pennsylvania
DEPARTMENT OF TRANSPORTATION

Electronic Construction Model Definition

FINAL REPORT

September 25, 2020

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Temple University

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

CONTRACT # 4400017651
WORK ORDER # TEM WO 02

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

Technical Report Documentation Page

1. Report No. FHWA-PA-2020-002-TEM WO 02	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Electronic Construction Model Definition		**5. Report Date** September 25, 2020 **6. Performing Organization Code**
7. Author(s) **Joseph T. Coe, Bechara Abboud, Ahmed Faheem, Trumer Wagner, and Francesca Maier**		**8. Performing Organization Report No.** TEM-WO-002
9. Performing Organization Name and Address Temple University 1947 N. 12th St. Philadelphia, PA 19122		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** **4400017651, TEM WO 002**
12. Sponsoring Agency Name and Address The Pennsylvania Department of Transportation Bureau of Planning and Research Commonwealth Keystone Building 400 North Street, 6th Floor Harrisburg, PA 17120-0064		**13. Type of Report and Period Covered** Final Report; 01/04/2019 - 09/30/2020 **14. Sponsoring Agency Code**

15. Supplementary Notes
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16. Abstract
3D modeling for horizontal infrastructure projects has been increasingly implemented by state transportation agencies. These agencies have found numerous benefits to using 3D models during both the design and construction phases. These benefits include greater efficiency, advanced conflict detection, improved construction quality, and advanced project management support. 3D models may also provide benefits during the post-construction stage, such as advanced as-builts. However, there are challenges that impede expanded 3D modeling adoption. These challenges include lack of guidelines, lack of expertise, lack of training, and questions regarding legality of providing 3D data for bidding. These challenges must be addressed as an agency moves toward full 3D modeling implementation. FHWA promoted 3D modeling in the second and third rounds of its Every Day Counts program. PennDOT's Digital Delivery Directive 2025 will establish a digital, 3D model-based workflow for the department that enables projects to be surveyed, designed, bid, constructed, and handed over using 3D modeling technology. Temple University's role in this effort has been to identify the previous efforts of PennDOT regarding 3D modeling and to review how other agencies have addressed aspects of their process to design and construct projects using a 3D model.

This Final Report provides a summary of all previous findings related to the TEM WO 002 research effort. The report will give an overview of 3D modeling for design through construction, discuss previous PennDOT efforts related to 3D modeling, provide a benchmark of other state DOTs, summarize best practices and recommendations for implementation, and create an implementation strategy. Additionally, the report will primarily focus on aggregating information from the previous TEM WO 002 deliverable reports in a way that will improve the understanding of 3D modeling practices and highlight the best actions to successfully implement 3D models.

17. Key Words 3D Modeling; Digital Delivery; Building Information Modeling; 3D Workflow	**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	101	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Statement of Credit

This work was sponsored by the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Electronic Construction Model Definition

TEM Work Order (WO) 002

Contract No. 4400017651

Report on Task 6 – Deliverable 6.2

Final Draft Report and Implementation Strategies

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September 25, 2020

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LIST OF ACRONYMS

3/4/5D	Three/Four/Five-Dimensional
AASHTO	American Association for State Highway Transportation Officials
ACEC/PA	American Council of Engineering Companies of Pennsylvania
AMG	Automated Machine Guidance
APC	Associated Pennsylvania Constructors
BIM	Building Information Modeling
CAD	Computer-Aided Design
CADD	Computer-Aided Design and Drafting
CAiCE	Computer-Aided Civil Engineering
CIM	Civil Integrated Management
CL	Confidence Level
CM/GC	Construction Manager/General Contractor
COBie	Construction Operations Building Information Exchange
CORS	Continually Operating Reference Stations
DGN	MicroStation design file format
DOT	Department of Transportation
DTM	Digital Terrain Model
DWG	AutoCAD design file format
ECMS	Engineering & Construction Management System
FHWA	Federal Highway Administration
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning Systems
HDS	High Definition Surveying
IFC	Industry Foundation Classes
LOD	Level of Development
MD	Model Density
MPS	Model Progression Specification
O&M	Operations and Maintenance
PPCC	PennDOT Project Collaboration Center
PDF	Portable Document Format
PennDOT	Pennsylvania Department of Transportation
QA	Quality Assurance
QC	Quality Control
RID	Reference Information Documents
RTK	Real-time Kinematic
RTN	Real Time Network
RTS	Robotic Total Stations
ROW	Right-of-Way
SS2/3/4	Select Series 2/3/4
SUDA	Subsurface Utility Design and Analysis
SUE	Subsurface Utility Engineering

EXECUTIVE SUMMARY

3D modeling for horizontal infrastructure projects has been increasingly implemented by state transportation agencies. These agencies have found numerous benefits to using 3D models during both the design and construction phases, leading them to pursue an entirely digital delivery approach to project development where the 3D models replace all or part of the 2D plans. The benefits of a digital delivery solution include greater efficiency, lower-cost bids, improved construction quality, and an opportunity to provide digital as-built information to improve the hand-over process when the facility transfers to Maintenance and Asset Management departments. PennDOT has committed to pursuing digital delivery through the Digital Delivery Directive 2025.

Thus far, 3D modeling implementation has capitalized on existing design software, but using it in new ways. Nevertheless, there are numerous challenges to developing the policy, technology, and workforce to meet 3D model-based project delivery requirements. These challenges have included lack of guidelines, lack of expertise, lack of training, and questions regarding legality of providing 3D data for bidding. There are additional downstream challenges for changing the medium of communication from 2D plans to 3D models. These include the need to perform model-based design reviews, develop new quality management procedures for 3D models, interoperability of the 3D models for contractors, and a need to develop and deploy new workflows and technology for construction engineering and inspection.

The Highway industry is pursuing 3D model-based digital delivery individually and collectively through cooperative research and AASHTO committees, as well as through programmatic partnering with their local industry. As State DOTs develop their own incremental solutions, they exchange knowledge to take advantage of lessons other State DOTs have learned. While no State DOT has a comprehensive digital delivery solution yet, collectively, there has been significant progress that PennDOT can learn from. This report summarizes many of the best practices and implementation recommendations from across the nation.

The Implementation Strategies presented at the conclusion of the report provides recommendations for approaching PennDOT's Digital Delivery Directive 2025. These are:

- defining the objectives as user-focused requirements and consistent with a data governance framework,
- defining the implementation in terms of the policy, technology, and workforce capabilities to develop,
- assessing areas in which PennDOT can glean insights from peer State DOTs,
- prioritized areas for early development, and
- strategic partnerships to pursue.

PennDOT is well placed to establish a digital, 3D model-based workflow for the department that enables projects to be surveyed, designed, bid, constructed, and handed over using 3D modeling technology, achieving the vision of the Digital Delivery Directive 2025.

1: INTRODUCTION

3D modeling for horizontal infrastructure projects has been increasingly implemented by state transportation agencies. These agencies have found numerous benefits to using 3D models during both the design and construction phases. These benefits include greater efficiency, advanced conflict detection, improved construction quality, and advanced project management support. 3D models may also provide benefits during the post-construction stage, such as advanced as-builts. However, there are challenges that impede expanded 3D modeling adoption. These challenges include lack of guidelines, lack of expertise, lack of training, and questions regarding legality of providing 3D data for bidding. These challenges must be addressed as an agency moves toward full 3D modeling implementation. FHWA promoted 3D modeling in the second and third rounds of its Every Day Counts program. PennDOT's Digital Delivery Directive 2025 will establish a digital, 3D model-based workflow for the department that enables projects to be surveyed, designed, bid, constructed, and handed over using 3D modeling technology. Temple University's role in this effort has been to identify the previous efforts of PennDOT regarding 3D modeling and to review how other agencies have addressed aspects of their process to design and construct projects using a 3D model.

BACKGROUND

Temple University's role in the TEM WO 002 efforts thus far has been to identify the previous efforts of PennDOT regarding 3D modeling and to review how other agencies have implemented 3D models for design and construction. The research team has delivered five reports. The first report, Task 1.1, described PennDOT designer's experiences with 3D modeling for design and construction. Task 1.2 provided an overview of PennDOT efforts related to 3D modeling based on previous literature and a review of PennDOT's SharePoint drive. The third report, Task 2.1, examined 3D modeling efforts at a national level, providing case studies and current practices from other state DOTs. Task 3.1 focused on how 3D models may be effectively implemented in the construction and post-construction phase. The following report, Task 4.1, discussed policies, business models, and 3D model criteria for the successful implementation of 3D models. The next report, Task 5.1, provided a summary of all findings from the previous reports and provided recommendations for the implementation of 3D models. This report, Task 6.1 is the draft final report and implementation strategy for the research project.

OBJECTIVES

Task 6.1 provides a summary of all previous findings related to the TEM WO 002 research effort. The report will give an overview of 3D modeling for design through construction, discuss previous PennDOT efforts related to 3D modeling, provide a benchmark of other state DOTs, summarize best practices and recommendations for implementation, and create an implementation strategy. Task 6.1 will primarily focus on aggregating information from the previous TEM WO 002 deliverable reports in a way that will improve the understanding of 3D modeling practices and highlight the best actions to successfully implement 3D models.

SCOPE

Task 6.1 will provide a summary of all previous findings from TEM WO 002 reports related to 3D modeling. The report will provide an overview of 3D modeling, highlight best practices, and include an Implementation Strategies guide to successfully implement 3D modeling. This report may be used to advance PennDOT's Digital Delivery Directive 2025.

2: 3D MODELING OVERVIEW

The following section provides an overview of 3D modeling. The intent of this section is to provide context for the terms and topics discussed later in the report.

3D MODEL DEFINITION

A 3D model is a digital graphical representation of proposed facility and site data consisting of X, Y, and Z coordinates for producing representations of objects in three dimensions. The model is used to communicate existing conditions, design intent, or as-built conditions. 3D models are useful for visualization, analysis, animation, simulations, plans, quantity take-off, and may support life-cycle asset management (Reeder & Nelson, 2015a). In this report the term '3D engineered model' will be used interchangeably with '3D model' unless otherwise specified. The 3D engineered model is the product of extensive survey, design, and coordination that accurately conveys design intent and communicates existing and proposed conditions to the contractor. A 3D engineered model can be used in combination with or replacing traditional 2D plans for a roadway or bridge projects and may include the following components:

Surface Models – a representation of the existing ground or proposed grading and pavement surfaces. Data may be exported for use by Automated Machine Grading (AMG) equipment for grading and paving operations.

Alignments – the horizontal and vertical alignment of a roadway are vital to a roadway project and can be used by AMG equipment for construction.

Proposed Utilities and Structures – the proposed utilities model may contain storm sewer, water main, utility poles, traffic signals, and any other utility that may be part of a roadway project. The structures model may contain structures such as box culverts, retaining walls, and bridges.

Existing Conditions – the existing conditions model can be a comprehensive 3D model that contains all relevant information about the existing conditions of a site. It may contain survey data, digital terrain models (DTMs), subsurface utility data, and existing structures.

BUILDING INFORMATION MODELING

3D models are a basis for Building Information Modeling (BIM) for Infrastructure, which applies BIM to horizontal design and construction projects. BIM is a construction process that allows the development of design scenarios and conveyance of those scenarios to project personnel, the client, or the public while maintaining a single model. BIM may incorporate project scheduling and cost (4D and 5D modeling, respectively) alongside 3D models.

Data exported from the 3D models can be transferred to AMG equipment that guides roadway construction equipment like bulldozers, pavers, rollers and excavators in real-time. Connectivity allows workers to receive and work with the most accurate, up- to-date models, for example when a design revision occurs (McAuley, 2013).

This research project focuses on how 3D models have been implemented among various state DOTs. Once a department has become familiar with designing in 3D, it may take steps to further develop a BIM process by incorporating elements such as scheduling, cost, and life-cycle analysis.

USES AND BENEFITS OF 3D MODELS

3D modeling allows roadways and/or bridges to be developed to various levels of detail and complexity in a way that is conducive to visualization. These models are used to more effectively connect a project's design and construction phases. They can also be applied to other phases of the project lifecycle to positively affect safety, quality, and efficiency during construction, maintenance, and asset management. 3D modeling has been used in the transportation industry for several decades, and although the focus has historically been on roadway design and construction, DOTs are exploring the adoption of 3D modeling practices for bridges and utilities. 3D models can be used during all phases of a project, from preconstruction to closeout.

For bridge design and construction, BIM offers significant advantages over traditional 2D design. BIM is a comprehensive digital representation of the physical and functional characteristics of a facility. The FHWA promoted 3D engineered models for bridges as part of their innovation deployment program from 2014-2016. (FHWA, 2017a) While 3D modeling practices for roadways have significantly matured over the past half-decade, 3D modeling for bridges is still emerging. The DOTs leading advancements in this area have begun to implement BIM on bridge projects. However, even in these states, BIM for bridges is still limited to pilot projects. Nevertheless, the benefits gained from the process are encouraging.

One of the major advantages of designing with parametric 3D models is that design changes can be propagated quickly and seamlessly. Using the traditional method, processing design changes was often a manual process that was time-consuming and prone to error. In contrast, adjustments to a parametric 3D model propagate dynamically across all the derivative products like alignment and profile sheets, cross-section sheets, and volume quantities. Using parametric 3D models with dynamic sheets can also improve accuracy of the plans compared to previous approaches because manual errors are avoided. Even labels are automated and update when the model changes. When 3D models that fully reflect the design intent are shared with contractors in a way that is compatible with their business systems, it eliminates their need to recreate 3D models from the 2D plans.

During the scoping and planning phases it is important to consider the goals of using a 3D engineered model. A clear understanding of the project objectives helps guide the design team to ensure 3D models are used efficiently. On a project-wide scale, 3D models could improve efficiency, decrease construction costs, improve safety, and facilitate coordination. During design, a 3D model can help identify conflicts and improve communication between disciplines. 3D models are beneficial to all design disciplines, from structural to geotechnical to hydraulic. Table

2.1 from Maier *et al.* (2017) identifies applications of 3D models at milestones during design development.

Design Stage	**3D Models Uses**
NEPA (National Environmental Policy Act) – 15%	Quantify impacts on sensitive environments Minimize Right-of-Way (ROW) impacts Compute preliminary quantities Review proof-of-concept constructability Minimize utility relocations (clash avoidance) Plan surface drainage systems
Preliminary – 30%	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%	Check site distance Perform visual impact analyses Review surface drainage Coordinate interdisciplinary design Create 3D graphics and 4D videos for ROW acquisition & public involvement Compute quantities Perform staging and constructability reviews Conduct maintenance of traffic conceptual planning Create ROW and utility relocation plans
Final Plans – 90%	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%	Create bid documents Create 3D model reference data
Award – 100%	Create contract documents Create staking/layout data Create AMG/real-time verification models

Table 2.1. Applications of 3D models during design development. (Maier, et al., 2017b)**.**

There is overlap in benefits when using 3D modeling for both roadways and bridges. However, 3D models are used in different ways for bridge design and construction than they are for roadways. As with roadways, the life-cycle uses of bridge models may be broken down into four main categories: Design, Construction, Operation, and Maintenance. Brenner *et al.* (2018) identified key uses of 3D bridge models from planning to construction which include:

- Visualization for design review and construction planning
- Computer-based clash detection
- Virtual assembly
- Enhanced automation for detailing and reinforcement schedule production
- Inventory data
- Collaboration with other disciplines such as terrain surfaces, alignments, and profiles

3D models may provide benefits to construction and inspection teams as well. 3D models could be used for construction management tasks, including constructability details, construction sequencing, and equipment placement. Mitchell *et al.* (2019) conducted a return on investment analysis on behalf of Michigan DOT, which included conducting a survey of eleven contractors to gauge experience with 3D models as Reference Information Documents (RID). The researchers found that most contractors use 3D models to prepare files to be used for AMG construction equipment. Other uses of 3D models included (Mitchell *et al.*, 2019):

- Performing quantity take-offs for bidding estimates.
- Identifying inconsistencies between the RID files and the plans.
- Validating contractor independently created models.
- Determining storage locations (i.e., defining haul distances, balancing earthwork, locating batch plant locations, and identifying waste and borrow areas) during the bidding process.
- Creating 4D models to visualize schedules.

