LandXML version 1.2 as a contract model format is that it is not consistently supported by different software applications, particularly for surfaces and cross-sections. At the time of writing this report, the most universally supported exchange format was LandXML version 1.2.(51) A newer schema, LandXML version 2.0, was in draft and research efforts were advancing InfraGML and industry foundation classes for exchanging highway data.(51) However, these newer schemas were not yet supported by software applications. Contract model packages should include a combination of 3D data in the exchange format, in the proprietary design format for those who have the software, and in a CAD graphics format to provide a means of checking the exchanged data.(12)

When producing LandXML outputs of surfaces, it is important to include both triangles and features in the surface definition.(46) Without the features, the software will retriangulate the surface, which may not match the design intent.

The data types and formats shown in table 23 are assimilated from policies implemented by Kentucky Transportation Cabinet (KYTC), FDOT, Iowa DOT, MDOT, Missouri Department of Transportation (MoDOT), ODOT, and WisDOT. (See references 52, 49, 46, 7, 45, 44, and 47.) Table 23 lists a set of generic outputs that can be used for bidding or construction.

Table 23. Type, format, and metadata for bid reference files.

Data Type	Data Formats	Metadata
Coordinate geometry	• CAD • American Standard Code for Information Interchange (ASCII) text	Survey metadata per table 7 embedded in CADD and/or in a ReadMe file in the folder
Alignment	• LandXML • ASCII text reports • CAD super-elevation tables • XML super-elevation report	• Survey metadata per table 7 embedded in CADD and LandXML and/or in a ReadMe file in the folder. • List of file names and description of content, including plan sheets and related corridors and surfaces, if applicable.
Original surface	• LandXML • CADD surface format • CAD triangle faces and boundary • CADD points and break lines	Survey metadata per table 7 embedded in CADD and LandXML and/or in a ReadMe file in the folder.
Final surface	• LandXML • CADD surface format • CAD triangle faces and boundary • CADD points and break lines	• Survey metadata per table 7 embedded in CADD and LandXML and/or in a ReadMe file in the folder. • List of file names and description of content, including related alignments and corridors, if applicable.
Interim surface	• LandXML • CADD surface format • CAD triangle faces and boundary • CADD points and break lines	• Survey metadata per table 7 embedded in CADD and LandXML and/or in a ReadMe file in the folder. • List of file names and description of content, including related alignments and corridors, if applicable.

Data Type	Data Formats	Metadata
3D line strings	• LandXML (surface features) • CAD graphics (3D line strings)	• Survey metadata per table 7 embedded in CADD and LandXML and/or in a ReadMe file in the folder. • List of file names and description of content, including related alignments, corridors, and surfaces, if applicable.
Cross section	• LandXML • CAD graphics (2D lines and text)	• Survey metadata per table 7 embedded in CADD and LandXML and/or in a ReadMe file in the folder. • List of file names and description of content, including related alignments, corridors, and surfaces, if applicable.
Corridor model	• Proprietary CADD format • CAD graphics (3D solids/ components)	• Survey metadata per table 7 embedded in CADD and/or in a "ReadMe" file in the folder. • List of file names and description of content, including related alignments, surfaces, and cross section files, if applicable.

It can save time and remove potential data exchange errors if the designer produces a tailored set of outputs specific to the contractor's and/or inspectors' intended uses. A notable practice is to include a transmittal letter with the 3D data that describes the content that is provided. This transmittal can be a list of the files and the associated metadata, as defined in table 23. The transmittal can also include a list of expectations and authorized uses with automation technology. For instance, if the 3D data are developed only for the purpose of creating plans, it may not be authorized for use in AMG or to measure and accept work as it may not have sufficient density.

CHAPTER 9. GUIDE SPECIFICATIONS

Many construction specifications are still methods-based, with prescriptive instructions on how to execute, measure, and accept work. While this leverages a deep institutional knowledge, methods specifications can be barriers to adopting new technology. The movement to performance-based specifications is certainly a broader issue than merely supporting the use of evolving automation in highway construction. The guide specifications are presented to avoid limiting the contractor or inspector to any specific methods or automation technology as well as to provide flexibility through describing the provision of data needed for automation technology, a vehicle to document agreed use of automation for construction and inspection, and flexibility to adapt performance measures for different approaches.

This chapter contains the following sections:

- Controlling Work: Plans and Working Drawings.
- Controlling Work: Conformance with Plans and Specifications.
- Controlling Work: Construction Stakes, Lines, and Grades.
- Controlling Work: Inspection of Work.
- Controlling Work: Quality Control Plan.
- Measurement and Payment.
- Earthwork, Fine Grading, Base Course, and Paving.

This chapter provides guide specifications that can be incorporated into specifications, special provisions, or special notes. The guide specifications follow the organization, format, and style of the AASHTO *Guide Specifications for Highway Construction* and are written to be performance-based.(53) The tolerances noted reflect current best-available practices. Each implementing agency needs to consider what constitutes aggressive, but achievable, tolerances for their current level of automation implementation and ways to provide flexibility to the engineer to adapt to project-specific construction activities and the capabilities, methods, and experience of the contractor and inspectors. This flexibility is incorporated by the provision for an automation technology work plan discussed in the Controlling Work: Quality Control Plan section.

Providing oversight to construction with automation technologies affects several chapters of the standard specifications.(53) These sections are identified in table 24 along with the considerations to support automation in highway construction for each section.

There is an evolution of special provisions to allow the incidental use of AMG and real-time verification. These guide specifications are adapted from special provisions, developmental specifications, and standard specifications from several agencies, including FDOT, Iowa DOT, KYTC, New York State Department of Transportation (NYSDOT), and WisDOT. (See references 54–59.)

Table 24. Areas of standard specifications affected by automation implementation in highway construction.

Typical Standard Specifications Section	Considerations to Support Use of Automation
Controlling Work: Plans and Working Drawings	Owner's provision of 3D data, review and agreement of electronic plan data, including 3D digital data, requirements for 4D/5D models, and provision of as-built records
Controlling Work: Conformance with Plans and Specifications	Standing of 3D data in relation to other contract documents
Controlling Work: Construction Stakes, Lines and Grades	Verifying control position, accuracy and usage; agreeing to a site localization; and staking requirements
Controlling Work: Inspection of Work	Provision of equipment for performing inspection and requirements for notification of work ready to inspect
Controlling Work: Quality Control Plan	Use of a work plan to agree use of automation technology in construction and inspection, including minimum requirements for equipment calibration
Measurement and Payment	Means of measurement and payment
Earthwork	Accuracies, tolerances, means of measurement, and payment
Base Material	Accuracies, tolerances, means of measurement, and payment
Fine Grading	Accuracies, tolerances, means of measurement, and payment
Asphalt Paving	Accuracies, tolerances, means of measurement, and payment
Concrete Paving	Accuracies, tolerances, means of measurement, and payment

CONTROLLING WORK: PLANS AND WORKING DRAWINGS

This section defines the 3D data that are provided with the plans. Refer to table 23 for a list of 3D data and the necessary associated metadata. State transportation departments may choose to use digital signatures to uniquely identify and validate the individual files. Another option is to use descriptive information, such as a unique file storage location on a document management system or other descriptive information that in combination uniquely identifies the files.[56]

Contract Documents

When 3D models are used as contract documents, they should be uniquely and easily identifiable, accessible, and protected from modification. Sample language that can be incorporated into specifications, special provisions, or special notes is as follows:

The agency will furnish one set of 3D model data and one transmittal letter. The transmittal letter shall indicate the authorized uses of the 3D model data. The 3D model data comprises several individual files that in combination represent the design in such detail as necessary to convey the design intent sufficient to meet the authorized use(s). The transmittal letter shall list file names, types, content, metadata, and any other descriptive information necessary to uniquely identify the 3D model data.