AMG is a significant primary use of 3D models for highway construction. For AMG, 3D models (e.g. surfaces or line strings) are loaded onto onboard computers, which work with sensor positioning information to provide guidance to the operator (e.g. for excavation) or to control the blade of the equipment (e.g. grading and paving) to provide real-time layout. AMG is widely accepted in the construction industry due to its ability to increase productivity and quality of work while also reducing labor time in the field. Benefits of AMG include reduced construction costs, reduced schedules, reduced fuel usage, increased quality, and increased safety.

4D and 5D modeling represents another use of 3D models. 4D and 5D models may be used for schedule simulation and cost simulation, respectively. A 4D model results from segmenting a 3D model and connecting discrete pieces of 3D geometry to tasks in a critical path method schedule. When that schedule is cost-loaded, the model is called a 5D model (Maier, et al., 2017b). Currently, 4D and 5D modeling are beyond the scope of most DOTs, although some agencies, such as New York State DOT, have begun to use 4D and 5D models, particularly for use on high-complexity bridge projects.

Uses of 4D and 5D models include (Maier, et al., 2017a):

- Construction progress and payment tracking
- Enhanced visualization
- Estimate and resource optimization
- Risk mitigation

Based on the knowledge gained from PennDOT workshops and experiences of other state DOTs, the following are significant benefits that could be expected from the implementation of 3D modeling:

- Increased accuracy by highlighting errors early in the project life and more closely adhering to the designer's intent
- Smoother and more efficient communication between the Department and the contractor.
- Better visualization for analysis and coordination.
- Time and cost savings. 30-40% time savings and 6% construction savings. (Bentley Systems and Montana DOT, 2016)
- Improved safety.

By implementing 3D modeling, the numerous benefits of AMG can also be fully realized. Federal Highway Administration (2013) reported total project cost savings of 4% to 6%, 15% to 25% efficiency gains for contractors' earthmoving activities, 66% savings for grade checking, schedule contractions, and productivity increases ranging from 40% to 50%. Additional benefits of AMG include accurate predictions of quantities, better paving smoothness, low opportunity cost for real-time verification, less rework, and a reduction in claims. However, it should be noted that asphalt paving generally does not appear to benefit from AMG; the paver and screed are less reactive to slope and grade changes and there are less opportunities to control yields at the paver. Although with fewer opportunities to control yields, the contractor may be able to utilize a less experienced crew and still receive a reliable surface (Maier, F. et al., 2017a.).

Many of the benefits of 3D modeling are realized during the construction phase by reducing the number of errors, inaccurate quantities, unresolved transitions, and inefficient methods. However, the investments to realize these benefits must be made during the project scoping and design phase through accurate survey and model development. For some projects, creating a 3D model may not provide significant benefits to the design team, but will greatly increase time savings and productivity during construction. The implementation of 3D modeling should be viewed in a holistic manner and should include costs and benefits spread across all project phases (Maier, et al., 2017b). During the final design phase, 3D modeling can provide benefits to several engineering disciplines including structural, hydraulic, and geotechnical.

Using BIM for bridges offers distinct advantages over traditional bridge design. 3D and 4D modeling for bridges can produce benefits during design, construction, and throughout the lifecycle of the bridge as models can reduce maintenance and repair costs. BIM uses a single source of bridge information that is exchanged for various applications in the bridge lifecycle. The following benefits are specific to bridge design and construction and may be realized by using 3D modeling (Brenner, et al., 2018):

- Avoid manual data entry, which is error-prone
- Avoid inconsistencies in duplicated data
- Reusing design data in construction or beyond
- Avoid physical pre-assembly through virtual fit-up
- Prefabrication, which accelerates construction

Value of 3D Modeling

3D models are particularly useful for planning, designing, constructing, operating, and maintaining transportation facilities (Turkan & Shane, 2016). However, DOTs, especially those in the early stages of 3D modeling development, must find a balance between efficiency gained and level of work required to develop a 3D model. The DOT should identify which types of projects will benefit most from being designed in 3D and focus designer's efforts on those projects. Factors that may influence the use of 3D modeling include project complexity, price, and nature.

Based on a return on investment analysis conducted on behalf of Michigan DOT looking at projects from 2012 to 2016, projects in the range of $5 million to $20 million benefit the most from the use of 3D models. However, as DOTs become more advanced, the range of projects that may benefit from 3D modeling will likely increase. Furthermore, regardless of project size, 3D models consistently produced bids that were lower than the engineer's estimate. Even when bids came in higher than the engineer's estimate, projects delivered with 3D models as RID produced fewer change orders than those with only 2D plans (Mitchell, et al., 2019).

While benefits of 3D models can be realized when used for a single function (i.e. roadway design), implementing 3D models across functional units will result in higher benefit realization and offers an opportunity to share the costs of data acquisition and technology deployment (FHWA, 2017b). It may be difficult to justify the costs and efforts to implement 3D modeling for one functional unit, but if the data is used across multiple disciplines such as roadway and bridge design, construction, and asset management, the benefit realization will be much higher. Using 3D data across multiple functional units may reduce cost for data collection, improve workflows for preconstruction activities, improve as-built records, and streamline procurement of technology.

As an example of the value added to projects, Georgia DOT began requiring 3D model files for projects that propose earthwork or grading operations while still in the early stages of 3D development. Examples of such projects include, but are not limited to (Georgia DOT, 2018):

- New location roadways
- Widenings
- Bridge replacements
- Grade separations
- Interchange reconstructions

- Roundabouts
- Turn lanes
- Passing lanes

3D models were not required for projects that did not propose earthwork or grading operations or for MicroStation V7/CAiCE projects. (Note: MicroStation V7 was replaced in 2004 and CAiCE software was discontinued in 2008. GDOT last updated their CAiCE support files in 2016.) Despite the benefits of 3D modeling, a model may not always provide enough value to warrant development. As an example, Figure 2.1 is a decision support tool to establish contractual requirements for 3D models. The different approaches between Michigan DOT and Georgia DOT highlight how the value added by 3D modeling is dependent on a number of factors.

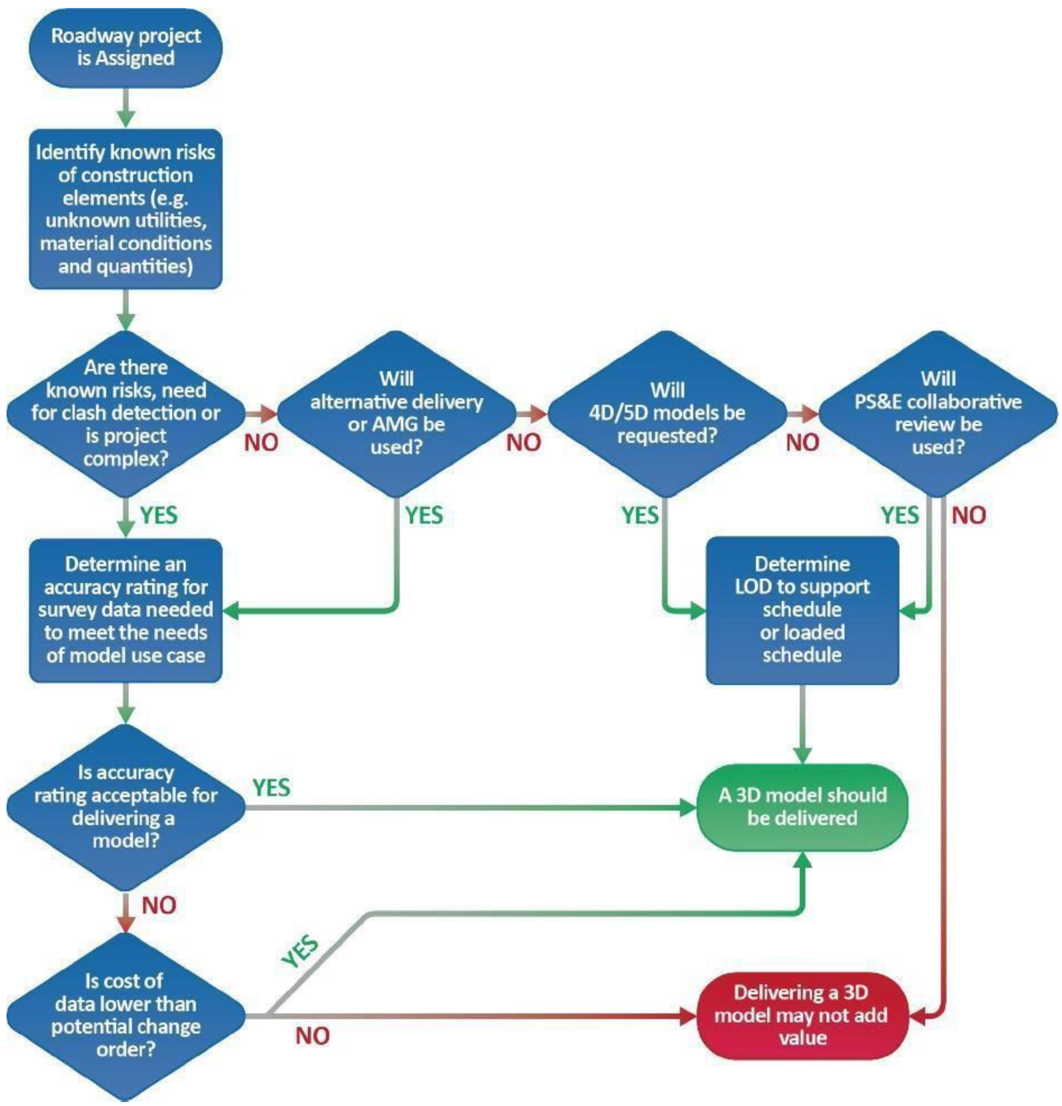

Figure 2.1. 3D Modeling Decision Tool (Mitchell, et al., 2019)**.**

CHALLENGES FOR IMPLEMENTING 3D MODELING

Adoption of 3D modeling by DOTs has been slowed by the difficulty in its implementation. As part of the Every Day Counts initiative, FHWA conducted a number of workshops at which participants identified the following challenges associated with adoption of 3D modeling ((Mitchell, 2014):

- Lack of guidelines or best practices
- Costs associated with setting up technical infrastructure (storage, bandwidth, accessibility, etc.)
- Mismatched technological advances (software vs hardware)
- Consistency in file standards and data exchange
- Lack of expertise
- Lack of investment in training and technology
- Accelerated deadlines reduce time to learn 3D modeling practices
- Lack of consistency from contractors
- Questions regarding legality of 3D data for bidding purposes
- Questions regarding the designer's ability to sign and seal a model
- Development of specifications
- Quality assurance (QA) and quality control (QC)

Transitioning to 3D modeling has a far greater impact than simply learning a new software package. It represents a significant change in the way state DOTs conduct business across multiple functional areas. 3D modeling adoption therefore requires a significant amount of new training that represents a direct expense when implemented across a large staff. This expense does not even consider the costs associated with short-term loss of productivity or the costs to purchase software, licenses, and survey equipment. Often, performance measures for DOTs are project focused, leading to "poor" performance on the first projects that attempt to use these new technologies.

Standardization of 3D models adds more elements beyond typical drafting standards. Drafting standards typically require consistency of file names, layer names, and line styles, colors, and weights. With 3D modeling (especially using BIM), object naming conventions are also important. Each DOT has specific needs related to file type and file transfer. While contractors typically use their own 3D modeling software and workflows, contractors' needs for file formats and preferences for content are similar. These are: surfaces, alignments, and 3D line strings with data points every 10 ft on tangents and every 2 ft on curves. (Maier, et al., 2017b)

Despite the clear benefits of sharing 3D models for construction, designers have enduring concerns regarding liability. Currently, project plans and specifications are considered legal contract documents. Designers are concerned that they will be held liable for errors or omissions in reference 3D models and states developed disclaimers to mitigate the risk. Some states require that the contractor certify the model before using it for AMG, while others consider the model to be the contractor's layout means and methods.

There are statutory issues regarding the designer’s ability to sign and seal the model. Having a single engineer sign-off on an entire model involves several disciplines that fall outside of his/her area of expertise, including work that is done by subconsultants. There are legalities that must be addressed in this area. States have overcome this by providing a memo indicating which specific files contain design elements that are certified by the various engineers in charge.

There is also significant variability in the development of specifications for using 3D models for construction layout and AMG. Some states are issuing specifications that merely permit the contractor to use AMG while others attempt to be more prescriptive and define the process that the contractor must follow to have their control and Global Navigation Satellite System (GNSS) localization information certified and shared with the owner’s engineer. The sections of the specifications that are affected by 3D modeling primarily relate to the contractor’s Control of Work and how the contractor and owner’s engineer exchange information. These sections include the survey clauses related to verifying and establishing control monuments, and the order of precedence of the 3D models related to coordinating contract documents. (Maier, et al., 2017b)

Finally, state DOTs want their surveyors and engineers to manage the quality of the 3D model. However, they have neither the training nor the manpower to do so. Protocols for managing the quality of 3D models are evolving. Another separate, but related concern is how to perform and document design checks using a model-based workflow.

Each DOT should subsequently identify challenges under its control and create a plan that fits the agency’s needs. When doing so, a review of other DOT practices is also extremely valuable.

3: OVERVIEW OF PENNDOT EFFORTS

As part of the Digital Delivery Directive 2025, PennDOT has held several workshops with industry leaders to discuss 3D modeling implementation for design through construction. During these workshops, PennDOT personnel met with designers, surveyors, and contractors to determine needs and best practices in regard to 3D modeling.

PennDOT has also been involved in several 3D design projects and, in 2015, began implementing 3D pilot projects. However, results from the Task 1.1 survey indicate that several of these pilot projects have not been completed or 3D files were not used through construction. Projects that were completed include the United High School Curve project in District 10, the US 219 Garrett project in District 9, and the SR 19-S02 Widening/Reconstruction project in District 1. PennDOT has also been involved in consultant-designed bridge projects with High Steel Structures, NTM Engineering, and Gannet Fleming.

The level of 3D modeling experience varies among PennDOT districts. Some districts rarely create 3D models, while other districts create 3D models for nearly every roadway project. As is the case with the many state DOTs currently implementing a 2D workflow, PennDOT designers typically create a digital representation of the project, convert the design to 2D plans, and then provide the 2D plans to contractors. Realizing the benefits of a 3D model, contractors often convert the 2D plans into a 3D model for construction. The contractor must also convert models to 2D shop drawings for review and approval. Due to the inefficiencies of the process, very few PennDOT projects are constructed using the model created by the design team.

PennDOT designers have cited several reasons to not design in 3D, including low project complexity, lack of survey information, inexperience, and the effort associated with creating a 3D model. Chapter 5 addresses strategies used by other DOTs to combat these challenges. PennDOT would like to expand on the current uses of 3D models to fully realize the benefits of designing and constructing in 3D. In aiming to deliver more information through digital means, PennDOT expects to see an increase in the number of projects in which 2D plans are not the sole source of information. Digital delivery aligns with the goals of the Digital Delivery Directive 2025 initiative, improves efficiency, and requires far less paper than traditional delivery methods. Digital models will contain critical information and components will have 3D geospatial coordinates.