Hold Harmless Statements

The implementing agency may wish to provide a liability disclaimer for the 3D model data. This disclaimer can be incorporated into the transmittal letter as a statement of authorized use of the data. Sample text that can be incorporated into specifications, special provisions, or special notes is as follows:

Providing the contractor with this 3D model information does not relieve the contractor from the responsibility of making an investigation of conditions to be encountered, including but not limited to site visits as well as basing the bid on information obtained from these investigations along with professional interpretations and judgment. The contractor assumes the risk of error if the information is used for any purposes for which the information was not intended. Assumptions the contractor makes from this electronic information or manipulation of the electronic information are at their risk.

4D and/or 5D Models

This section defines any 4D or 5D models that are required from the contractor. The 4D or 5D models can be designated as working drawings or working models. The specifics of the 4D or 5D models are described in an Automation Technology Work Plan section in this chapter. Sample language to specify 4D or 5D model requirements is as follows:

Create working 4D and 5D models. The 3D model data shall be supplemented with 3D model data representing the temporary construction work necessary for the construction of the permanent works to the extent needed to simulate construction activities. This includes but is not limited to bracing, falsework, formwork, scaffolding, shoring, temporary earthworks, sheeting, cofferdams, and special erection equipment. The 3D model shall be segmented into discreet elements that are affected by each simulated task in a critical path method schedule. The working 4D model shall connect the discreet 3D model elements to the critical path method schedule tasks for the purposes of simulating the progress of construction. A 5D model shall connect the discreet 3D model elements to the cost-loaded critical path method schedule tasks for the purposes of simulating the progress of construction and tracking the costs as construction progresses.

3D As-Built Records

This subsection defines the as-built 3D models that are required from the contractor. The specific requirements for as-built 3D models depend on how the implementing agency uses the data (i.e., either in a programmatic way or just for the individual project). Project-level uses of as-built data and the project-specific requirements are defined in the automation technology work plan referenced in the Controlling Work: Quality Control Plan section in this chapter.

As-built records can be captured directly during the normal process of executing work with some automation technologies like AMG. Field surveying methods or LiDAR can be used to perform as-built surveys using the same processes and methods as normal topographic surveying. The contractor needs to have the requirements for the as-built data collection, storage, and delivery defined. This can typically reference the agency's survey manual. At the time this report was written, an ASCE committee was progressing industry standards for collecting as-built records of subsurface utilities installed or located during construction. Additionally, there is currently no defined industry standard for the use or collection of as-built data for asset management purposes. As this area emerges, the requirements can be incorporated. Table 25 summarizes the different uses of as-built data and provides references to the requirements for the different uses.

Table 25. Requirements for as-built data by intended use of data.

As-Built Data Use	Description	Requirements	Example
Acceptance	Data captured to review and document acceptance using real-time verification processes.	Staking tolerances	Verify earthwork, fine grading, subbase, base, and paving layout by comparing as-built points to 3D design data.
Measurement	Data captured to review and document measurements using real-time verification processes.	Measurement precision	Topographic survey of borrow pit before and after construction to compute volume.
Asset management	Data captured and stored in a statewide repository to maintain a digital inventory of highway assets.	No current standard	Defined and mature uses of 3D data in asset management are emerging.
Subsurface utility location repository	Data captured and stored in a statewide repository of subsurface utilities in the right-of-way.	Standard being developed	Inverts, pipe sizes, and material for gravity systems. Tops of joints, pipe size, and material for pressure systems.

Sample language that can be incorporated into specifications, special provisions, or special notes is as follows:

As-built 3D models of the completed facilities shall be provided in accordance with the topographic survey requirements of the agency's survey manual.

CONTROLLING WORK: CONFORMANCE WITH PLANS AND SPECIFICATIONS

This section defines the order of precedence of the 3D model data in the contract documents. Ideally, the plans should be created using the same 3D model data. However, as described in figure 21, the 3D model is an approximation of the design intent in areas where there is horizontal or vertical curvature. The 3D model data may be used for AMG or real-time verification, but in the case of a discrepancy, the true curvature shown in the plans should govern. The following text that can be incorporated into specifications, special provisions, or special notes to address this topic.

If there is a discrepancy, the governing ranking is as follows:

Dimensions:

- *Plan.*
- *3D model data.*
- *Calculated.*
- *Scaled.*

Information:

- *Special provisions.*
- *Plans.*
- *3D model data.*
- *Supplemental specifications.*
- *Standard plans.*
- *Information received at mandatory prebid meetings.*

CONTROLLING WORK: CONSTRUCTION STAKES, LINES, AND GRADES

The current AASHTO *Guide Specifications for Highway Construction* use real-time layout with survey instruments.(53) As shown in the following paragraph, the language can be modified to be less specific and provide flexibility for evolving survey instruments and methods.

Furnish all stakes, templates, straight edges, and other devices necessary to check, mark, and maintain points, lines, and grades. Ensure that contract staking conforms to standard procedures used by agency engineering personnel. Use of field survey technology that provides equivalent control points, lines, and grades can be furnished if acceptable to the engineer.

CONTROLLING WORK: INSPECTION OF WORK

This section can be used to require the contractor to provide the necessary field inspection tool for automating processes to measure and verify tolerances of completed work. It is important that the provision of the equipment complies with State and Federal regulations. Providing equipment for the inspector’s autonomous control and use during the duration of the contract is a practice that has been used by several State transportation departments. The work plan can be used to document the specific instruments, training, and timing for providing the equipment. Currently, GNSS rovers are widely applicable and usually needed for the duration of construction. However, total stations and other survey instruments may be needed only for limited periods (e.g., during bridge construction). The following text can be incorporated into specifications, special provisions, or special notes:

Furnish the necessary field survey technology for the engineer’s dedicated use during the duration of the contract.

This section can also provide for spot checking the contractor's field survey and AMG systems to ensure that they are functioning correctly. The following text can be incorporated into specifications, special provisions, or special notes:

The engineer may perform spot checks of the machine control results, surveying calculations, records, field procedures, and actual staking.

CONTROLLING WORK: QUALITY CONTROL PLAN

There is a lot of latitude for how 3D data may be used with automation technology for construction and inspection. The selection of automation technologies depends on a variety of project-specific factors. In order to support unique project opportunities and the constant evolution of technology, it is a growing practice to incorporate a requirement for the contractor to develop an automation technology work plan, which is an addition to the overall quality control plan.

The automation technology work plan should document the agreement over the timing of, responsibility for, and methods of the following:

- Verifying control.
- Agreeing site localization or base station setup.
- Agreeing on a model of record.
- Determining low-accuracy position.
- Documenting specific uses and requirements of 4D and 5D models.
- Checking the layout.
- Verifying tolerances.
- Measuring pay quantities.
- Performing daily calibration checks on AMG systems and field survey technology.

During the early phase of implementing AMG and real-time verification, it may be helpful to discuss and document information on the following:

- The expertise and experience of personnel.
- Training provided to the engineer.
- Activities for which 3D data will be used.

- Specific information about AMG systems.

- The origins of the 3D data that constitutes the "Model of Record."

The following language can be incorporated into specifications, special provisions, or special notes in order to specify the requirements for an automation technology work plan:

At least 1 week prior to the preconstruction conference, submit a written automation technology work plan to the engineer for review, which includes the following:

- *Construction activities that will use automation and the specific technologies that will be used.*

- *Proposed changes to the 3D model data in the model of record.*

- *Origins and applications of working 4D models or working 5D models.*

- *Proposed methods for low-accuracy positioning.*

- *Proposed methods and field technologies for high-accuracy positioning.*

- *Contract control plan.*

- *Description of the format, origin, network accuracy, and density of the proposed as-built data for the engineer's use in acceptance.*

- *Description of the format, origin, network accuracy, and density of the proposed as-built data for the engineer's use in measuring pay quantities.*

- *Proposed items and automation methods for measuring pay quantities.*

- *Proposed automation methods including equipment types and models to be furnished to the engineer for dedicated use during the duration of construction.*

- *Proposed timing for the provision of the specific automation technologies.*

- *Proposed formal training provided to the engineer and the timing of that training.*

The automation technology work plan will be discussed during the preconstruction conference. Within 7 days of the preconstruction conference, submit to the engineer for review an updated written automation technology work plan which reflects any changes agreed during the preconstruction conference. When the engineer has accepted the automation technology work plan, submit a contract control plan that has been signed and sealed by a licensed surveyor.

MEASUREMENT AND PAYMENT

This section introduces methods for measuring payment quantities using field survey technologies in accordance with the automation processes described in the Automation for Construction Engineering and Inspection section in chapter 10. The primary change is to introduce an alternate method to measuring volumes than the average end area method. The following language can be incorporated into specifications, special provisions, or special notes:

Field survey technologies may be used to determine upper and lower bounding DTM surfaces for the purpose of calculating volumes using the surface-to-surface comparison method where agreed in the automation technology work plan. The DTM surfaces shall have accuracies and densities needed to provide sufficiently accurate volume computations.

EARTHWORK, FINE GRADING, BASE COURSE, AND PAVING

When defining positional tolerances, it is important to consider the broad range of implications of the defined accuracies and tolerances. Tight tolerances require line-of-sight instruments for positioning, which constrains productivity. However, tolerances that vary for each pavement material will lead to variable depths of materials. Depending on the contractor's use of automation technology, it may be more efficient to place material high and trim it to grade immediately prior to placing the next course.

Requiring the same tolerance from fine grade up will facilitate consistent depths and good yields on the higher value materials. This can be particularly important when different construction activities are performed by different contractors. If tolerances are agreed in the preconstruction meeting that exceed those of the specification, they should be noted in the automation technology work plan.

It is recommended that tolerances for positional acceptance be set to staking tolerances for those construction activities. A written tolerance to allow material to be placed at grade or below might provide incentive to one sub-contractor to leave the finished grade low, causing overruns on the next material placement. Table 28 in chapter 10 provides guidance to inspectors in selecting field survey technologies based on staking tolerances. Tolerances for the as-built observations used to measure completed work for payment may need higher local accuracy to produce accurate volume quantities.

The next chapter provides guidance to inspectors in selecting field survey technologies based on measurement considerations. Sample specification language is as follows:

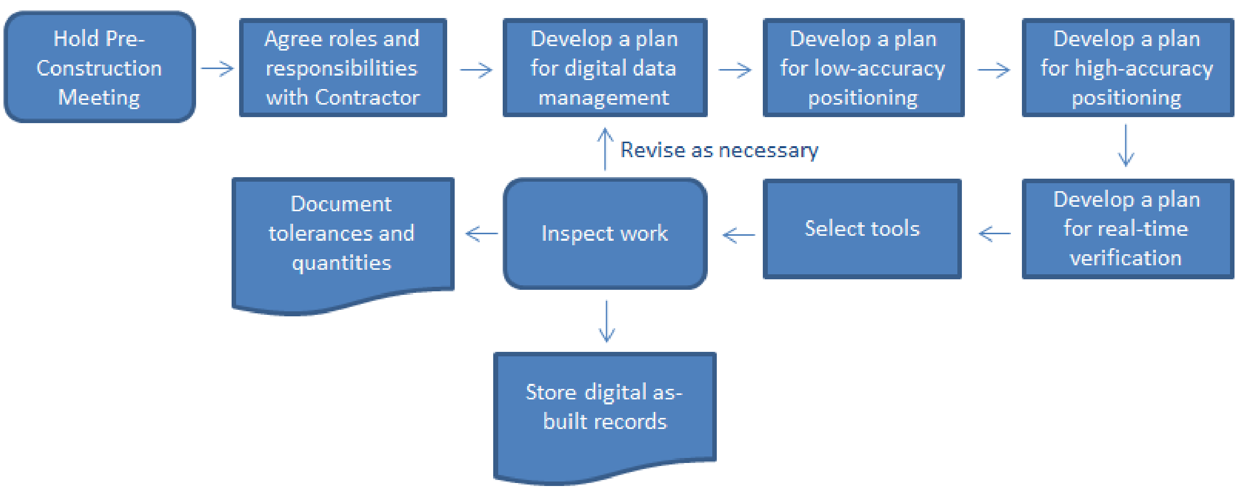
Construct the base to the width and section the plans show. Shape and compact the base surface to within 0.04 ft of the plan elevation.

CHAPTER 10. CONSTRUCTION

This chapter covers the owner's role of quality assurance when automation technologies do not require stakes or string lines. The following topics are discussed:

- Construction data management.
- Low-accuracy positioning.
- High-accuracy positioning.
- Agreeing control and site localization or mapping projection.
- Automation for construction engineering and inspection.

One of the most important considerations is how the inspectors identify their location onsite, which is necessary for quality assurance functions that do not change with automation, like daily diary entries. New functions are described for providing appropriate oversight to AMG operations as well as automated methods to verify construction tolerances in real time and measure pay quantities. The chapter briefly covers the opportunity to capture digital as-built records, especially as-located and as-built subsurface utility information. Figure 34 shows a workflow for managing construction with automation technology.



Source: FHWA.

Figure 34. Flowchart. Managing construction with automation technology.

CONSTRUCTION DATA MANAGEMENT

Automation in highway construction requires and produces a vast amount of 3D digital data. There is the potential to use some or all of this data in executing, measuring, and accepting construction as long as it is subject to good data governance. Data governance ensures that there is control over the quality and management of data in accordance with standards and rigorous processes. The following three areas need to be managed:

- Establishing a model of record that reflects the design intent shown in the contract documents.
- Updating the model of record when there are design or field changes.
- Producing robust digital as-built records.