3D MODEL DELIVERABLES

The district decides whether or not to provides 3D files to the contractor using guidance provided in a Strike-Off Letter. When no 3D data is provided, the contractor often digitizes the plan sets to create their own 3D model. However, some districts do share 3D models. Even among these districts, 3D files are not always provided to the contractor despite the potential improvement in quality and reduction in costs (McAuley, 2013). To produce uniformity and consistency that will increase the contractor’s understanding of the design intent, PennDOT provides directions to designers when modeling in 3D. These directions may be found in PennDOT Pub 14M (DM-3).

Standard deliverables based on construction needs are integral to the successful adoption of 3D modeling. The following deliverables are recommended as a minimum for PennDOT projects (PennDOT Bureau of Project Delivery, 2016):

Plan Set (can be derived from the DGN/DWG file). The plans produced from the 3D model must appear as the previously accepted plan sets.

- DGN or DWG file(s) of:
    - Horizontal and vertical alignments
    - Coordinate geometry of points used in model development
    - Component lines, areas, and volumes
    - 2D and 3D line work
- LandXML translation (3D Model) for:
    - Horizontal and vertical alignments
    - Surface triangles of each corridor
    - Surface features of each corridor
    - Cross sections of each corridor
- Reports
    - Alignment
    - Point/feature names
    - Key station report
    - Coordinate system used to create data in the 3D model
- Survey
- Final Design zip file

All districts interviewed for the Task 1.1 report provide LandXML and DTM surface files as a minimum when delivering 3D data. Several designers responded that they provide as much 3D data as possible with the bid package. However, some respondents noted that contractors generally only request 2D CADD files.

CONSTRUCTION AND CONTRACTOR REQUIREMENTS

PennDOT recognizes that there are numerous benefits to 3D engineered models for construction. These benefits include labor savings, greater accuracy, reduced traffic impacts, increased productivity, increased efficiency, and the ability to utilize AMG. (McAuley, 2013)

According to PennDOT, 82% of contractors reported they recreate the 3D model from the 2D plan set provided to them at least half the time (Reihart, 2016). It is evident that contractors see benefits to using 3D models, and PennDOT aims to make it easier to construct using 3D by requiring 3D data files to be included in the bid package.

Constructability Analysis

The purpose of a constructability review is to examine a project's design to assess its construction efficiency. PennDOT requires that constructability reviews be conducted by constructability teams at various stages throughout project development. These teams should always consist of district personnel from design, construction, and maintenance, as well as consultant staff, Central Office staff, and FHWA staff as needed. 3D digital models should be reviewed whenever they are available. The following general requirements are essential for successful constructability reviews: (PennDOT Bureau of Project Delivery, 2018):

- Integration of constructability reviews into the early design process prior to final plans submission.
- Uniform and flexible methodology that can be implemented according to individual project requirements and the abilities and available resources of each District.
- Proper tools for each District. This includes training in constructability as necessary and access to using the statewide open-end agreements for consultant services.
- Involvement of experienced construction personnel.

Additional information regarding constructability review procedures for highway and bridge projects may be found in Appendix N of DM-1 (PennDOT Bureau of Project Delivery, 2018).

PennDOT only allows users to download the standard configuration of approved mobile applications (also called "apps"). PennDOT currently uses apps such as:

- Mobile Construction, which allows field staff to access plans and other project documentation from Engineering and Construction Management System (ECMS) on their iPads,
- MC Project Site Activity for inspection data input,
- MC Punchlist for managing contractor requirements throughout the project duration to avoid a last-minute rush to closeout,
- Office Lens, which converts scanned images or photos to editable documents, and
- Air Watch, which is a mobile device application management tool.

PennDOT issued over 300 iPads to department staff for entry of Mobile Construction Docs information. PennDOT estimates that Mobile Construction apps realized an overall cost savings of $28 million (Schneider & Weisner, 2017).

SURVEYS

An accurate survey is a critical component of a successful 3D model. Survey data is used to generate maps, original ground surface, earthwork cost estimates, and more. Conventional field surveys may still be used with success, but newer equipment types and survey methods are often helpful to increase productivity and obtain enhanced accuracies for creating a 3D model. Such survey methods include static and mobile lidar, digital levels, robotic total stations, UAS photogrammetry, and real-time kinematic (RTK) devices like GPS/GNSS rovers.

According to PennDOT questionnaire respondents, conventional field survey is the most popular method of survey collection for projects designed in 3D. However, other methods such as GPS rovers, mobile and static lidar, and photogrammetry are also used to gather data; the extent to which these methods are used varies by district and project. The department typically uses vehicle-mounted mobile lidar on existing corridors, supplemented by photogrammetry outside the corridor, especially in vegetated areas. This reduces the need for lane closures and limits the exposure of survey crews to active traffic. Static lidar is used for specialized projects, especially where other survey methods are limited by safety concerns. Surveyors for PennDOT use static lidar to capture specific smaller portions of roads, bridges, and rugged terrain. PennDOT's photogrammetry unit is typically involved in more than one hundred projects a year. (Krot, 2018)

PennDOT designers have noted issues with survey products when creating 3D models. There have been instances where the initial survey fails to cover all the required areas on the first attempt, so supplemental surveys are required to collect more information. Some designers have also noted that survey accuracy is not always sufficient for 3D design; most designers agreed that additional survey detail would be beneficial.

QUALITY MANAGEMENT

QC and QA are two distinct, but related critical quality management processes that are used in design and construction. The switch from 2D plans to 3D models affects how these processes are executed. With mature quality management protocols, constructors should be able construct using the information in the design model without design revisions. However, State DOTs are still developing and refining procedures to manage 3D model quality, including programs to check the model before it is sent out with bid documents.

PennDOT has established that there should be a different review checklist for the 3D model than what is used with the 2D plans. The Department obtained a review checklist from Michigan DOT to use as a template, and developed quality management guideline for 3D modeling projects. The PennDOT QA/QC process consists of Review of Plans and Digital Models, Conduct Meetings to Discuss Stage Reviews, Prepare and Disseminate Reports and Presentations, and Prepare an Implementation Plan for Recommendations. Further details on this QA/QC process can be found in the Task 1.2 report.

DATA MANAGEMENT AND SHARING

PennDOT made pre-bid electronic files available through its ECMS at the start of 2014. The ECMS site provides current information on PennDOT construction projects, construction contracts, and consultant agreements. The system handles biddings, estimates, approvals, work orders, consultant agreements, and project closeout documentation. PennDOT has also published a user guide for the ECMS. However, between January 2014 and August 2016, only 120 design consultant firms signed up to access the files in the ECMS. In that time period, about 122 projects, or just over 24% distributed pre-bid design files (Reihart, 2016).

PennDOT uses ECMS, PennDOT Project Collaboration Center (PPCC), and Electronic Construction and Materials Management System as primary technologies for administering construction contracts and managing construction and materials data. PPCC is a SharePoint-based platform that allows for submittals from both PennDOT and contractors with automated workflows and shared project files and photographs. PPCC is estimated to provide an overall cost savings of $29.1 million, with $5.2 million in development costs (Crawley, et al., 2015).

PennDOT uses electronic approvals in certain instances, with formal digital signatures in others (e.g., contract documents and change orders). The Department has used electronic signatures since 2015 and, in 2017, had approximately 300 people signed up for the service, half of whom were contractors (Crawley, et al., 2015).

MODEL OF RECORD AND AS-BUILT RECORDS

PennDOT has established that both the DOT and the contractor should use the same model after both parties have reviewed and approved the model. Subsequently, the constructed 3D model will become the Model of Record for future projects and asset inventory. Maintenance will have access to the Model of Record for incident management, system impact review, and for inclusion in their asset management system. An as-built model should be created after construction that contains metadata about the features that can be utilized for asset management. PennDOT designers have identified 3D models as being particularly useful for future maintenance and inspection purposes.

TRAINING

PennDOT has identified training as a significant hurdle towards the adoption of 3D modeling practices. There has been a lack of training on developing a construction-ready design model. PennDOT aims to develop design training with new standards and a focus on construction.

Responses to the Task 1.1 survey questionnaire show that PennDOT designers have not received formal 3D modeling training for many years—since 2010 for some personnel. Additionally, no training had been carried out for the new OpenRoads software at the time of the survey. Instead, many designers had to teach themselves or learn from colleagues to become proficient with the 3D modeling software. PennDOT identified the need for separate ‘design’ and ‘construction’ training sessions for 3D modeling.

The FHWA held a 2-day workshop in Harrisburg in July 2014. The workshop was used as a training and information session that covered topics regarding 3D modeling practices such as the national state of practice, uses for construction inspection, QA/QC methods, and implementation strategies. The workshop worked well as an introductory session, but hands-on training is needed to improve designers’ ability and confidence with the 3D modeling software.

WORKFLOW

PennDOT workflow varies by district. The following workflow for the creation and delivery of a design applies to the majority of PennDOT districts:

1. Analysis and design using 2D or 3D models
2. Documentation using 2D contract plans
3. Contractors/Fabricators take the 2D drawings and recreate a 3D model

In districts that regularly design in 3D, a 3D model is created during the analysis and design phase. In these districts, the survey is performed in 3D, the design team creates 3D models, and the 3D files may be provided to the contractors at project advertisement. However, these 3D files are not governing documents and are not always provided. In cases where a 3D model is not created or is not part of the bid package, the contractor may convert the 2D plans to 3D for construction. Both designers and contractors have noted that the 3D model files usually are inconsistent with the 2D plans because designers use manual edits to the plans for expediency. Often, it takes the contractor longer to identify and address these differences than it takes to digitize plans and recreate the 3D model.

PennDOT has outlined requirements for its new workflow when designing and constructing in 3D. A description of the workflow tasks may be found in the Task 1.2 report.

3D MODELS FOR PUBLIC PRESENTATION

PennDOT recognizes the importance of using 3D modeling for visualization purposes. 3D renderings of major roadway and bridge projects are an effective way to communicate a design concept to the public and non-technical stakeholders. The department has divided 3D models for public engagement into three main categories:

- Static, two-dimensional
- Three-dimensional without animation
- Three-dimensional with animation

Additional information about these types of renderings may be found in the Task 1.2 report. PennDOT has also made efforts to create physical models for visualization. In 2015, PennDOT obtained a 3D printer to make models for roadway and bridge projects. The Department reached out to districts to provide the 3D printing service for public meetings and outreach.

4: A BENCHMARK OF STATE DOTS

This section provides an extensive review of DOT experiences with 3D modeling. Publications from other state DOTs such as implementation guides, design manuals, presentations, project reports, and research papers were examined to benchmark these agencies and determine 3D modeling experiences on a national scale.

OVERVIEW OF EFFORTS

Leading DOTs have many years of experience working with 3D models and have completed a significant number of projects using 3D modeling technologies. Some of these DOTs have integrated 3D models into project deliverables as reference information documents. These agencies have published many reports including implementation plans and 3D modeling guides that will be useful to PennDOT in their efforts with 3D modeling. In particular, several state DOTs have either institutionalized the use of 3D modeling and CIM technology for roadway and bridge design or are making significant strides towards their adoption:

- Utah DOT
- Michigan DOT
- Oregon DOT
- Iowa DOT
- Minnesota DOT
- New York State DOT
- Wisconsin DOT
- Texas DOT
- Florida DOT
- Massachusetts DOT

This section of the report includes a brief description of the 3D modeling efforts of each of the DOTs named above. Case studies and reports from these DOTs have been examined and recommendations for 3D modeling practices have been based on this review.

Utah DOT

Utah DOT began their 3D modeling implementation plan in early 2014 with a peer exchange with Iowa DOT and a FHWA-sponsored workshop and peer exchange. Utah DOT estimated that as much as 50% of the time spent designing a project was used to convert the engineers' 3D model into 2D paper plans to be provided to the contractors. The department's plan was divided into three sections: a short-term; mid-range; and long-range plan. In short, the implementation plan aimed to gather information on 3D design, modify provisions, begin training, and address the specifics of transitioning to a 3D model-based workflow. Starting in 2014, Utah DOT began formally supplying digital surfaces and other design files, along with the paper plan sheets, to contractors as part of the bidding package (Lukes & McDowell, 2017). As of 2018, Utah DOT pre-releases information to contractors and uses Google Sites for requests for information from bidders. The Utah DOT specification requires the contractor to provide a GNSS rover (including training and maintenance) for the inspectors' use when the contractor elects to use AMG. UDOT equips inspectors with iPads, and laptops.

In 2014, Utah DOT also moved forward with a pilot program to use what they called Intelligent Design and Construction, which is a 3D model-based or BIM-based workflow using the 3D model as an official contract document, replacing most 2D plans. (Note: Utah DOT now uses the term "Digital Delivery of Model-Based Design and Construction" or simply "digital delivery.") Utah DOT initially used Intelligent Design and Construction on pilot projects using construction manager/general contractor (CM/GC) procurement and subsequently expanded to design-build and design-bid-build procurement. Utah DOT's first pilot project was completed in 2016 and was named 2016 Utah DOT Innovative Project of the Year (Lukes & McDowell, 2017). Utah DOT uses a combination of in-house designers and consultants for design work. Utah DOT initially used digital delivery on low complexity roadway projects and increased the complexity with increasing experience. Utah DOT has now completed more than ten digital delivery projects.

A key component of Utah DOT's 3D modeling system is the department's integrated data management system. In 2007, Utah DOT began to develop a data visualization tool called UPlan to improve their long-range planning process (FHWA, 2016b). UPlan is a web-based geographic information system (GIS) that allows users to share and customize maps of geospatially located data. After realizing the potential of UPlan, Utah DOT developed UGate, the Department's geospatial data warehouse, between 2009 and 2011. The system acts as Utah DOT's central geospatial data repository and pulls data from different Utah DOT databases that is then accessible through portals. Beginning in 2012, Utah DOT began using statewide mobile lidar data to extract features representing roadway assets to update the asset inventory residing in UGate. The point clouds are also in UGate, which allows the department to examine any feature across the state.

As per the department's 2017 Intelligent Design and Construction Guide, Utah DOT uses the following packages to produce, deliver, and transmit the project deliverables:

- Bentley MicroStation
- Bentley InRoads/OpenRoads
- Bentley ProjectWise
- Bentley OpenRoads Navigator
- Utah DOT Electronic Project Management
- Utah DOT Project Development Business System
- UPlan/GIS

Utah DOT has subsequently updated their design modeling guidance. The latest copy is available on the Utah DOT Digital Delivery website. (Utah DOT, 2019)

Michigan DOT

For over a decade, Michigan DOT has used 3D modeling practices for roadway design, survey, and construction. Michigan DOT was one of the lead states for 3D modeling that assisted the FHWA with the Every Day Counts rounds 2 and 3 deployments of 3D Engineered Models. The department is currently using both Bentley OpenRoads and OpenBridge Modeler software for roadway and bridge design, respectively and was a lead state for using paperless project delivery or "e-Construction." In 2012, Michigan DOT began providing 3D models as RID to contractors as part of the bidding package. As of 2015, Michigan DOT has required all RID to include 3D models and all Michigan DOT's construction and materials offices use a paperless document management system (Crawley, et al., 2015). Michigan DOT's e-Construction solution uses ProjectWise, the electronic document management tool the department has used since 2003.

With well-developed 3D design for roadways, Michigan DOT began considering using BIM for bridge design. In 2016, Michigan DOT initiated a research project to evaluate how to incorporate 3D and 4D modeling into bridge design. The research was conducted in four phases: (1) preliminary review of 3D modeling practices; (2) further review of modeling practices; (3) demonstration of 3D modeling for bridges; and (4) training development and a final report. The researchers completed an extensive literature review of 3D and 4D modeling for bridge design, resulting in a number of practical applications and recommendations that can be used to advance the use of 3D modeling for bridges. The primary opportunity identified was to use 3D models during the preconstruction process to automate plans production. For most projects, the first use of 3D data would be during the Study phase, which follows the Scoping phase. During the Study phase, topographic survey is collected, and alternatives are considered to a high level of detail (Brenner, et al., 2018).