Establishing a Model of Record

The model of record is not a single file; it includes a variety of digital data, usually 3D, that define the design intent. This includes coordinate geometry, horizontal and vertical alignments, existing ground surfaces, interim ground surfaces, final ground surfaces, and 3D line strings. Table 26 lists the data types that can constitute the model of record and the design intent they depict.

Table 26. Data types that can constitute the model of record.

Data Type	Design Intent Depicted
Coordinate geometry	Control points, right-of-way corners, and geometry points on alignments. May also include point features depicting locations for sign posts, piles, light standards, etc.
Alignments	Baselines for layout, including primary and secondary alignments and interim roadways. Includes horizontal and vertical layout information. May include retaining walls, pipes, and other linear features with stationing.
Original surfaces	Existing ground condition.
Final surfaces	Final constructed condition.
Interim surfaces	Subgrade surface. May also include other interim surfaces between top of subgrade and final ground. Can also include temporary roadways, excavation limits, undercut limits, and interim grading.
3D line strings	Linear features, including edges of pavement, curb lines, ditch lines, trench excavation limits, guardrail, and shoulder break points.

The minimally sufficient information for the model of record is as follows:

- Coordinate geometry for control points.
- Primary alignments.
- Existing ground surface.
- Final ground surfaces for temporary and final roadways.

Data are needed for all construction activities that use automation technologies, but the primary data types for AMG and real-time verification are alignments, 3D line strings, and surfaces. The existing ground surface is an important component of the model of record. It can be used to compute earthworks volumes.

A quality assurance survey prior to the preconstruction can be conducted to review the accuracy of the existing ground surface at tie-ins and other important locations. This would identify any potential design revisions, quantity changes, or other material changes in site topography since the original survey was conducted.

The model of record can be used to layout construction, execute construction with AMG, and inspect completed work. In order to realize all three uses, the owner and contractor must agree on a single set of data. Figure 35 shows a workflow for establishing the model of record.

Source: FHWA.

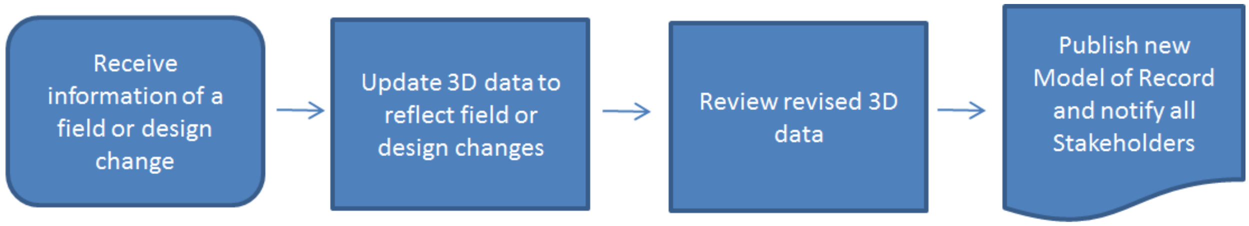
Figure 35. Flowchart. Establishing a model of record.

There are many sources of data for the model of record. Ideally, the model of record will be produced during the design phase. Frequently, the model used for layout and AMG construction differs from the 3D design data. The most common reason is that the 3D design data do not depict the design intent to the extent necessary for construction operations. This could be because the design was conducted before the State transportation department implemented rigorous 3D design practices. The survey upon which the design was based may have lacked sufficient accuracy in some areas or in the vertical control. Value engineering or ATCs may have modified the design intent.

If data are to be used to construct and inspect work, then consistency is necessary to isolate construction issues from data differences. Many factors may lead to differences, both large and small, between the original design data and the data that are ultimately used in construction. If the design data cannot be used as model of record, then it is possible for the contractor to provide the data and the engineer or designer review and agree to it. Consistency arises when the engineer and contractor agree on a single set of data that represent the design intent of the contract documents. That way, survey instruments read tolerances in real time relative to that data, and any issues will be real construction issues rather than differences in data sources or instrumentation.

Managing Design and Field Changes

Processes need to be established to manage design or field changes to the model of record. If AMG construction is used, then any design or field changes are necessarily incorporated into a 3D model prior to construction. If that model is reviewed and agreed by the engineer, it may be accepted as an updated model of record and used by the inspector. Figure 36 shows the workflow for keeping the model of record current.

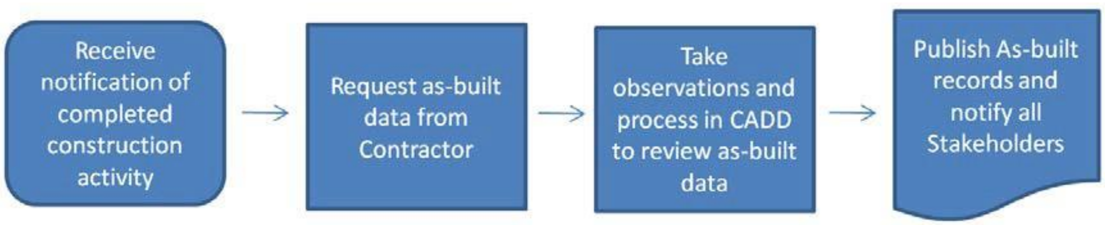


Source: FHWA.

Figure 36. Flowchart. Managing field or design changes in model of record.

Digital As-built Records

As-built data can be of use during construction by both the contractor and the engineer. Contractors can capture as-built data during AMG operations or in quality control observations. Some contractors use as-built data to track productivity and quantities. Inspectors' observations should also be captured and stored as independent as-built observations. These can be used to verify the contractor's as-built data. Figure 37 shows a workflow for preparing digital as-built records.



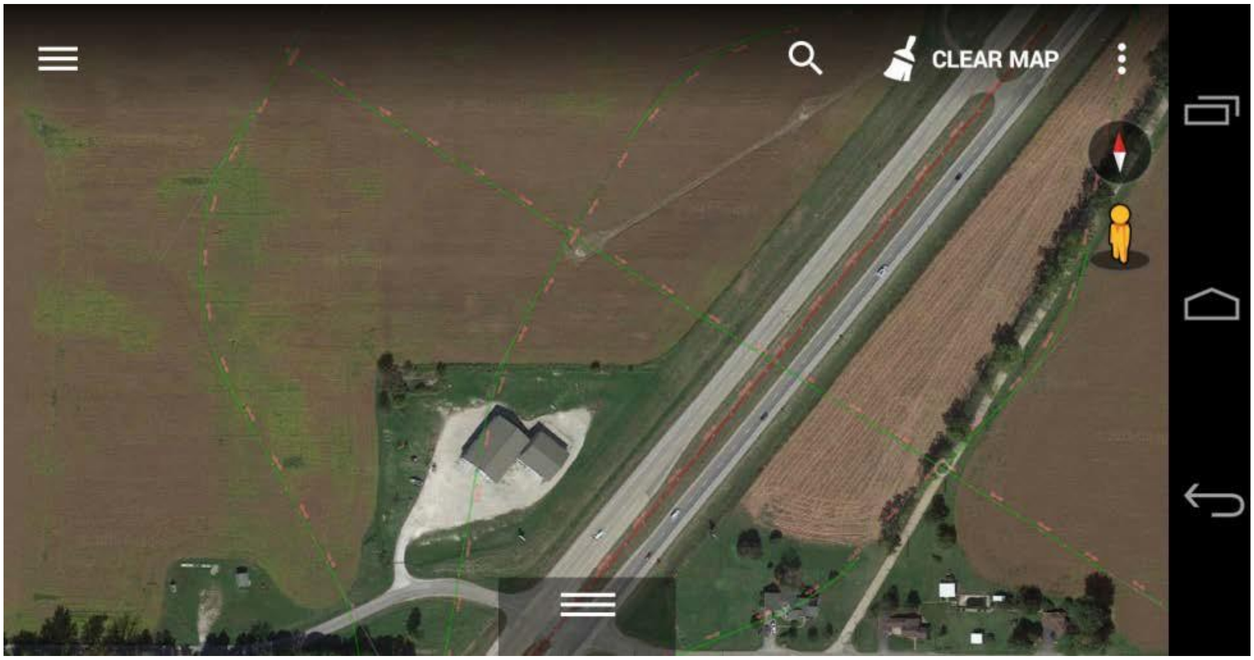
Source: FHWA.

Figure 37. Flowchart. Preparing digital as-built records.

Digital as-built data provide a robust digital record of construction. These data can be used to measure pay quantities and verify tolerances. The Automation for Construction Engineering and Inspection section in this chapter explains how as-built data can be used by the inspector to automate measurement and acceptance processes. There may be uses for the data to substantiate claims, resolve disputed quantities, or plan future operations or after the facility has been commissioned. The ability to share auditable data with the contractor increases transparency and trust between the contractor and the engineer.

LOW-ACCURACY POSITIONING

Not all construction observations require the precise positioning realized by survey-grade equipment. One option is to use stakes or paint to mark stations at an agreed interval. Positioning from mobile devices like smart phones and mobile tablets may be sufficiently accurate for recording locations for daily diary entries and permit compliance observations (e.g., for storm water pollution prevention). To use low-accuracy horizontal positioning with mobile devices, the inspector needs software that has the primary alignments preloaded. Figure 38 shows a screenshot from a mobile device where the alignment information has been preloaded.



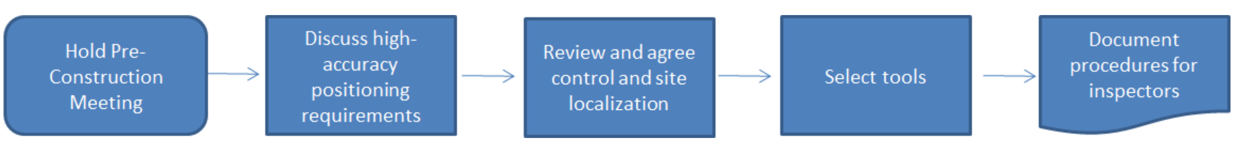
Source: FHWA.

Figure 38. Screenshot. Alignment preloaded in a mobile device.

Inspectors can use mobile devices in this way to overcome their reliance on stakes for low-accuracy location awareness onsite. Mobile devices can also enhance inspectors' productivity by using voice recognition to dictate notes, capturing photos and videos to document site conditions, and using video conferencing to discuss and show issues in real time with remote participants.

HIGH-ACCURACY POSITIONING

High-accuracy positioning, or survey-grade positioning, is a requirement for AMG construction for measuring pay quantities, such as earthwork, and for accepting work for many activities, such as paving and bridge construction. Some of these activities, like bridge construction, require high-accuracy positioning because of the tolerance required by the specifications. Other activities, like seeding areas, require high-accuracy positioning in order to measure quantities with sufficient precision. Many activities, like earthwork and fine grading, require survey-grade positioning for measuring both tolerances and quantities. Figure 39 shows a workflow for establishing a plan for high-accuracy positioning onsite.



Source: FHWA.

Figure 39. Flowchart. Establishing a plan for high-accuracy positioning.

Regardless of whether the contractor uses AMG at all, inspectors can make use of automation processes to measure and accept completed work. When the contractor and engineer use a common model of record and a common site localization or mapping projection, any issues identified by real-time verification will be true construction issues and not discrepancies arising from differences in dataset or site localization. Consistency between 3D data and survey methods is particularly important when verifying construction within tolerances as tight as 0.02 ft. Generally, there is synergy when the contractor uses AMG and the inspector uses automation processes to measure and accept completed work.

AGREEING ON CONTROL AND SURVEY METHODS

As described in the Establishing Site Control section in chapter 6, the original mapping control is important for constructing the project in accordance with the design intent in the contract documents. One of the first steps of site mobilization is to recover the original control, identify any control that is missing or has been disturbed, and determine if the control is still within its prescribed tolerance.

As noted previously in table 6, construction control requirements in the vertical may exceed the requirements for cadastral surveying. Vertical control is extremely important for high-accuracy AMG operations, particularly those using total station control, as shown in figure 40. Low vertical accuracy resulting in inconsistency in control will be felt in the ride where the RTS-based machine control switches from one setup to the next. There may be a need to improve the accuracy of the vertical control, and, as indicated in figure 11, there may be a need to set additional vertical control to ensure a robust site localization.

Source: FHWA.

Figure 40. Photo. High-accuracy AMG operations.

There are two options for data collector setup: using site localization or using a horizontal mapping projection and a geoid model for elevation. The choice of site localization or mapping projection and geoid model resides within the data collector. It is independent of the source of RTK correction for GNSS positioning and is equally applicable to line-of-sight based positioning methods like total stations or laser-augmented GNSS.

AMG systems work effectively with a site localization, often achieving tighter vertical closure than with a mapping projection and geoid model. It is a simpler setup than the mapping projection and is commonly used by contractors; however, it is not as easy to reproject to a geospatial coordinate system.

In order for observations to be comparable, it is important that the contractor and inspector use the same data collector setup. Observations taken with different data collector setups will almost certainly be different and can be significantly different when following some of the tighter required tolerances for inspection. It can be helpful to have a standard form for agreeing on the construction control and mapping projection or site localization.(12) Table 27 indicates the pertinent information for a surveyor to review and accept the construction control plan to be used by the contractor and engineer.

Table 27. Pertinent information for a contract control plan.(58)

Element	Description
Original mapping control	Unrecovered horizontal and/or vertical control points; disturbed control or control that is out of tolerance of original position.
Survey network diagrams	Control should be used for construction.
Coordinate differences	If any control has been disturbed, note methods used to check existing points and the northing, easting, and elevation of the new location
New control	Note methods used to establish the new control and the description, northing, easting, and elevation. Note intended uses for the new control.
Mapping projection and datum	Note the full metadata for the mapping projection and datum per table 7.
Method of RTK correction	The method of RTK correction should be defined (base station, CORS, RTN, etc.).
Site localization	If used, note computations for horizontal and vertical transform parameters.
Surveyor’s seal	Seal and signature of a licensed surveyor should be used.

Source of RTK Correction for GNSS

Frequently, the contractor uses a base station for RTK correction for GNSS operations. Inspectors should use the same site localization or mapping projection as the contractor regardless of whether they use the contractor’s base station, a CORS network, or an RTN. When the inspectors do not use the same source of RTK correction as the contractor, it is important to understand the potential differences in RTK correction that can occur between the two sources.