Oregon DOT

In May of 2008, Oregon DOT published a 25-year plan for the development and implementation of "Engineering Automation." The plan detailed the importance of transitioning to 3D design and included key concepts such as information technology infrastructure, survey networks, and construction automation. (Singh, 2008) The (current) 2012 Highway Design Manual has been updated to include a chapter on 3D Roadway Design and an appendix for 3D model quality control. (Oregon DOT, 2015)

Like Utah DOT, Oregon DOT developed a system to manage survey data in a way that is best suited for 3D design. The department first established the Oregon Real-Time GNSS Network. This system allowed for GNSS positioning algorithms that would give accurate positions without having to set up a temporary base station. Next, Oregon DOT improved the Oregon geoid model through a height modernization campaign with the National Geodetic Survey. Finally, Oregon DOT created a new coordinate reference system that would minimize distortion to achieve values as close as possible to actual ground coordinates (FHWA, 2016c).

In 2014, Oregon DOT began tracking their 3D modeling progress, identifying 10 projects across four regions using 3D modeling deliverables with the bid package. That number rose to 18 projects in five regions in 2015 and almost doubled to 30 projects in four regions in 2016. Oregon DOT's contractors had used AMG on several projects and have worked with Oregon DOT on updates to the specifications to further promote the use of 3D design data. Currently, Oregon DOT allows AMG to be used instead of traditional survey staking. Oregon DOT currently designs all resurfacing, restoration, rehabilitation, and modernization projects in 3D using Bentley InRoads SS2. 3D design may also be used for smaller projects that include designed grading work.

Iowa DOT

The Iowa DOT's first pilot project for 3D modeling was the Sibley Bypass project in 2006. The Iowa DOT was one of the lead states that supported the FHWA with their deployment of 3D Engineered Models during Every Day Counts rounds 2 and 3 (Guo, et al., 2014). In 2015, the department published an implementation manual: 3D Engineered Models for Highway Construction: The Iowa Experience. (Reeder & Nelson, 2015a) The manual is intended to act as a guide for other state DOTs who wish to transition from 2D plan sets to 3D engineered models. Iowa DOT provided guidance for topics such as standards, information provided to the contractor, surveying, and tolerances.

Currently, Iowa DOT uses Bentley software for both roadway and bridge design. The department uses lidar when warranted to develop existing ground models and Bentley GEOPAK for modeling software. The department creates the 3D model first (model-centric design) and provides pre-bid 3D files to contractors via the department's website. Iowa DOT's letting process submits all files to the department's electronic records management group for long term storage. The department has piloted OpenBridge Modeler for bridge design in 3D and has completed a pilot project using the 3D model for a bridge as the primary contract medium, building on the success using 3D roadway models as the primary contract medium. Iowa DOT is looking to advance its 3D modeling practices to include more robust BIM practices to further streamline design.

Minnesota DOT

Minnesota DOT has made significant efforts to develop a full 3D workflow and is currently working towards expanding the use of 3D modeling in construction. One region in MnDOT has institutionalized 3D inspection methods for construction. In September 2016, Minnesota DOT published a report detailing the current state of 3D modeling practices in Minnesota and provided a summary of key lessons learned from European countries and other state DOTs who have successfully implemented 3D modeling practices. Minnesota DOT provides electronic PDF plans and specifications for bidding. After bidding, Minnesota DOT provides 3D models to the contractor through their file transfer protocol site (Turkan & Shane, 2016). The department shares its CAD models and other data through ProjectWise and their file transfer protocol sites. Minnesota DOT also has detailed digital as-built requirements (Minnesota DOT, 2017).

New York State DOT

For years, New York State DOT has been regarded as one of the nation's leaders in 3D, 4D, and 5D modeling since their pilot project on the Koskiuzko Bridge (Maier, et al., 2017a). The department uses 3D models created with Bentley InRoads and MicroStation for design, construction, and electronic as-built production for both roadway and bridge projects. In 2010, 3D models for substructures became mandatory for all new and replacement projects (New York State Department of Transportation, 2017). New York State DOT uses digital information and BIM technologies on any project of any size if the project may benefit from the uses. Recently, the department has purchased field tablets for using automated tools to review the 3D model during construction, process shop drawings, and access specifications or other data electronically.

New York State DOT's bridge program is advanced compared to most other DOTs. Using Bentley MicroStation, New York State DOT creates models that are used for geometric analysis and detailing but are not used for structural analysis. The models aid in plans production, quantity take-off, and interdisciplinary coordination. The 3D bridge models are available to contractors as part of the bid reference documents; (New York State Department of Transportation, 2017) however, they require advanced MicroStation knowledge and access to the software to export each model individually (Brenner, et al., 2018).

New York State DOT undertook a research effort to examine 3D data-driven design in fabrication and shop drawing review for bridge steel. The project was initiated starting with MicroStation InRoads files and then transferring in steel elevations. There was a focus on ensuring data integrity within the model over developing the visual side of the model; file compatibility was an important consideration (Brenner, et al., 2018).

New York State DOT has met with the contracting industry, consultant industry, and academia since 2016 to identify risks and challenges of using 3D models as contract documents for construction. The department found that using a 3D model has improved communication and coordination, data for control and construction build out, construction inspection capabilities, and contract delivery (Bell, 2018).

Wisconsin DOT

Wisconsin began their 3D modeling initiative in 2009 with the development of an Implementation Plan. The plan was prompted by prominent initiatives between 2007 and 2009 including the decision to implement a 3D design process and the option for contractors to use AMG for grading beginning in 2009. The 2009 3D Technologies Plan included five initiatives: (1) Real-time Kinematic GPS Network; (2) DTM Data Collection; (3) 3D Design; (4) Automated Machine Guidance; and (5) Field Technology and Inspection (Vonderohe, 2013). Wisconsin DOT's 2009 plan was updated in 2013 to include a new vision statement that targeted adoption of 3D methods and seamless data flows throughout initial survey, design, contracting, construction, as-built survey, and other applications included within the infrastructure lifecycle (Zogg, 2013).

In 2010, WisDOT implemented Civil 3D as its roadway design software. After 4 years of piloting the sharing of 3D design information with contractors, the department implemented 3D design delivery requirements in 2014. Designers are now required to provide contractors with 3D design models, pre-bid, for most earthwork projects (Wisconsin DOT, n.d.).

WisDOT has started a number of 3D modeling projects since this initiative began, most notably the large Zoo Interchange process that is currently under construction. The Zoo Interchange (or Southeast Freeways project) has used a combination of Bentley LEAP software and rapid geometric modeling software tools to develop bridge models (Brenner, et al., 2018). The department began its first stringless paving project using AMG equipment in 2017.

Texas DOT

Texas DOT's designers and contractors have used advanced 3D modeling on design-build projects for many years, including the DFW Connector project in Grapevine, TX. The department had its first 3D designed project let for construction in 2015 following a statewide roll out of the OpenRoads technology offered in GEOPAK SS3 earlier that year. In 2016, Texas DOT began a statewide hardware upgrade to accommodate modern 3D design practices. The department began one-day 3D/ProjectWise training in 2016 and began three-day 3D design training in 2017. In February 2018, Texas DOT implemented a mandatory 3D conversion and aimed to adopt OpenRoads Designer by Summer 2019. The 25 district offices identified about 100 projects over a two-year period that will use 3D models in their design.

Texas DOT's 3D design implementation plan applies to in-house design projects and consultant projects. The plan also applies to all construction projects that require geometric design, rehabilitation projects, and reconstruction projects. Texas DOT's implementation plan does not apply to local let, design-build, seal coat/overlay, or restoration projects (Proctor Jr. , 2017).

Not only must all new projects as of February 2018 be designed in 3D, all existing projects must also be converted to 3D. Texas DOT is requiring the conversion to 3D in order to increase safety, productivity, return on investment. The department provides the contractor with the 3D model files for bid preparation and AMG.

Florida DOT

Florida DOT has been identified as one of the leaders in 3D modeling for design through construction. The department was noted as a driving agency for CIM implementation and received the highest score possible for CIM usage (O'Brien, et al., 2016). Florida DOT has expertise in using 3D, 4D, and 5D modeling for transportation projects. The department began allowing consultants to use a choice of CADD platform, either GEOPAK/MicroStation or AutoCAD Civil 3D, in 2008. Florida DOT were then early adopters of OpenRoads SS4 in 2013. Florida DOT has included significant sections on 3D design in its Design Manual, detailing when a model should be developed, deliverables, QA/QC checklists, and more.

In 2015, Florida DOT began working on a data governance initiative known as the Reliable, Organized, and Accurate Data Sharing initiative, or "ROADS." The initiative intends to streamline information across the organization to enable better, faster decisions by removing barriers that prevent effective information sharing (Causseaux, 2019).

The department has also created an extensive course guide for roadway design and 3D modeling. The 2018 guide was developed to introduce roadway designers to OpenRoads SS4. The curriculum introduces how to design with OpenRoads and includes sample exercises on a sample project data set.

Massachusetts DOT

Massachusetts DOT began using AutoCAD Civil 3D design tools for roadway design in 2012. The department has created standards and specifications, design templates, and supporting documentation for all stakeholders to assist in preparation of design files for highway projects. These specifications and templates support data sharing and management between multiple disciplines and contractors working with the department. Massachusetts DOT uses SharePoint to manage and share information during design and construction. The online service, Bid Express, is used to handle bidding processes and submittals (O'Brien, et al., 2016). Massachusetts DOT also introduces

The department utilizes an expansive GNSS network of continually operating reference stations (CORS) to obtain real-time positioning for operations such as surveying and GIS mapping. Massachusetts DOT has used mobile lidar to collect high-resolution point cloud data and colored imagery of the state highways and numbered roads in Massachusetts. Advanced CIM technologies have been deployed on several pilot projects (O'Brien, et al., 2016).

5: BEST PRACTICES AND IMPLEMENTATION RECOMMENDATIONS

This chapter contains implementation strategies and recommendations for each major phase of project development.

IMPLEMENTATION STRATEGIES

The implementation strategy at a state agency will affect the way in which 3D modeling will be mainstreamed. For example, some DOTs have adopted formal, agency-wide implementation plans, while others have implemented 3D technologies on a project-by-project basis based on resources and interest at the regional/local levels (Maier, et al., 2017b). A formal implementation plan is a popular method to mainstream 3D modeling among leading state DOTs.

One of the largest challenges to 3D modeling implementation is the need to explicitly quantify the benefits of implementing 3D technologies. Most of the cost overruns associated with the traditional 2D delivery process are accrued in the construction phase. However, the investments to realize the benefits of 3D modeling must be made in the project scoping and design phase through accurate survey and 3D model development that facilitates better construction. The implementation of 3D modeling should be thought of in a holistic manner and should include costs and benefits spread across all project phases (Maier, et al., 2017b). Implementing technologies and policies to create 3D data during design is a necessary first step to adopting 3D modeling for design through construction. The following flowchart from Maier et al. (2017b) defines a workflow for building capacity with enabling technologies and policies to drive forward implementation of 3D modeling:

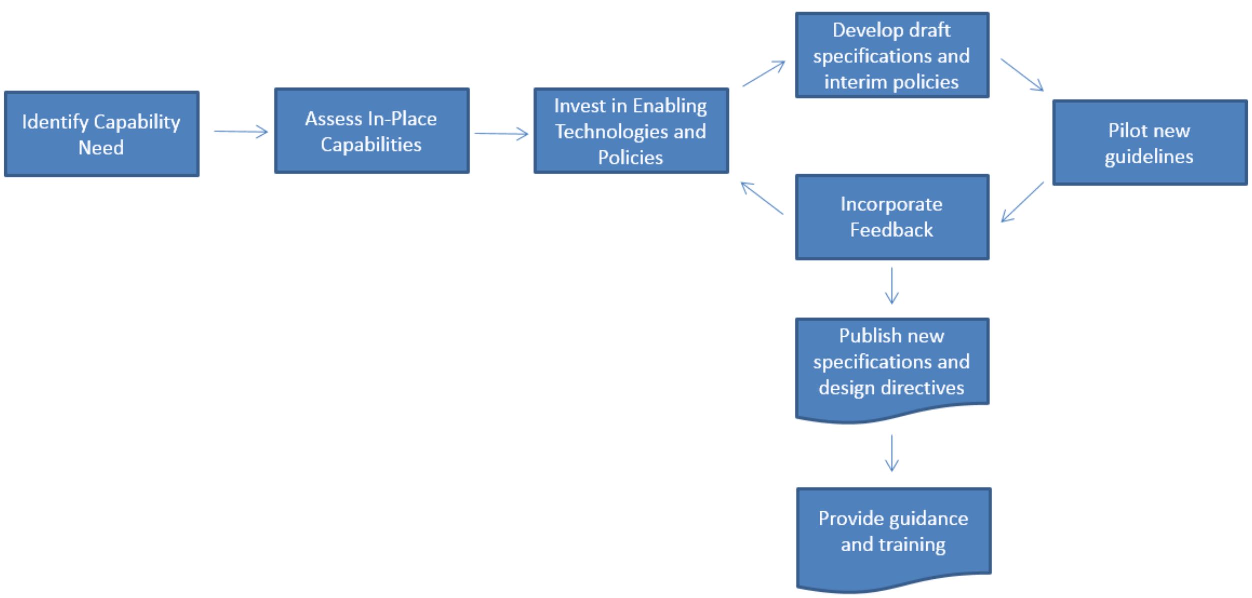

Figure 5.1. Increasing capacity with enabling technologies and policies (Maier, et al., 2017b)**.**

Montana DOT has provided recommendations for organization change management based on efforts from Utah DOT, Iowa DOT, and FHWA. The following framework may be applied to the transition from 2D to 3D (Bentley Systems and Montana DOT, 2016):

- Create a Climate of Change
    - Increase urgency
    - Build guiding teams
        - Establish teams and leads
    - Get the vision right/create a vision statement
- Engage and Enable the Whole Organization
    - Communicate for buy-in
    - Enable action
        - Remove organizational barriers and promote leadership support
    - Create short term wins
        - Begin and complete pilot projects
- Implement and Sustain the Changes
    - "Don't let up"
        - Monitor and measure progress
    - "Make it stick"

Implementation Maturity

O'Brien et al. (2016) identified requirements for intermediate and advanced levels of CIM implementation (Table 5.1). CIM, as defined by FHWA, is the technology-enabled collection, organization, managed accessibility, and use of accurate data and information throughout the life cycle of a transportation asset. The focus of CIM is on promoting successful and effective life-cycle applications of modern technologies – such as information modeling, advanced surveying methods, subsurface utility mapping, and AMG. 3D modeling is a primary component of CIM.

O'Brien et al. (2016) defined intermediate level implementation as the usage of model-based tools for performing certain functions; information deliverables are matured with points of integration across phases. Advanced level of implementation was defined as a matured approach for project delivery where CIM-based functions dominate the project workflow with full information across phases. (O'Brien, et al., 2016) Table 5.1, modified from O'Brien et al. (2016), defines intermediate and advanced levels of maturity based on project phases.