RTK corrects a number of sources of positioning errors. Some of these, like multipath errors, may not be consistent between the contractor’s base station and the station(s) upon which a CORS or RTN solution is based. A networked solution like CORS or RTN provides better correction of atmospheric distortions. It is important that field observations are properly overseen by a surveyor, especially if the inspector and contractor use different sources of RTK correction.

Base Station Setup

Using a base station with GNSS rovers and a mapping projection and geoid model requires that the location of the base station is a known geospatial position tied to the NSRS. This is not necessary for a site localization. However, data collector software can interchange between using a site localization and a mapping projection and geoid model if the base station is set up over a known point. There may be a need to collect as-built data on a different mapping projection, which is more easily achieved if the data collector switches to that mapping projection when collecting that data. Figure 41 shows the horizontal and vertical errors at the control points used to compute the site localization. A minimum of five control points are needed to compute a site localization.

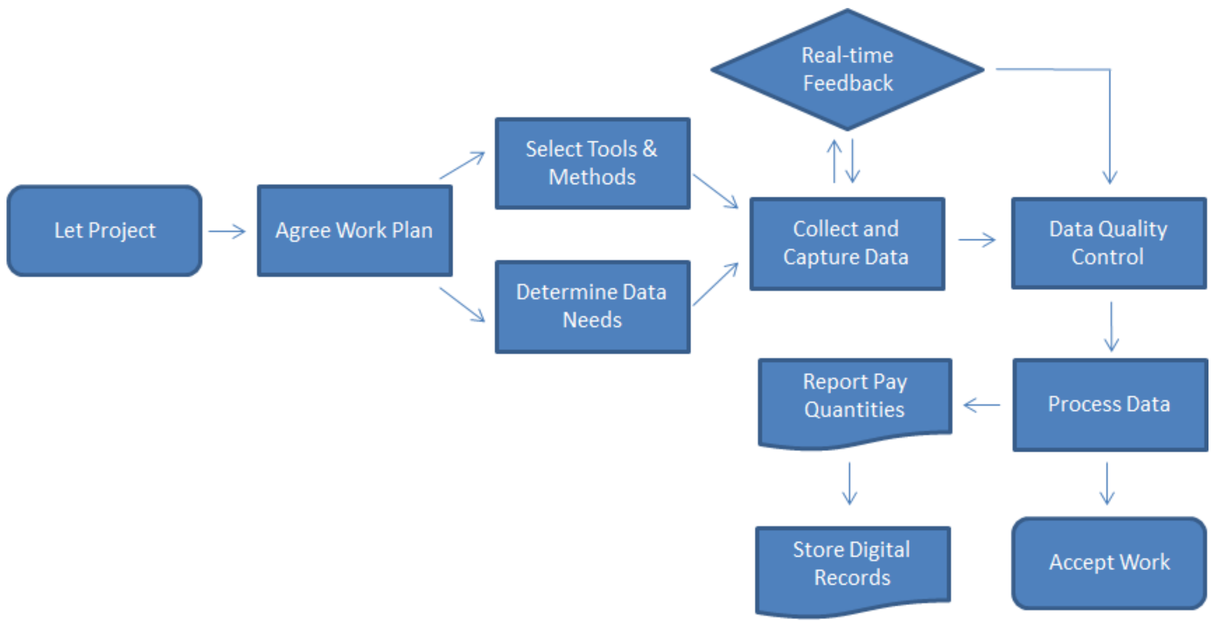
Source: FHWA.

Figure 41. Photo. Horizontal and vertical errors at the control points.

To determine the base station location with high accuracy, the base station should occupy the position for at least 2 h. A longer occupation results in a more accurate position (24 h is preferable). The collected data can then be uploaded to the National Geodetic Survey's Online Positioning User Service (OPUS), which provides a corrected position that is tied to NSRS.(60) The elevation from OPUS can be verified by using a high-accuracy vertical surveying method such as leveling or a total station. The data collector can then be set up with the original mapping projection from the control plan. Geoid definitions change frequently, and the differences in elevation can be significant in some areas. If a newer geoid definition is used, there may be serious errors when checking into control and at tie-ins.

AUTOMATION FOR CONSTRUCTION ENGINEERING AND INSPECTION

Methods for inspecting work should verify performance-based construction outcomes and not be method-driven. A range of as-built data are available from automation technologies like AMG, intelligent compaction, and real-time smoothness profilers. Non-destructive testing equipment like ground-penetrating radar and infrared thermal profilers also produce digital as-built data. These data can be spot-checked by the inspector to independently verify the accuracy and confidence in the data. These as-built data can then be used as a resource for verifying compliance with specifications or measuring completed work. Figure 42 shows a workflow for using real-time verification in construction inspection.



Source: FHWA.

Figure 42. Flowchart. Using real-time verification in construction inspection.

Use of As-Built Data for Measurement and Acceptance

Using these as-built data can greatly enhance the efficiency and safety of inspectors onsite, reduce interruptions to the contractor performing operations, and provide a robust record of construction that can increase transparency in pay quantity measurements or equitably resolve claims. However, implementing these data-dependent processes requires creating resources and skillsets that traditionally are absent from the owner's role in construction. Using the contractor's as-built data requires skill, understanding, and the use of methods to independently verify the quality of the data.

An important consideration when developing methods for automating inspection processes is the difference between local accuracy and network accuracy. Inspectors need to understand the difference between local accuracy and network accuracy and how it relates to measuring quantities and checking tolerances. Local accuracy refers to the position of one element in relation to another (e.g., the distance between the final wearing course and the base course). A very high local accuracy is needed to ensure smoothness, consistent depths, and high material yields. For this reason, contractors select a high accuracy method for AMG construction. However, the network accuracy, which is the location of the constructed facility in the world, only needs to be within 0.25-inch accuracy where that facility must tie into an existing facility like a bridge or an existing roadway.

Capturing As-Built Data with Field Survey

Using AMG as-built data for measurement and inspection relies on the contractor performing work with AMG systems that meet the tolerance necessary for measurements with the appropriate network and local accuracies. Where this is not the case, inspectors may use field survey methods to create the necessary data. The range of field survey tools available to inspectors for field surveying includes total stations, GNSS rovers, digital levels, and laser-augmented GNSS rovers. These tools have a range of accuracy thresholds; as such, it is important for the inspector to choose the right survey tool for the job. Tool selection is based on the tolerances required by the construction specification. Each instrument needs to be calibrated and serviced regularly. Inspectors should check into control before, during, and after performing observations to verify that the instrument is functioning correctly. It is anticipated that UAVs with photogrammetry will soon be an additional resource for data collection. Current remote sensing tools are discussed later in the following section: Capturing As-Built Data with Remote Sensing.

Figure 43 shows an RTS rover being used to check grade off the back of the paver. Any tolerance issues would be caught immediately. Grade checks are most important when switching from one total station setup to another. The grade checker can store a data point for each grade check, capturing a digital as-built with no additional effort beyond pressing a button.

Source: FHWA.

Figure 43. Photo. RTS rover being used to check grade off the back of the paver.

Table 28 summarizes the appropriate tools for capturing field survey observations to check work. The table is organized by the tolerance required by the specification. Total stations are versatile tools because of their high accuracy, but they require line-of-sight to control and the area to be surveyed. GNSS is the most efficient tool because it is not limited by line-of-sight, but the vertical accuracy is insufficient for some activities. Levels provide accurate vertical positioning. In some cases, it may be optimal to check the horizontal tolerance with GNSS and the vertical tolerance separately with a level. In other cases, using a total station to check horizontal and vertical tolerances at once may be more efficient. Laser-augmented GNSS has line-of-sight limitations to the laser that provides the vertical accuracy.

Table 28. Inspector tool selection guidance.[(61)]

Horizontal Tolerance (ft)	Vertical Tolerance (ft)	Example Activities	Total Station	GNSS	GNSS and Laser	Level
0.50	0.16	Rough grading	H and V	H and V	—	—
0.16	0.10	Subgrade, street lights, and utility poles	H and V	H and V	—	—
0.16	0.07	Waterlines	H and V	H only	H and V	V only
0.16	0.03	Finished grade, base, paving, sewers, and drainage structures	H and V	H only	H and V	V only
0.03	0.02	Curbs, bridge bearing seats, bridge beams, and structural concrete	H and V	—	—	V only

—Indicates that the technology is not sufficient/recommended for the outlined tolerances/activities.
H = Horizontal.
V = Vertical.

When using the tools in table 28 to capture as-built data, it is important for the inspector to understand the accuracy limitations of the tool and the necessary accuracy to verify tolerances and measure pay quantities in accordance with the specification. Positional tolerances relative to a geospatial datum are indicated by the staking accuracy for each work item. Positional tolerances required by the specification may be lower than the lowest tolerance in table 28.

Generally, an inspector should choose a tool that can achieve the needed local accuracy so data only need to be captured once. Table 29 shows methods and tools for using as-built data to compute measurements. The survey tool for capturing the as-built records should support the needed accuracy on the measurement. For instance, a total station should be used to measure structural concrete volumes, whereas GNSS is appropriate for computing borrow pit excavation quantities.

Table 29. Use of field surveying tools to measure payment quantities.

Quantity	Example	Tools	Method
Volume	Earthworks excavation and rock excavation	GNSS and CADD	• Conduct topographic survey of top and bottom surfaces (e.g., original and final ground). • Compute DTM surfaces for top and bottom in CADD. • Perform surface-to-surface volume calculation in CADD. • Produce exhibit and calculation sheet.
Volume	Pavement materials	Total station and CADD	• Conduct topographic survey of top and bottom surfaces. • Compute DTM surfaces for top and bottom in CADD. • Perform surface-to-surface volume calculation in CADD. • Produce exhibit and calculation sheet.
Volume	Structural concrete	Total station and CADD	• Collect as-built points. • Create faces and solids in CADD. • Compute solid volumes in CADD. • Produce exhibit and calculation sheet.
Volume	Concrete curb	GNSS, CADD, and spreadsheet	• Collect flowline as-built points. • Compute length in CADD. • Multiply length by cross-sectional area in spreadsheet. • Produce exhibit and calculation sheet.
Area	Seeding clearing and grubbing	GNSS and CADD	• Collect points on the perimeter. • Create boundary in CADD. • Compute area in CADD. • Produce exhibit and calculation sheet.
Length	Culvert and water line	GNSS and CADD	• Collect as-built inverts/pipe joints with field codes. • Produce flow lines in CADD. • Compute lengths in CADD. • Produce exhibit and calculation sheet.
Length	Curb, striping, and silt fence	GNSS and CADD	• Collect as-built points with field codes. • Create line work in CADD. • Compute lengths in CADD. • Produce exhibit and calculation sheet.
Unit	Bridge piles and traffic control devices	GNSS and spreadsheet	• Collect as-built points with field codes. • Sort points by field code and count in spreadsheet. • Produce calculation sheet.

In some cases, it may be optimal to check the horizontal tolerance with GNSS and the vertical tolerance separately with a level. In other cases, using a total station to check horizontal and vertical tolerances at once may be more efficient. Laser-augmented GNSS has line-of-sight limitations to the laser that provides the vertical accuracy.

Capturing As-Built Data with Remote Sensing

Table 28 and table 29 are not the only tools available to capture independent survey data to verify and measure construction outcomes. In some cases, remote sensing applications are viable alternatives to capture the data. In certain conditions, aerial remote sensing can be an efficient method to capture the data necessary for computing earthwork volumes.[(62)] It is also possible to use tripod-mounted LiDAR to collect data to verify and measure earthwork construction.[(63)]

Aerial photogrammetry can capture a wide area in a short period but requires more intensive data processing than does field survey data. Clearing and grubbing must be complete prior to capturing the aerial photography to prevent missing data in occluded areas. Aerial photogrammetry results in a DTM and may be used to capture either or both the original and final ground conditions. The DTMs can then be used to cut cross sections or for surface-to-surface volume computations. The latter is more accurate than average end area method computations from cross sections.

There are several factors that determine whether aerial photogrammetry is practical or economical, including the following:[(62)]

- Safety considerations that make field survey more risky.
- Volume of unclassified excavation (100,000 yd^3 is a threshold).
- There is a 20-acre threshold for the area to be surveyed.
- Considerations that require multiple flights to capture the data.
- Visual occlusions like water bodies or areas that cannot be cleared.
- Availability of individuals to perform field survey or photogrammetry.
- Turn-around time available for processing the data.
- Ability to reuse the data for other purposes or to consolidate data acquisition.

It is anticipated that UAVs will make photogrammetry more viable and cost effective for capturing DTMs due to enhanced accuracy and lower costs compared to normal methods. It is also feasible to use static, tripod-mounted LiDAR for capturing the data needed to measure earthwork quantities for payment.[(63)] Productivity rates affect the economic feasibility of using static LiDAR. Setup time, scanning time, and the minimum distance between setups required to achieve sufficient accuracy affect whether static LiDAR is more or less cost effective than other survey data acquisition methods like GNSS rovers and RTSs.

The workflow for using static LiDAR to collect data for earthwork computations is as follows:

1. Enforce control every 800–1,000 ft along the highway alignment.
2. Establish secondary temporary control to supplement the primary control to identify and eliminate sources of systemic error in data collection. These should be established to provide full radial coverage within the effective radius of the scan.
3. Establish the coordinates of the scanner and instrument height at each setup.
4. Select the density of point acquisition taking into account (e.g., scanning time, accuracy, and data storage, transfer, and manipulation).
5. Migrate the point cloud data to a workstation.
6. Register scans to each other to provide a contiguous dataset.
7. Filter and classify points to extract finished ground points.
8. Perform quality control procedures on the dataset.
9. Create a DTM from finished ground points.
10. Use surface-to-surface comparison to calculate the earthwork volumes.

In a 2010 study with data captured with an older static LiDAR system (a Trimble® GS200 scanner), productivity rates of 18 h/mi for finished ground surface were achieved as compared to 30 h/mi for capturing the necessary data with a total station and a two-man crew.(63) Newer systems, like the one shown in figure 44, can achieve the necessary accuracy with a larger interval between setups and can achieve a wider vertical coverage angle; however, scan planning is important, especially where there are visual occlusions.

Source: FHWA.