Phase	Intermediate Level	Advanced Level
Construction Planning and Procurement Phase	● Use of 4D/5D Models for visualization purposes only ● Real-time tracking of materials using CIM tools and web-based solutions ● Traffic Control Plans developed in 2D, but visualized in 3D	● Use of 4D/5D models for visualization, constructability analyses, progress monitoring, and cost control ● Real-time tracking of materials ● Traffic Control Plans developed in 2D and visualized in 3D with real-time traffic data
Construction Phase	● Use of AMG extended to finished surfaces ● Use of remote site monitoring ● Use of intelligent compaction ● Use of mobile digital devices for field verification ● Use of rovers/RTS for QA/QC checks and as-built records are frequent	● Extensive use of AMG ● Use of remote site monitoring and active control ● Use of intelligent compaction ● Use of mobile digital devices for field verification ● Use of rovers/RTS for QA/QC checks, drones for inspection; frequent, accurate as-built records
Operations and Maintenance (O&M) Phase	● Electronic data with GIS platforms to support various functions of O&M ● Database systems are integrated, geo-referenced, and synchronize with new information ● O&M activities are functionally separate from other phases	● Model-based data and advanced GIS platforms to support various functions of O&M ● Data and model elements are connected and geo-referenced ● O&M operations are functionally integrated with other phases of a project's lifecycle
Information Management	● Most work processes and deliverables are document and data-centric; some are model-centric ● Only document-based information is digitally signed, but most information is geo-referenced ● Different disciplines develop their own document, data, and model-based information, which is shared in a collaboration platform ● All disciplines follow the same industry data standards ● Most information handover occurs simultaneously	● Most deliverables are data and model-centric; some deliverables are document-centric ● All information is digitally signed and geo-referenced ● Different disciplines work on the same document, data, and model-based information, which is stored and managed in one collaboration platform ● All disciplines follow the same industry data standards ● Information handover occurs simultaneously

Table 5.1. CIM capabilities maturity model (O'Brien, et al., 2016)**.**

Agencies can use these requirements to analyze the maturity of 3D modeling and CIM throughout their divisions. It is difficult to quantify the efforts required to reach each level of maturity. However, in general, moving from initial implementation to intermediate maturity requires the following (O'Brien, et al., 2016):

- Envisioning a specific strategic vision and mission statement for CIM implementation
- Overcoming learning curves for all related CIM functions
- A committed leadership for investment and implementation requirements
- A participatory approach from all major stakeholders with willingness to overcome individual barriers for achieving project goals

Transitioning to the advanced level of maturity necessitates additional requirements:

- Using CIM functions across multiple projects (agency wide)
- Standardization of business workflows
- Sustaining innovative efforts to find solutions to overcome barriers (technical, financial, human, and process-related)
- Rapid and effective dissemination of information to all stakeholders (lessons learned, best practices, and updates to standards or specifications)

An agency's Design Manual, guides, and policy documentation must be updated to successfully adopt 3D modeling practices. According to Brenner et al. (2018), the Design Manual should include any pertinent information for understanding the 3D model derivative produces (such as 3D PDFs, images, videos, and simulations) that are used in decision making. This includes the following, at a minimum (Brenner, et al., 2018):

- Level of Development (LOD) Definitions
- Guidelines or definitions for visual quality
- Identification of derivative products that support decision-making

The Design Manual can also provide information about how 3D models and their derivative products can be used at each decision-making milestone.

Construction workflows will undergo significant changes with the implementation of 3D modeling. Figure 5.2 shows a workflow for managing construction with automation technology:

Figure 5.2. Workflow for using automation technology for inspection (Maier, et al., 2017b)**.**

DESIGN

Designers need to understand how 3D data will be used in order to create a 3D model that will meet construction needs. A model's level of detail may vary depending on the expected uses of the model. The 3D design can be a high-density model that depicts design intent with sufficient accuracy to be used for both AMG and real-time verification. However, other uses of 3D design data may not require such high levels of detail or accuracy (Maier, et al., 2017b).Table 5.2 gives descriptions of several common design methods.

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 to model 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 signposts.

Table 5.2. CADD design methods and their uses. (Maier, et al., 2017b)**.**

As defined by Bentley Civil Help, Corridor Modeling tools aggregate a variety of civil data. The geometry is created with the Horizontal and Vertical Geometry tools, while the existing ground is defined by a MicroStation mesh or Civil Terrain Model. Plan view elements, such as edges of pavement, shoulders, curbs, etc. can be 2D or 3D. Superelevation information is defined within a design file using standards or imported data. Templates are utilized from one or more template libraries.

Model Content

With the traditional 2D workflow, contractors often create their own 3D model based on the 2D cross sections. However, this model does not account for the gaps between the provided cross sections. Topography may change significantly over an alignment, so high and low points may be lost in these gaps. When converting from 2D plans to a 3D model, contractors are left to 'connect the dots' which can lead to errors and costly rework. In contrast, a 3D model provides a continuous surface for all areas of the project.

A large amount of information can be included in a 3D model. It is important that the model contain all features necessary to accurately convey design intent and prevent errors during construction. Iowa DOT lists the following as potential elements of a fully designed 3D model (Reeder & Nelson, 2015a):

- Topographic survey information.
- Subsurface utility engineering (SUE) data.
- Proposed utilities (storm sewer, sanitary sewer, water main, conduits, etc.).
- Grading surface.
- Drainage features (ditches, swales, culverts, etc.).
- Pavement subbase layers.
- Pavement surfaces.
- Sidewalks and recreational trails.
- Bridge structures and appurtenances (including pile, footings, piers, and berm grading).
- Traffic signalization and underground wiring.
- Lighting features.

While 3D models can contain an abundance of information, it is important for DOTs to find a balance between level of detail and amount of effort required to complete the model. Iowa DOT has also found that it is not necessary for designers and consultants to spend a large amount of time merging side roads and additional features into a single model. Contractors will take any information they can get and merge information to match their specific staging operations (Reeder & Nelson, 2015a).

Table 5.3 from Maier et al. (2017b) relates specific 3D model content to the CAD design methods that can generate that content and the CADD data format that is needed for automation in highway construction.

Feature	CADD Design Method	CADD Data Type
Roadways	Corridor model	Alignment, 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	Strong 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
Pavements markings	Corridor, string, or feature modeling	3D string lines
Curbs and gutters	Corridor, string, or feature modeling	3D string lines
Retaining walls	Corridor, string, or feature modeling	3D string lines

Table 5.3. 3D Model content by CADD data type. (Maier, et al., 2017b)**.**

Level of Development

The LOD describes two attributes of the 3D data – Model Density (MD) and Confidence Level (CL). The Model Density is how much detail is incorporated into the model. The Confidence Level is a qualitative statement of the uncertainty associated with the original ground depiction (Maier, et al., 2017b). An LOD designation can help identify and assess the uncertainty, risks, and impacts of using 3D data for construction. For example, New York State DOT uses designation LOD 100 to LOD 500, with LOD 100 being the lowest level, pertaining to limited analysis, and LOD 500 being the highest level, associated with asset management applications and future planning.

The following generic LOD designations may be used by DOTs aiming to implement 3D models for construction. The LOD designations apply to both roadway and bridge projects. (Brenner, et al., 2018):

- *LOD-V (Visualization):* Graphics are sufficiently developed to support a corridor study, and high planning level cost estimates. This type of model may be sufficiently developed for visualization for public outreach. The geometry looks correct, but elements are depicted as single objects showing only exterior features.
- *LOD-A (Analysis)*: The model geometry is accurate for major systems, but there may be simplifications where the detail does not affect the analysis. The model communicates sufficient engineering intent to estimate costs but lacks the details to create plans or details.
- *LOD-P (Plans)*: Graphics and design intent are sufficiently developed to support final design plans, including constructability reviews, macro clash-detection, and most plans production. The model is geometrically accurate to the measurement precision with sufficient detail to create plans and take-off quantities, and geometry is based on robust analysis. Graphics and design intent are sufficiently developed to support final design plans.
- *LOD-F (Fabrication)*: Graphics and design intent are sufficiently developed for contractor use. The graphics are sufficiently developed for fabrication, in the case of bridge elements. This LOD would essentially be guidance to contractors on what to deliver for shop model review and to keep for post-construction applications.

These definitions have been adapted from the Association of General Contractors to apply to roadway and bridge design. Specific LODs for horizontal projects have been less thoroughly explored compared to vertical projects. The following table provides descriptions LOD's for common elements of a horizontal highway project. These LOD designations have been divided into low, medium, and high, but may be adapted to other LOD scales.

Major Project Elements	LOD	Work Area
Non-roadway Surfaces	High	Design
Roadway features and surfaces	High	Design
Drain-storm Sewer	High	Design
Bridges (all features)	High	Bridges
Retaining Walls	Medium	Design
Other Structures	Low	Various
Proposed Special Foundations	Medium	Design
Proposed Special Foundation Walls	Medium	Design
Lighting	High	Utilities
Intelligent Transportation Systems	High	Traffic
Signs	High	Traffic
Traffic Signals	High	Traffic
Proposed Water Main	Medium	Utilities
Proposes Sanitary Sewer	High	Utilities
Existing Utilities	Low	Utilities
Traffic Simulations	Medium	Traffic

Table 5.4. LOD designations for specific model elements (Sankaran & O'Brien, 2015)**.**

Throughout the design process, it is possible to go through phases of LOD from low to high and back again. However, a level of detail can be reached that is too high, which creates the risk of not being able to use older, out of date models. Efficient model development requires addressing the level of detail on a case by case basis, known as the "use case." With a broad range of use cases, there is a need for a broad range of software, each with its own benefits (PennDOT, n.d.).

The level of detail of model information must be clearly defined and documented. Sometimes, a higher level of detail may be used to reduce the file size. If too much detail is included in the model, the file size becomes too large and the file becomes unusable. Furthermore, the level of detail may vary based on feature type, location, and the probability of unexpected field conditions.

3D Model Density

Surface models and 3D string lines are only exact through horizontal and vertical tangents and other areas of constant grade. Once horizontal and vertical curvature is introduced, the model is an approximation (Maier, et al., 2017b). Model density represents how much detail is in the model.

Therefore, the accuracy of 3D model data is directly related to the point density in the surface. High model density typically has less approximation and interpolation, while low model density has more approximation and interpolation.

For corridor modeling, the setting that controls model density 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. Template drops can be placed automatically at key stations that are defined by horizontal, vertical, or offset geometrics (Maier, et al., 2017b). Maier et al. (2017b) summarized the following recommendations for key stations from the design manuals for Iowa, Oregon, and Wisconsin DOTs.

- 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.

Model density is graded based on the authorized use for the data. Low density data should only be used for preliminary design, while higher density data may be used for construction layouts and as-built records. Table 5.5 adapted from Maier *et al.* (2017b) gives model density definitions and authorized uses:

Model Density Grade	**Typical Density**	**Authorized Uses**
MD-1	Regular stations and key geometry points. Transitions in 2D.	Preliminary design Right-of-way engineering Permit applications
MD-2	25-foot tangents 10-foot curves 5-foot transitions	Final design Bid documents Quantity take-off
MD-3	10-foot tangents 2-foot curves 2-foot transitions	Quantity take-off Pre-construction quality control Construction orientation
MD-4	5-foot tangents 1-foot curves 1-foot transitions	Construction layout AMG construction Real-time Verification
MD-5	25-foot tangents 10-foot curves 5-foot transitions	As-built record documentation Measure pay quantities Asset inventory

Table 5.5. Model density definitions and authorized uses. (Maier, et al., 2017a)**.**

Confidence Level

A CL designation uses a graded scale similar to that used for subsurface utility information. Maier *et al.* (2017) defined the grading CL-D, CL-C, CL-B, and CL-A with CL-A being the highest confidence level and CL-D being the lowest. The confidence level in a 3D model should increase as the project progresses as highlighted in Figure 5.3. The following table lists Maier *et al.* (2017) definitions for CL grades:

Confidence Level Grade	**Definition**
CL-A	Control is sufficient for AMG construction Contro and topographic accuracy have been verified as: < 0.15 ft on natural surfaces < 0.05 ft on hard surfaces
CL-B	Control is sufficient for AMG construction Metadata indicates topographic accuracy is: < 0.15 ft on natural surfaces < 0.05 ft on hard surfaces
CL-C	Complete metadata is available for control and topographic survey Low probability that field conditions have changed since survey was collected
CL-D	Basis of original ground survey is unknown or low probability that original ground survey accurately reflects field conditions.

Table 5.6. Definitions of Confidence Level designations (Maier, et al., 2017a)**.**

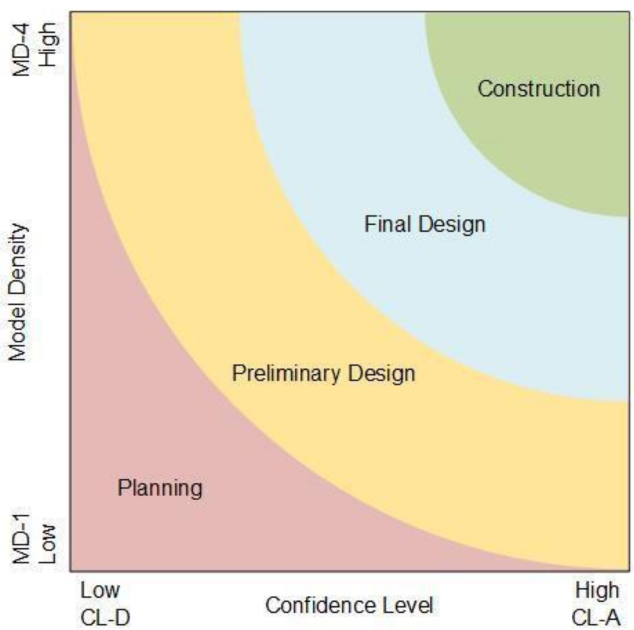

Figure 5.3. Relationship between MD, CL, and use (Maier, et al., 2017a)**.**

The purpose of this CL designation is to make designers more risk-aware and to regulate their effort toward refined designs against confidence in the original field conditions. It is wasted effort to create a high-density model if the confidence level is low (Maier, et al., 2017a).

Design Templates

It may be beneficial to develop roadway typical sections, or templates, that have standard setups and individual components. Many DOTs provide the building blocks for modeling common roadway design elements with corridor and string models as part of their standard CADD resource files (Maier, et al., 2017b). For example, Iowa DOT has developed several CAD templates and individual components that can be accessed by designers. Each template is made up of multiple points that represent individual components of the roadway such as the edge of pavement, subbase, and shoulders. If none of the available templates match a project, designers may modify the existing template that most closely resembles that project.

Florida DOT has also developed an extensive Template Library for its Florida DOT SS4 Workspace. An Florida DOT template comprises a series of points and components that represent break line features that are processed using Corridor Modeling commands. Roadway features that have been processed are saved to the design surface. Templates are stored in the Template Library (Florida DOT, 2018). Florida DOT has created project-specific template libraries and a template should always be used to start a project. Florida DOT's Roadway Design and 3D Modeling course guide provides detailed information on template creation, settings, and components.

Model Format

Due to the lack of an open data format for 3D data, the data exchange process can be an arduous, manual process. FHWA case studies and interactions with project teams indicate that a complete, open data format would save significant time and reduce risk for contractors and resident engineers (Maier, et al., 2017a). It is also important to consider the future use of 3D models. Software and format should be developed to support the ability to access and modify 3D models for years after the original design is completed. LandXML is currently the preferred file format to share DOT data between designers, surveyors, and contractors. Most civil construction software supports the import and export of XML files for estimating, planning, modeling, and tracking. By making this data easily accessible to contractors pre-bid, states will attract more bidders. By reducing risk and uncertainty, states will receive more competitive bids.

While Land XML is currently the most common and widely supported exchange format for 3D roadway data, it is not the optimal format. There are a variety of software products that are used for highway and bridge construction, and proprietary formats are not universally supported. The design teams and construction teams may not use the same software packages, making the exchange of 3D data files difficult. Furthermore, LandXML does not cover all aspects of highway design and is primarily relevant to roadway design.

Open exchange formats such as the Industry Foundation Classes (IFC) present a solution to incompatibility between data files and software. The IFC format is intended to describe architectural, building, and construction data and is platform neutral, meaning it is not controlled by a vendor. The American Association of State Highway and Transportation Officials (AASHTO) executive committee passed a resolution adopting IFC as the national standard for AASHTO states (AASHTO, 2019), although the standard is still being extended to support roads and bridges. Contract model packages should include a combination of 3D data in the exchange format, in the proprietary format, and in a CAD graphics format.