Figure 44. Photo. Static LiDAR being used to collect as-built data.

GNSS rovers are able to achieve the same 0.1-ft vertical accuracy without line-of-sight limitations, allowing much faster data acquisition for the limited purpose of earthworks computations. A GNSS rover may be mounted onto an all-terrain vehicle and set to capture a data point every 10 ft. This is a fast and efficient way to capture the information necessary to create a DTM. The processing time is much shorter than for LiDAR data; the points can be downloaded directly into CADD to produce a DTM within hours.

Limitations of Real-Time Observations

Data collectors can display the tolerance achieved relative to a design surface in real time and can perform real-time distance and volume computations. However, the survey observations need to be conducted with the proper oversight of a qualified individual. The data then need to be manipulated by a qualified CADD operator to produce transparent supporting materials for the quantity computations.

One of the benefits of using these inspection protocols is that they free up the inspector's time to observe construction activities, resulting in a better quality product. Inspectors can quickly capture data to measure and verify work with GNSS rovers and RTSs. The process of capturing the data for measurement and inspection can be close to real time behind the equipment. However, surveying and CADD skills are not necessarily appropriate for inspectors to develop and maintain. It may be more efficient to have dedicated construction surveyors and CADD operators who are trained to review and manipulate the data to measure quantities and produce exhibits and reports for the inspectors. CADD skills are useful onsite to prepare or review the data for field changes prior to execution.

Migration of data between the field and the office is expedited with network accessible sites. Commercial solutions use cloud-based data storage and cellphone or wireless Internet connectivity to migrate data from the data collectors in the field. Data can be manually transferred from the construction office using document management systems and network connectivity. While not real time, the turn-around time can be sufficiently short to flag any potential issues early and resolve any quantity discrepancies in the field while the field observations can be revisited.

CHAPTER 11. AUTOMATION TECHNOLOGY INTEGRATION

3D data can enhance decisionmaking and the functions of all phases of the highway asset lifecycle. Indeed, 3D data frequently integrate automation technologies. However, there is a perception, borrowed from the implementation of BIM in vertical construction, that automation technology integration culminates in a common repository of 3D data that is used throughout the asset lifecycle. Most building assets like windows; doors; heating, ventilating, and air conditioning systems; or walls are discrete objects that do not change in physical character between planning, design, construction, operation, and maintenance. This is a fundamental difference between buildings and highways and affects the way that asset management systems create, maintain, and use 3D data.

Highway assets are formed on and, in many cases, with the environment in which they reside. Furthermore, the character of the constituent parts changes as facilities are constructed, used, and maintained. Frequently, substantial effort and resources are invested in extensive temporary works. Settlement occurs, bridges may be struck, concrete may spall, and pavements may rut. These physical changes have a measurable impact on structural integrity and other performance measures. This means that as highway assets progress through their lifecycles, the existing 3D data about the assets are rendered obsolete. That does not dispel the notion of automation technology integration across lifecycle phases, but caution and careful planning are important.

One of the greatest challenges to a central repository of 3D digital data at the statewide level is the ability to maintain high orders of network accuracy. This is a challenge that the industry has yet to resolve. The value of such a system is proportional to the confidence users have in the spatial accuracy of the 3D data. For GIS systems, especially for subsurface utility data, confidence is currently low.

As noted in chapter 6, investment in mapping control has a long-term impact on the value of data captured using that control. Verifying the currency, quality, and integrity of the existing data is of the utmost importance, especially for subsurface utilities and the tie-in points on existing features. There is a need for frequent data capture, especially during construction. When automation technology is used, this data capture serves multiple purposes, including executing construction with AMG, tracking productivity, and verifying and measuring completed work.

Currently, automation technology integration occurs in an ad hoc fashion. Agencies have not yet created policies to require automation technologies in a broad or integrated manner, and much of the contractor's use of automation is market-driven. Standards are emerging for requiring 3D engineered design programmatically for many project types, typically those with cross sections or significant earthwork quantities. Significant strides have been made in recent years to pass this data on from design to the construction phase, increasingly as the contract document. The owner's use of automation in inspection is most often linked to the contractor's use of AMG.[(10)] Many agencies have special provisions or alternate specifications for intelligent compaction and AMG.

The most common uses of automation in highway construction are using 3D data for estimating and planning construction, executing grading and excavation with AMG, growing the usage of AMG for paving and emerging the usage for milling, and growing the usage for inspection.[9] Using 3D data for planning crane mobilization and lifts, as well as for 4D and 5D modeling, is growing at the project level.[12] Use is still typically for large, multiyear, multicontract projects, especially those involving complex bridge or interchange reconstruction. Projects such as the Southeast Freeways, the San Francisco-Oakland Bay Bridge, the New Haven Harbor Crossing, Presidio Parkway, Sellwood Bridge, Dallas-Fort Worth Connector, and Horseshoe Interchange have made extensive and integrated use of automation. (See references 3 and 64–69.) Contractors act as sophisticated creators and consumers of 3D models to support automation.[12] Automation technology integration may also occur on smaller projects, but these are more difficult to identify, especially where contractors see the use of automation as a market differentiator.

Changes in how highway assets are managed emanate from the *Moving Ahead for Progress in the 21st Century Act*.[70] The act changed the focus from construction to system preservation and performance, implementing requirements for data-driven, performance-based strategies for maintenance and replacement of highway assets. Capitalizing on mobile technology, e-Construction, which is a paperless approach to construction management, is rapidly emerging. The current trend for e-Construction is to utilize a digital page, but in the future, as the use of 3D data by inspectors proliferates, e-Construction may evolve to make more extensive and direct use of 3D data from other automation technology applications.

The highway industry is steadily improving the flow of data from one phase of project development to another. As was noted in the Notable Implementation Strategies section in chapter 3, this was a central part of the automation technology implementation vision for some agencies. There are project examples where there has been a concerted effort to improve the data flow between phases and automation applications. The most significant challenges identified during EDC round 2 webinars were a lack of guidelines and best practices, a lack of expertise and training, and the ability to learn new methods while responding to accelerated deadlines for design.[9]

CHAPTER 12. CONCLUSIONS

The coordinated planning for and use of automation in highway construction from project scoping through construction acceptance has the potential to add significant value across project delivery but especially in construction and beyond. While clear benefit/cost analysis is not yet available to prioritize investment in automation technology implementation, digital data migration into and out of the construction phase is one limiting factor to fully exploiting the potential benefits. The challenge of digital data management is optimizing the collection and creation of data such that they are available in the right resolution when they are needed, but those needs vary across the project delivery—or asset—lifecycle.

This report describes a snapshot in time of automation technology implementation, which is an ongoing process in almost every State transportation department across the United States. Much as the in-place capabilities nationally will continue to advance, so too will the opportunities presented by automation. Ongoing research activities seek to quantify the benefits and costs of, or explore the potential of, a variety of automation technologies that will bring with them changing data needs and products. At the same time, outreach initiatives are currently deploying some of the more mature automation technology uses, such as post-construction survey, e-Construction, new data sources for asset management decisionmaking, and the incorporation of schedule and cost information into 3D models. The products of these efforts will likely provide information that helps implementing agencies to focus their investments and efforts for supporting automation in highway construction.

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