The following are file types typically associated with 3D modeling:

- *ALG* – InRoads alignment file
- *AMG* – Automated Machine Guidance
- *DDM* – Digital Design Model
- *DGN* – MicroStation® drawing file
- *DTM* – InRoads 3D surface file
- *DWG* – AutoCAD drawing file
- *DXF* – AutoCAD Drawing Exchange Format
- *GEN* – GEOPAK multi-line cross section report (station, offset and elevation text file)
- *GPK* – GEOPAK alignment file
- *KCM* – CAiCE alignment file
- *KMZ/KML* – GoogleEarth Keyhole Markup Language file *Raster* – Scanned PDF or TIFF image file containing only pixels *PDF* – Portable Document Format
- *TIFF* –Tagged Image File Format
- *TIN* – GEOPAK 3D surface file (Triangular Irregular Network)
- *TN3* – Topcon Trimesh for GPS machine control
- *TTM* – Trimble Trimesh for GPS machine control
- *Vector* – First generation PDF file containing extractable linework
- *XML* – Extensible Markup Language
- *XSR* – InRoads cross section report (station, offset and elevation text file)

Bentley OpenRoads is the name of the common technology for the new SELECTseries 3 releases of GEOPAK, InRoads, MXROAD, and Power Civil for Country. OpenRoads is a DNG based software. OpenBridge Modeler is a similar 3D modeling software for bridges. It also uses a DNG file format.

In late 2017, Mitchell et al. (2019) conducted a survey questionnaire of contractors and consultants who had worked with Michigan DOT to determine experiences with 3D models as RID. Several of the questions related to 3D models file formats. The majority of the respondents to this survey found that 3D line strings, LandXML files of alignments and profiles, and LandXML files of DTMs were at least beneficial for construction and more than half of the respondents found each of these files essential (Mitchell, et al., 2019). However, opinions on the benefit of MicroStation files was divided with approximately one-third split between unnecessary, beneficial, and essential.

Mitchell et al. (2019) conducted a cost benefit analysis on 3D highway design models in which the department received survey responses from contractors in the state. The survey revealed that contractors working on Michigan DOT projects use a variety of software packages for 3D projects. The software utilized by the contractors includes Agtek, AutoCAD/Civil 3D, Carlson, MicroStation/GEOPAK/PowerGEOPAK, Leica, Topcon Magnet, and Trimble Business Center. Trimble Business Center was the software package most commonly used by the respondents.

For the department's pilot projects, Utah DOT hired a senior project manager to be the liaison between Utah DOT, its design consultants, and the Bentley developers. The PM had extensive background in OpenRoads. Utah DOT notes it is essential to have high-level, experience support when implementing 3D design/modeling. The 3D models must contain the same data as the traditional plan set. Furthermore, not all software is compatible, so it is important to be able to convert/adapt/problem solve software issues.

In regard to converting files when designing in 3D, file conversion should be avoided whenever possible. As experienced by Utah DOT in their pilot projects for roadway design, file conversion created a significant amount of extra work and hampered efficiency.

Model Quality Management

Historically, QA/QC of 2D plans have been limited by the reviewer's ability to visualize the 2D plan drawings in a three-dimensional space. A 3D model offers significant advantage over 2D models during the QA/QC process because it allows the reviewer to view the project from multiple angles without any additional steps. The 3D model can also adjust the horizontal and vertical exaggeration of elements to aid in error detection and can highlight any utility conflicts. New York State DOT has found that when modeling a project in 3D, the inspection process is greatly streamlined and intuitive.

Findings from DOT research efforts emphasize the need for iterative and continued collaboration throughout the design and construction phases of each 3D modeling project to ensure constructability risks are identified and mitigated early in project development (Mitchell, et al., 2019). 3D models provide an opportunity to improve the quality control and inspection processes. Models can be used for QA/QC during all phases of construction.

State DOTs are encouraged to develop their own QA/QC process specifically for 3D models in order to check for errors or inaccuracies before the files provided to the contractors. A checklist is a popular method of QA/QC for 3D models. For example, GDOT requires the reviewing engineer on the design team to perform a high-level QA review of the model once in preliminary design and once in final design. GDOT expects the overall process of QA/QC to be defined in each consultant's specific QA/QC plan.

Some techniques that may be used by the reviewer for QA include (Georgia DOT, 2018):

- Request files from designers such as:
  - 3D MicroStation file (.dgn) of proposed surface showing proposed triangles and proposed surface features
  - Existing DTM file (.dtm)
  - Proposed DTM file (.dtm)
  - InRoads file (.alg, .ird, .itl, .xin)
  - Standard 2D DGN files to compare to model
- Overlay 3D model with 2D design files to check for consistency (rotate view to "top")
- View proposed contours of the 3D surface using a small interval and check for continuity of surface.
- View triangles of the 3D surface and check for good triangulation
- Color triangles by slope
- Display valleys and ridges

Reeder & Nelson (2015a) recommend that the following be included in the checklist, at minimum:

- Visualize either contours or the triangles in a 3D file.
- Verify that the contour interval matches the tolerance of the purpose.
- Cut a profile of the XML surface down the centerline and visualize this profile on top of the design profile from the plan.
- Cut the surface that has been imported from the XML on top of the design cross sections and verify that section lines lie on top of each other.
- Look at visualized contours or flow arrows from the XML surface and check structure flow lines.
- Verify that the horizontal alignment matches the survey control.
- If possible, load the model into the same software that will be used by the contractor to ensure the model appears as intended.

Oregon DOT recommends that an independent review of digital design data be performed by a qualified roadway designer at the Advanced Plans phase, which occurs between Preliminary and Final plan phases. On large or complex projects, it may be beneficial to review design data at earlier milestones as well (Oregon DOT, 2015).

During preconstruction, a plan should be developed how to use the 3D models for inspection and what equipment will be necessary. This stage should primarily be used to set the groundwork for the construction and post-construction phases. Focus should be placed on developing on a Model of Record which all parties treat as the governing model. During construction, the model may be used for independent and transparent verification of constructed features, documentation of field observations, measurements of pay quantities, and more. (FHWA, 2017d)

At Michigan DOT, contractors are required to submit their 3D highway model before construction to be certified against the RID model by a subconsultant who then develops an independent model.

This independent model is used to check both the RID model and the contractor's model. Feedback is communicated to the contractor and the contractor updates their model accordingly. A final check is conducted before the model is accepted for construction. Michigan DOT realizes there may be an opportunity to improve this process by providing contractual design data models and removing the creation of multiple models (Mitchell, et al., 2019).

Florida DOT recognizes QA and QC as two processes that ensure the public receives a quality product. The department divides the responsibility of QA and QC. Quality Assurance is the responsibility of and is performed by the Central Office. Quality Control is the responsibility of and is performed by the Districts and their consultants. For QC, the model is reviewed by a number of parties, including consultant designers, engineers, outside agencies, contract estimators, and contractors (Danforth, 2016). Florida DOT has developed a 3D Engineered Model QC Checklist. Checklist items include:

- Horizontal/vertical curves, tapers, and k-values
- Pavement lanes, shoulders, sidewalks, and curbs
- Slope check including superelevation and slope breaks
- Clearances, conflicts, utilities, drainage, signs, etc.
- Depths

When asked "How would you document model requirement revisions?", a 2017 survey of Michigan DOT contractors showed that seven out of eight respondents would document changes to the models as they take place (Mitchell, et al., 2019). The authors recommended creating a process for tracking and monitoring all changes made to the model post-award including, at a minimum, file submittal procedures, documentation and reason for changes, the party responsible for making the changes, and the conflict resolution/escalation strategy.

New York State DOT has created special provisions for field revisions to electronic files. The revision workflow outlined below is provided to help facilitate the field revision process during construction (Crudele, 2019):

1. The context of the revision will determine the timeframe for providing revised electronic files. If the revision is determined to be non-critical, New York State DOT will collect and consolidate revision requests to reduce the number of versions of electronic files.
2. Revisions will be posted on ProjectWise under the project specific folder structure.
3. An email summarizing the revision will be provide to the Engineer in Charge by the Engineer of Record. The Engineer in Charge will be responsible for alerting the contractor to the revision. The contractor is responsible for providing the revision information to their sub- contractors.
4. The naming convention for electronic files will be the same as for plans as outlined in the Construction Administration Manual Section 91.
5. With each electronic file revision submittal, plan sheet drawing number "ELE-01" will be updated with the revised name, data, and time and included as part of the submittal.

6. The description of the alteration to electronic files will be listed in tabular form on drawing number “ELE-01.”
7. A saved view of the alteration will be created for all revisions to the “i.dgn” contract files.

Implementation Recommendations for Design

Leading state DOTs are creating detailed 3D models during design and providing those models directly to contractors for construction. It is important that the model contain all features necessary to accurately convey design intent and prevent errors during construction. Generally, contractors will benefit from receiving as much 3D data as possible. Most contractors agree that LandXML files of alignments, profiles, and DTMs are beneficial.

However, the model’s level of detail may vary depending on the expected uses of the model. DOTs should find a balance between level of detail and amount of effort required to complete the model, especially if a DOT is in the early stages of 3D adoption. It is recommended that DOTs just starting with 3D models primarily use models for moderately complex projects. These projects will benefit more from a 3D model than simpler projects but will not exceed the experience level that designers have with 3D models.

A 3D model standard must be developed to define what to model and how much detail to include in the model. The following workflow details the creation of a 3D model standard, applicable to both roadway and bridge design (Maier, et al., 2017b):

1. Determine automation uses to be supported as standard practice
2. Determine 3D model content needs
3. Determine highest order density (accuracy) needs
4. Determine data segmentation needs
5. Define standard 3D model requirements

Having complete design and CADD standards is essential for being successful in implementing 3D models for design and construction. In 3D workflows, the 3D CADD standards contain design elements, which are defined by design standards, in addition to drafting standards. Each agency should establish standard designations for 3D models, namely LOD, MD, and CL. A model framework may be used to clearly define the 3D model requirements and data limitations for each intended use. Brenner et al. (2018) created the following framework (Brenner, et al., 2018):

- Model requirements
- Model element organization
- Level of development
- Visual quality
- Managing distance distortions
- OpenBridge Modeler formats and metadata
- Derivative products

An agency must consider which 3D technology is worth supporting and the impact of creating 3D data relative to the value generated by that data. 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 (Maier, et al., 2017b).

Communication and collaboration will be significantly impacted as a result of transitioning to 3D modeling. Traditional 2D design work processes normally consist of "design silos" working on the same project. In these design silos, design data is typically shared via "hand off" between organizations. This process can sometimes create "walls" between organizations and detract from the overall project collaboration (Bentley Systems and Montana DOT, 2016). To successfully adopt 3D models, major design changes must be communicated amongst all the affected design groups to ensure consistency and reduce unexpected results. Project file management will be impacted because the 3D shared data is "live."

Design Templates

It is highly recommended to cultivate a design library to aid in the creation of a 3D model. Michigan DOT recognizes the efficiencies that can be gained from building a library of parametric detailing models for standard elements and systems. These models include pre-defined plan sheets and schedules that automatically update with changes to the geometric parameters (Brenner, et al., 2018). The Michigan DOT workspace provides the automation tools and resources that designers and technicians use to develop 3D models and plans. It is recommended to build upon the preliminary workspace and create sample models. Michigan DOT's preliminary workspace contained (Brenner, et al., 2018):

- Sample models
- Libraries of standard parametric components and templates based on DOT standards
- Library of materials used in construction
- Libraries of Feature Definitions and Element Templates to incorporate standard level symbology, and standard view with level presets
- Seed files for OpenRoads and OpenBridge software

Quality Management

Findings from DOT research efforts emphasize the need for iterative and continued collaboration throughout the design and construction phases of each 3D modeling project to ensure constructability risks are identified and mitigated early in project development (Mitchell, et al., 2019). 3D models provide an opportunity to improve the quality control and inspection processes. Models can be used for QA and QC during all phases of construction.

Each transportation agency should develop a QA/QC process specifically for 3D models in order to check for errors or inaccuracies before the files are provided to the contractors. Among leading DOTS, a checklist is a popular method of QA/QC for 3D models. Iowa DOT recommends that the following be included in a QA/QC checklist, at a minimum:

- Visualize either contours or the triangles in a 3D file.
- Verify that the contour interval matches the tolerance of the purpose.
- Cut a profile of the XML surface down the centerline and visualize this profile on top of the design profile from the plan.
- Cut the surface that has been imported from the XML on top of the design cross sections and verify that section lines lie on top of each other.
- Look at visualized contours or flow arrows from the XML surface and check structure flow lines.
- Verify that the horizontal alignment matches the survey control.
- If possible, load the model into the same software that will be used by the contractor to ensure the model appears as intended.

During preconstruction, a plan should be developed how to use the 3D models for inspection and what equipment will be necessary. Independent reviews of digital data should be performed by a qualified roadway designer. Deliverable requirements and formats should be developed that help contractors to better utilize available project data and minimize rework. These requirements may include, but are not limited to, geometric information, existing and proposed surface information, and design requirements.

At Michigan DOT, contractors are required to submit their 3D highway model before construction to be certified against the RID model by a subconsultant who then develops an independent model. This independent model is used to check both the RID model and the contractor's model. Feedback is communicated to the contractor and the contractor updates their model accordingly. A final check is conducted before the model is accepted for construction. Michigan DOT realizes there may be an opportunity to improve this process by providing contractual design data models and removing the creation of multiple models (Mitchell, et al., 2019).

Michigan DOT also uses an RID Review Checklist to document the quality assurance performed on the design files for each stage of the project development phases (Mitchell, et al., 2019). This document should be used as the basis for developing a standard Model Progression Specification (MPS) or Model Inventory to keep track of model elements and their certified LOD. The Model Inventory acts as the "read me" file for to communicate information about the model. The MPS documents the LOD by milestone. (Brenner, et al., 2018)

SURVEY

A critical element to the development of 3D models is the collection of detailed survey data. This data is used to generate maps, DTMs, cost estimates, and more. Survey technologies collect data actively (e.g., Lidar) or passively (e.g., total stations or GNSS receivers) and can be georeferenced (e.g., grid coordinates) or localized (e.g., ground coordinates). Typically, a combination of surveying methods is used to collect survey data, which is then developed into a base map in a process known as data fusion (FHWA, 2017c). The base map data serves as the foundation from which the design is built, so the more accurate this data, the more robust and effective the design will be. The base map should include (FHWA, 2017c):

- 2D land boundary data
- 3D planimetric data
- 3D alignment data
- 3D surface data with contours and breaklines
- Aerial imagery

The original survey data collection effort should be well planned to ensure sufficient reliability and accuracy (Turkan & Shane, 2016). Model-centric workflows and design intent are dependent on the underlying data to enable sound decision making and, therefore, require confidence in the accuracy of the existing conditions base survey models (Mitchell, et al., 2019).

Inaccurate survey data can cause major issues during construction. Collecting an accurate initial topographic survey reduces the chances of design changes or significant quantity differences during construction. The original ground survey should be verified in locations where design changes would have the largest impact. Ideally, original ground verification should occur immediately prior to construction. However, this timing may not be practical. Accurate survey may not be possible until construction has started. For example, dense woods may need to be cleared and grubbed before Lidar survey is conducted. In another example provided by an FHWA case study, asphalt pavement had to be milled off to expose the concrete base. These are two examples in which design changes from the original survey may be significant.

The accuracy and density of survey data necessary to support 3D modeling and AMG is often much higher than what has been typically collected. Lidar enables efficient survey data collection with an adequate level of accuracy for 3D modeling. Lidar develops "point clouds", a mass of data points that represent a three-dimensional space, that can be imported into 3D modeling software to help build a virtual representation of the finished construction project. An initial survey first establishes locations of physical features and key points as a baseline, after which Lidar is used to scan the area and produce a point cloud (Brenner, et al., 2018). Lidar data is often collected by air via a survey aircraft. Iowa DOT has noted that Lidar data is typically used to make project planning decisions in its department. Aerial Lidar can be used to compare alternative routes, seek preliminary ROW, and calculate rough earthwork quantities.

Lidar provides better efficiency than traditional surveying methods and can also be used to collect as-built surveys. Including as-built data in the agency's database may improve asset management practices and rehabilitation of transportation assets (Turkan & Shane, 2016). Lidar and ground survey are sufficient for projects without steep terrain or dense vegetation. For projects with steep terrain and dense vegetation, the accuracy of the survey is negatively affected, but may be supplemented by methods such as photogrammetry and ground survey.

3D Laser Scanning, also known as High Definition Surveying (HDS) or ground-based Lidar, is a process by which large volumes of highly accurate data is captured at a rapid pace via a small laser beam that scans objects and structures. HDS can offer a safer, more accurate, and less expensive survey than aerial Lidar, low-altitude mapping photography, or traditional survey methods. The laser system measures millions of points with XYZ coordinate values which form a point cloud that can be converted to a number of formats such as AutoCAD and MicroStation. The data can then be viewed, navigated, and analyzed much like a traditional 3D model. HDS is particularly beneficial for surveying dangerous work zones such as busy roadways, bridges, tunnels, power plants, and quarries. HDS also excels when surveying complex structures such as brides, buildings, mechanical rooms, and towers. Because it works under the tree canopy, HDS eliminates the blind spots typically associated with aerial survey in dense vegetation areas. The point clouds collected from HDS can be used to verify as-built conditions and finalize the 3D model.

Additional Methods of Survey

While lidar is a popular and useful method of survey collection when designing in 3D, it often cannot be relied on as the sole data source for mapping data acquisition. To supplement lidar, there are many other advanced surveying tools that can improve on coverage, speed, cost, and/or data accuracy in comparison to traditional methods. These methods of survey may be used for site mapping, utility mapping, ROW map development, environmental analysis, or inventory mapping. The following list provides examples of such sensing tools (O'Brien, et al., 2016):

- Aerial Photogrammetry
- Global Positioning Systems (GPS)
- Robotic Total Stations (RTS)
- Ground Penetrating Radar
- Radio Frequency Identification
- Real Time Network (RTN)
- Integrated Measurement Systems
- Drones/Unmanned Aerial Vehicles

These methods are often used in combinations to provide a complete and accurate survey.

Selection of Survey Type

At the start of a project, the design and survey teams should discuss what type of survey technology would be best suited for the project. During the discussion, the teams should consider the following factors:

- Design intent
- Level of accuracy and detail needed
- Safety concerns
- Satellite reception
- Traffic conditions
- Weather patterns and vegetation coverage

- Necessity of a control survey
- Budget
- Schedule
- Staff availability

Accuracy of the survey method is a large factor when selecting the type of equipment that should be used. Various methods exist for collecting lidar data including aerial, mobile, and static lidar collection systems. 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. 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. Static lidar has long setup times, capturing vast datasets of relatively high network accuracy (Maier, et al., 2017b). Table 5.7 adapted from Iowa DOT lists approximate accuracies and costs of popular survey equipment:

Equipment	Horizontal Accuracy	Vertical Accuracy	Cost/Mile
Total Station	0.02 ft	0.02 ft	$4,000
RTK GPS Unit	0.03 ft	0.06 ft	$2,000
Mobile Lidar (1A Accuracy)	0.03 ft	0.03 ft	$5,000
Mobile Lidar (1B Accuracy)	0.30 ft	0.30 ft	$1,500
Static Scanning	0.02 ft at 300 ft	0.02 ft at 300 ft	N/A

Table 5.7. Approximate accuracy and cost of survey equipment. (Reeder & Nelson, 2015b)**.**

Table 5.8, from Maier et al. (2017b) shows the suitability of lidar methods for specific topographic features:

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

Table 5.8. Lidar method suitability by topographic feature (Maier, et al., 2017b)

Different methods of lidar collection are more suitable for certain project characteristics. Project characteristics that can decide ideal lidar type include the area to be mapped, type of project, terrain, and time sensitivity. Other factors include traffic conditions, necessity to capture roadside features, and opportunities to consolidate data acquisition (Maier, et al., 2017b). Table 5.9 from Maier et al. (2017b) lists lidar suitability for various 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 Volume	Suitable	Suitable	Consider
High Traffic Speed	Suitable	Suitable	Consider
Urban Area	Consider	Suitable	Suitable

Table 5.9. Applicability of lidar methods to project characteristics (Maier, et al., 2017b)**.**

According to Vonderohe (2013), rapid technological advances are being made in lidar and digital mapping data acquisition technologies, while traditional means and methods for data collection are becoming obsolete (Vonderohe, 2013). A 2012 survey of state DOTs by WisDOT's Photogrammetry Unit showed that spatial data acquisition systems vary widely by state. The systems to obtain survey data are constrained by necessary changes to workflows and data outputs, variations in standards and procedures, training needs, costs of technologies, and diminished human resources (Vonderohe, 2013). While lidar has advantages over traditional surveying techniques when designing in 3D, it is still not a common practice. Typically, only the DOTs advanced in 3D modeling use lidar regularly. Other agencies use lidar much less frequently, largely due to inexperience with the technology.

Continuously Operating Reference Stations

Accurate survey control is critical when using 3D survey and design methods. The topographic survey that is obtained on the existing conditions must be correctly linked to the survey control for an accurate 3D engineered model. In states with numerous base stations, accurate survey control is not a major factor. However, some states struggle with obtaining an accurate survey, resulting in a 3D model that may be off by several vertical inches (Reeder & Nelson, 2015a).

Recently, many states have begun to set up networks of CORS, which are permanent base stations to facilitate RTK surveying. For example, Iowa DOT, Utah DOT, and Oregon ODT developed the Iowa RTN, The Utah Reference Network, and Oregon Real-Time GNSS Network, respectively. Iowa RTN is a base station network that allows the user to connect remotely via the use of a cell phone modem to the nearest base station to receive range corrections. The Iowa RTN is a free service. The Utah Reference Network greatly expanded Utah DOT's survey network for 3D modeling. There are 95 stations in The Utah Reference Network, including those in Utah and those in surrounding states. The annual access fee for The Utah Reference Network is significantly cheaper than purchasing a base station.

Implementation Recommendations for Survey

Survey data must have the necessary accuracy to meet the requirements of 3D design and construction. This data is used to generate maps, DTMs, cost estimates, and more. Survey technologies collect data actively (e.g., lidar) or passively (e.g., RTSs or GNSS receivers) and can be georeferenced (e.g., grid coordinates) or localized (e.g., ground coordinates). Typically, a combination of surveying methods is used to collect survey data, which is then developed into a base map.

Most leading DOTs have implemented lidar as a survey collection tool. It is recommended that specifications be developed for using lidar on survey and construction projects. Lidar should be implemented into survey workflows or, if already used on certain projects, be expanded to include a wider range of projects. Leading DOTs have found success blending different surveying technologies while increasing the use of advanced survey methods such as lidar.

Standards and workflows should be developed for creating features from point cloud data. Additionally, policies should be created to specify when a point cloud is needed, how designers need to receive point cloud information, and how/when to get a survey contract executed to keep design schedules on time (Lukes & McDowell, 2017).

Agencies must balance the probability of the 3D technology being used with the cost of producing the necessary survey data. Several DOTs have found that, initially, it may be beneficial to use the new survey technology as a check against traditional methods. This practice can allow personnel to become more familiar and comfortable with the survey tools. Additionally, quality control should be consistently employed to regulate the accuracy of a 3D survey.

Policy changes regarding survey specifications will need to be made in order to bring survey accuracy to the level required for 3D modeling. Consistency should be established for 3D surveys and accuracy tolerances may need to be modified to adapt to 3D design and construction. In many cases, the accuracy and density needed from the topographic survey to create a 3D model are much higher than what has typically been collected. The flowchart from Maier et al. (2017b) details a workflow for developing topographic and control survey products that support 3D modeling:

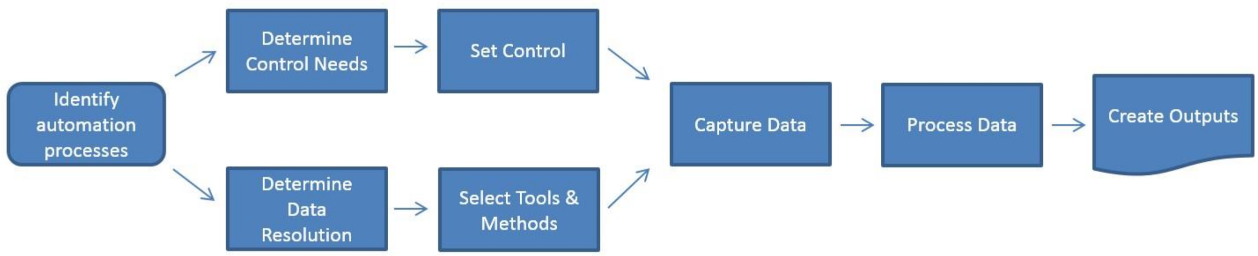

Figure 5.4. Producing survey products to support 3D modeling (Maier, et al., 2017b)**.**

In addition to selecting the correct tool for the needed accuracy, it may be necessary to decrease the maximum distance between points of some survey shots when using traditional field survey methods. This practice will increase the accuracy of field surveys with respect to point density, which in turn leads to more accurate 3D models. Several DOTs have found success delivering all field surveys in 3D MicroStation files, in addition to the 3D TIN and other survey deliverables. OpenRoads Survey has also been implemented by several DOTs, with success.

The output for surveys will change from delivering 2D/3D survey design files to delivering primarily 3D survey design files. The 3D design files will contain survey topographic and cadastral data. Right-of-way and other property and easement graphics may remain in 2D, however. A LandXML file of the DTM may also form part of the deliverables to the construction contractors (Bentley Systems and Montana DOT, 2016).

Utah DOT recommends that guidance be developed for how and when to perform the initial survey control, when to contract for the survey, and how to define the survey. Additionally, a method should be developed that allows contractor survey crews to verify and accept the preconstruction survey. The following workflow from Maier et al. (2017b) can be used for setting site control:

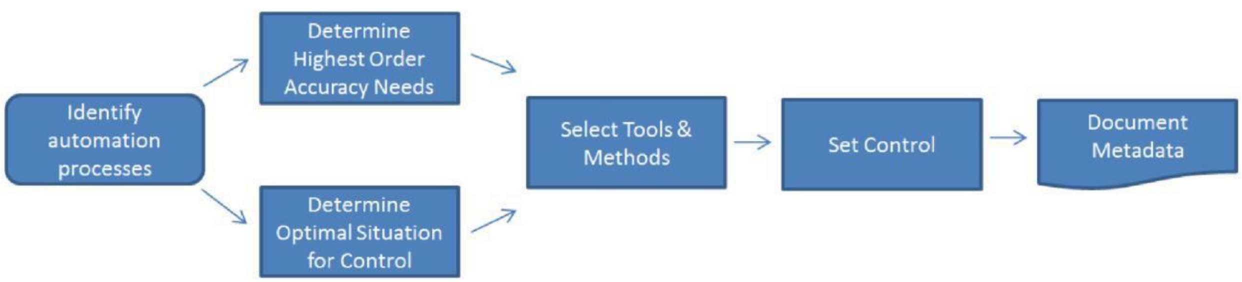

Figure 5.5. Setting site control to support 3D construction. (Maier, et al., 2017b)

BID PACKAGES

The benefits to be gained by using 3D models during construction present a number of reasons to provide 3D models with bid documents, and many DOTs have implemented policies to do so. However, others provide 3D data post-award or not at all. Many designers and contractors do not feel comfortable using 3D data deliverables instead of traditional plans. Ideally, confidence in 3D models for construction will improve as personnel gain more experience, but compromises may have to be made during the early stages of implementation.

Table 5.10 adapted from Maier et al. (2017b) lists a set of generic outputs that can be used for bidding or construction deliverables. The information has been assimilated from policies implemented by Kentucky Transportation Cabinet, Florida DOT, Iowa DOT, Michigan DOT, Missouri DOT, Oregon DOT, and Wisconsin DOT.

Data Type	Data Formats
Coordinate geometry	• CAD • American Standard Code for Information Interchange text
Alignment	• LandXML • American Standard Code for Information Interchange text reports • CAD super-elevation tables • XML super-elevation report
Original surface	• LandXML • CADD surface format • CAD triangle faces and boundary • CADD points and break lines
Final surface	• LandXML • CADD surface format • CAD triangle faces and boundary • CADD points and break lines
Interim surface	• LandXML • CADD surface format • CAD triangle faces and boundary • CADD points and break lines
3D line strings	• LandXML (surface features) • CAD graphics (3D line strings)
Cross section	• LandXML • CAD graphics (2D lines and text)
Corridor model	• Proprietary CADD format • CAD graphics (3D solids/components)

Table 5.10. Type, format, and metadata for bid reference files (Maier, et al., 2017b)**.**

A model inventory documents the final model state at a predefined exchange point such as delivery with the contract plans for construction. The model inventory is like a "read me" file for the model, and should include (Brenner, et al., 2018):

- Model requirements
- Model Element Organization
- Level of Development
- Visual Quality
- How to managing geospatial distance distortions

- OpenRoads or OpenBridge Modeler format files and metadata
- Derivative products, such as images, details, schedules, and 2D plans.

Deliverables Provided by Leading DOTs

The following section describes bid package deliverables provided by lead state DOTs.

Michigan DOT

A key success factor when delivering contractual 3D models is the ability to communicate the purpose and need of each deliverable (Mitchell, et al., 2019). Many DOTs recommend providing 3D models during bid preparation; contractors are typically interested in any 3D data that can be provided. However, few DOTs that use 3D modeling consider the 3D models as the governing documents. For example, many DOTs provide 3D models to contractors but considers the 2D paper plans the "signed and sealed" data. While not a full 3D workflow, this practice still sees the benefits of 3D models and saves the contractor a significant amount of time. Still, a number of DOTs are working towards making the 3D model the sealed deliverable for part or all of the contractual information. Utah, Iowa, New York State DOTs have piloted this practice for road and bridge projects.

Iowa DOT

Iowa DOT provides the 3D model to contractors during the bid preparation process. Because of the lengthy bidding process, there may be months between finalizing the design and beginning the bidding process. This delay may make it difficult for the design team to gather all relevant files to provide to the contractor. Therefore, Iowa DOT recommends providing design files immediately after final design.

The department also only provides generic file formats to contractors:

- Alignment – LandXML
- Surfaces – LandXML
- 3D String Lines – DFX

Iowa DOT found that providing file formats were compatible with individual pieces of construction equipment was very time consuming. Therefore, the department now provides the above file types and the contractors convert these files into the necessary formats before uploading them to their system. The department also recommends that all deliverables provided to contractors should be well documented for each project. Agencies should develop a standardized checklist that can be used on all projects to ensure consistency for project deliverables.

Ohio DOT

Ohio DOT provides 3D model files to the contractor as a courtesy only. The 3D model files are not governing documents and contractors are completely responsible for any digital data converted or derived from model data provided by Ohio DOT (Ohio DOT, 2018). Design deliverables that are incomplete or incorrect may cause issues during plans preparation, bidding, and/or construction. Therefore, Ohio DOT is committed to productive, lean, efficient, and effective organization of 3D data deliverables. Electronic files required to be submitted for Ohio DOT projects consist of (Ohio DOT, 2018):

- CADD Files
  - Basemap files, for example:
    - Existing survey
    - Proposed roadway
    - Right-of-way
  - Sheet files, for example:
    - Roadway title sheet
    - Roadway general notes
    - Roadway plan and profile
- Alignment Files
  - LandXML files
  - Alignment report files
  - Native format (i.e. GEOPAK ".gpk")
- Surface Files
  - Existing DTM
  - Proposed DTM
- Engineering Data
- Survey Files
- Plan Set
- 3D Models

Florida DOT

Florida DOT has developed a standard list of deliverables to be supplied to the contractor. The 3D deliverables supporting AMG for 3D projects and their corresponding file types are as follows (Florida DOT, 2018):

- Design alignments and profiles (XML)
- 2D proposed planimetric design (DWG/DGN)
- 2D existing survey (DWG/DGN)
- 3D existing survey surfaces (XML)
- 3D proposed surfaces (XML)
- 3D proposed breaklines (DWG/DGN)

Digital Signatures

Digital signatures are an essential means of authenticating digital contract documents. 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 (Maier, et al., 2017b). While most policy changes are in the control of the state transportation departments, policies for digital signatures and seals are not. These policies are managed by the state engineering board.

At a high level of 3D modeling implementation, technology and policy supports digitally signed PDF documents, which can be 2D or 3D documents. Florida DOT, for example, has developed software to review and digitally sign LandXML files using a public/private key encrypted digital signature. Michigan DOT and Oregon DOT have also implemented digital sealing and digital signatures (Bentley Systems and Montana DOT, 2016). Agencies should develop guidance on how to package models for advertising with digital signatures.

Implementation Recommendations for Bidding and Deliverables

3D data should be provided as part of the bidding process. A full selection of electronic 3D model files should be delivered to bidders. A standard list of deliverables that are provided during bidding should be developed. Delivering LandXML files and MicroStation design files is recommended. The existing ground DTM and survey base map, all geometry, all linear design features, and all design DTMs should be delivered as LandXML and 3D meshes (Bentley Systems and Montana DOT, 2016).

The DOT should meet with the contractor after award to further refine the needed information for their equipment and controllers. Longer term, the design team should provide intelligent models with embedded pay items to enhance the payment business process (Bentley Systems and Montana DOT, 2016).

In the early stages of 3D implementation, many designers and contractors do not feel comfortable using 3D data instead of traditional plans. Several practices have been adopted by leading agencies to increase the confidence in 3D data as deliverables:

- Create special provisions or construction specifications that accommodate the use of 3D models
- Initially, provide 3D information for reference only with 2D plans still being the legal documents
- Longer term, give precedence to 3D models over 2D plan sets
- Contractually require contractors to use the 3D models
- Develop extensive training programs for 3D design and construction

A notable practice by Oregon DOT 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 (Maier, et al., 2017b). These recommendations and practices may help to encourage the use of 3D model data from design through construction.

Utah DOT has found that methods should be developed through which contractors can receive and comment on the 3D model and ultimately agree to accept it as a legal document. The following flowchart (Figure 5.6) from Maier et al (2017b) shows a workflow for providing contract models:

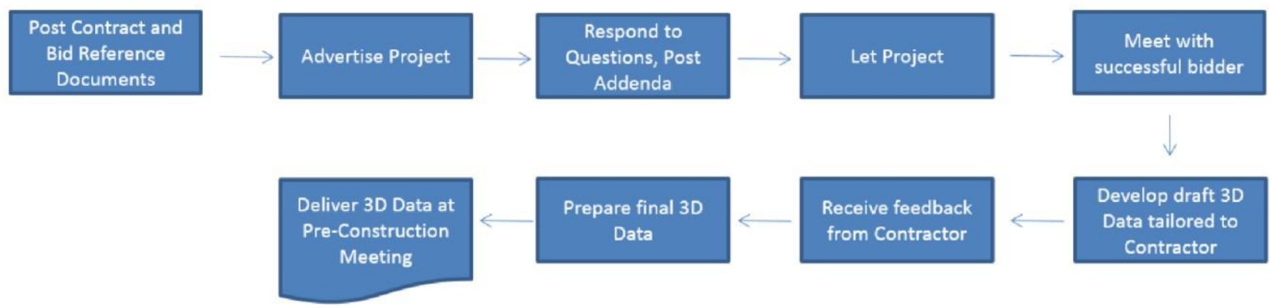

Figure 5.6. Flowchart for providing contract models (Maier, et al., 2017b)**.**

DATA MANAGEMENT

Data management is a critical requirement for successful 3D modeling implementation. To achieve the benefits of 3D modeling, all project parties must have appropriate access to the models. This open-access methodology requires an advanced workflow and information sharing system. Data interoperability between different systems should also be considered (FHWA, 2013a).

If the 3D model will be used during the project delivery to coordinate with multiple design team members and/or disciplines, it is important to coordinate the staged development of a model using a MPS. An MPS is like a model inventory, but it is a blueprint for the development of a model, documenting the agreed LOD by element at each milestone. The purpose of an MPS is to clearly communicate information about the model to stakeholders in order to manage expectations and coordinate information exchanges. Designers need to know the level to which models should be developed, and those receiving the models must understand the quality and reliability of information they will receive, and when (Brenner, et al., 2018). A MPS or model inventory should be included with each bid package to describe the model detail and how much information can and should be taken from the model.

The use of 3D models during construction requires and produces a large amount of data that must be appropriately managed. This data may be used for executing, measuring, and accepting construction as long as it is subject to good data governance. Information management remains relevant throughout a project's life cycle. The management of digital data is a continuous process that has the potential to yield significant benefits if the data deliverables from other project phases support continuous utilization.

Maier et al. (2017b) identified three key areas that need to be properly managed:

- Establish a model of record that reflects the design intent shown in the contract documents
- Update the model of record when there are design or field changes
- Produce robust digital as-built records

An information management system have the following characteristics (O'Brien, et al., 2016):

- Capabilities to produce and deal with information deliverables in document and model-based formats
- Ability to deal with increased usage of digital signatures by different functional areas for approvals, submittals, and review purposes
- Potential to seamlessly integrate geospatial information to enhance the robustness and utility of the asset data throughout its life cycle
- Adoption of common industry standards across the agency for generating and sharing the information (e.g. LandXML, TransXML, IFC, and common coordinate systems for surveying and GIS)
- Information handover at the completion of respective project activities

Data management and sharing is important when working with AMG equipment. Data files will be divided into paving segments to manage storage space on the machine's onboard computer. Contractors should be determining the limits of the data segments according to their operational plans and needs (Reeder & Nelson, 2015b). The contractor needs to be able to easily access the 3D model and upload the model to AMG equipment. Once the contractor has received the 3D files, the files may need to be converted or condensed before being transferred to AMG equipment. 3D model information can be uploaded to equipment via traditional methods such as memory cards or USB devices, or by through wireless methods. Some new AMG equipment has Wi-Fi built in, so 3D files may be sent wirelessly to machines in the field.

Model documentation was the most mentioned area for improvement in a 2019 survey of Michigan contractors. The majority of contractors noted that there is a need for creating a method for documenting changes to the models during construction as they occur. It can be inferred that changes to the model during construction may or may not require a change order depending on needs. For example, minor changes to address contractor means and methods may not require a change order but should be documented in the model (Mitchell, et al., 2019).

Model Management Plan

It may be very beneficial to require a contractor to prepare and maintain a Model Management plan. Some DOTs also require that the contractor designate a CADD/Model Manager for the project. The Model Manager should have a thorough knowledge and understanding of the required 3D modeling and 4D schedule simulation (if applicable). The Model Management plan should include (Maier, et al., 2017b):

- Strategy for model creation, maintenance, and control of the Model of Record
- Software including CADD, 3D modeling (4D/5D modeling if used), and 3D grade control software to be used on AMG equipment
- Management plan for keeping models current with milestone submittals
- Roles and responsibilities of the contractor's modeling team
- QA/QC process for auditing change management of the 3D model

Naming Conventions

Standardizing naming conventions is an important aspect of file management. All 3D data should be named and stored in such a way that it is easily accessible and identifiable by all relevant parties. Data files should include appropriate level symbology and intuitive naming to clearly indicate what each element of the model represents. Designers should use consistent symbology and naming conventions to avoid confusion during construction (Reeder & Nelson, 2015a).

Implementation Recommendations for Managing 3D Data

An intuitive, high-capacity, statewide system is recommended for data management and sharing of 3D models. Receiving changes to the model without proper documentation is considered high risk by most contractors. Thus, it is highly recommended to create a process for tracking and monitoring all changes made to the model post-award including, at minimum, file submittal procedures, documentation and reason for the changes, the party responsible for making the changes, and the conflict resolution/escalation strategy (Mitchell, et al., 2019). Such a process will reduce the risk associated with data exchange. Leading DOTs have developed information management systems to efficiently manage 3D data and files related to design and construction.

According to Bentley Systems and Montana DOT (2016), document management system capabilities should include:

- Check-in and check-out
- Document history
- Title block fill-in
- Customizable attributes
- Searchable
- CADD compatible
- Manages CADD file dependencies
- Versioning
- Point cloud streaming
- Create, track, and manage transmittals
- Project status monitoring
- CADD Workspaces can be assigned to different files/folders
- Automated PDF creation
- File indexing

- Internet and mobile device compatible
- Search for documents based on spatial location
- Extensive collaboration functions
- Easy to use and customizable interface
- URL links to files
- Extensive file, folder, and project security
- Integrate design applications and dependencies

Field changes to the design during construction should be done electronically. Redlining and markup software should have the following capabilities, at a minimum (Bentley Systems and Montana DOT, 2016):

- Ability to redline or markup files that contain the plan sheets
- Simple to use
- Produces files that can be overlaid to the plan sheets for ease of updating
- Ability to add comments and assign priorities, due dates, update status, and assignments

During implementation of 3D modeling practices, each DOT should develop guidelines to manage 3D data at each phase of the project development process. DOTs should also aim to develop guidelines for managing 3D data post-award. ProjectWise, a common data environment used by many DOTs, can be used by contractors and construction staff to submit, access, and manage files. Mitchell et al. (2019) recommend that a model inventory be kept up to date with post-award changes, including the reason for the changes, when the changes occurred, who updated and certified the model, and for what the model was used. This process is important for resolving any discrepancies between layout, placement, and inspection.

Once a DOT makes 3D models contractual, there needs to be a protocol for documenting changes and managing versions of the files, as well as the responsible party to make the adjustments to the model and schedule modifications. Unless the designer continues to support model changes during construction, it is important to define which changes require a professional engineer to certify the model versus which changes may be certified by a non-licensed professional (Mitchell, et al., 2019).

State transportation agencies should consider developing enterprise-level repositories that can meet all the 3D data requirements of a facility's life-cycle—from surveying through O&M. Existing asset management databases can be extended to achieve this objective. This process also requires strong management support and collaboration between all the divisions and information technology support groups in the agency (O'Brien, et al., 2016).

Quality Management

As an example of a model quality management system, Michigan DOT currently uses a RID Review Checklist that lists the project manager, model reviewers, and other project information. The RID Review Checklist is also used to document the quality assurance performed on the design files for each stage of the project development phases (Mitchell, et al., 2019). This document should be used as the basis for developing a standard MPS or model inventory to keep track of model elements and their certified LOD. The model inventory acts as the “read me” file for to communicate information about the model. The MPS documents the LOD by milestone.

Computing Capabilities

As noted by Bentley Systems and Montana DOT (2016), moving to a 3D information modeling solution may require additional network bandwidth. This is due to increases in file sizes and a change in how Districts and organizations will collaborate on projects. Point cloud computing requires a significant investment in both the remote sensing equipment and the computers used to process the data. It is recommended to establish a working group to evaluate information technology needs. Estimates of network load should be established for 3D workflows and based on the number and size of 3D models at headquarters and regional offices. Storage needs should also be evaluated based on typical workflows and projects (point clouds generated by lidar, in particular, are very large in size). Note that designers rarely access the point clouds; surveyors reduce the point clouds to DTMs and survey base maps for the designers’ use.

RESPONSIBILITIES AND OWNERSHIP

Although they recognize the benefits of a 3D workflow, many designers are hesitant to provide 3D models as governing contract documents (i.e. replacing 2D plans) due to perceived liability. Addressing these legal aspects may take a long time (Turkan & Shane, 2016); however, some DOTs have had noted success with the practice, including Utah, Iowa, and New York State DOTs.

In an effort to move to a paperless system, some DOTs, such as Iowa, Michigan, and Oregon use electronic signatures to sign off on certain project documents, including cross sections from 3D models. However, some of these DOTs still require an ink signature and seal on the title page of the project plan sets (Turkan & Shane, 2016). The requirements for digital sealing vary and are controlled by each State engineering board. On its digital delivery projects, Utah DOT delivers the model to the contractor in lieu of a 2D plan set and require that the contractor use the model.

Often, engineers do not feel comfortable sealing CADD files due to the ease with which the files can be modified. While CADD files can be digitally signed, sometimes the signature is invalidated if the contractor downloads it onto their system, meaning that the contractor cannot validate that the file is unmodified (Maier, et al., 2017b). To mitigate this concern while still taking advantage of the benefits of 3D modeling, some state DOTs have recommended providing the contractors with 2D plans that are produced from the 3D models, providing a means to validate that the information is unchanged.

Brenner et al. (2018) recommend defining roles and responsibilities during the scope verification phase of the project. The department recognizes three key stakeholders in the 3D model project delivery process: the parties who create, use, and manage the model. The model creators are responsible for developing elements of the 3D model. The user is any party who consumes information derived from the model. Lastly, the manager is the single point of contact for all inter-disciplinary and model-related issues. The model manager is responsible for managing the collaboration and quality control process, as well as overseeing other duties to ensure successful use of 3D models during project delivery (Mitchell, et al., 2019).

Brenner et al. (2018) recommend assigning responsibilities for modeling and data entry to individuals who are part of the discipline advancing the design of the relevant elements. Each of these elements is has a designated LOD which defines the amount of detail and engineering intent represented by the model element. Authorized use of the 3D model information can then be assigned by model element (Brenner, et al., 2018).

Table 5.11 provides an example of how responsibilities can be assigned for the 3D modeling based on several work tasks on a New York State DOT 3D modeling project. The table also lists reviewers for each task.

Work Task	Responsible	Reviewer
Contractor submits 3D CADD Model Management Plan	Prime Contractor	New York State DOT
Update 3D CADD model throughout construction	Prime Contractor	New York State DOT, Scheduler, Construction Inspection Contractor
Risk assessment	Prime Contractor, Construction Inspection Contractor, New York State DOT Construction	New York State DOT
3D CADD as-built model deliverable	Prime Contractor	New York State DOT
3D GIS as-built data set	Prime Contractor	New York State DOT

Table 5.11. NYSDOT roles and responsibilities for critical work items (Bell, 2018)**.**

Model of Record

The Model of Record is the governing 3D model for construction and post-construction to which all updates and changes will be made. However, the Model of Record is not a single file; it includes a variety of data, usually 3D, that define the design intent (Maier, et al., 2017b). A model of record can be used to layout construction, perform construction with AMG, and inspect completed work. To realize these uses, the owner and contractor must agree on a single set of data. The Model of Record should be agreed upon at the preconstruction meeting.

The following workflow can be used to establish a Model of Record (Maier, et al., 2017b):

1. Hold preconstruction meeting
2. Receive 3D original ground and design data and share it with the contractor

3. Agree on responsibilities and processes for updating and reviewing 3D data
4. Review 3D data from the contractor and agree on a Model of record
5. Publish the Model of Record and notify all stakeholders

The DOT could alternatively provide a Model of Record from the design process, but a Model of Record at this stage would not capture the contractor's staging, discrepancies between survey data and actual field conditions would need to be addressed, and the data would need to be exchanged to be compatible with the inspector's field survey equipment (FHWA, 2017d). When the contractor and engineer use a common Model of Record and a common mapping projection, any issues identified will be true construction issues and not issues caused by discrepancies between different models or site localization. An agreed Model of Record, developed using the process identified above, increases transparency and confidence for both the engineer and contractor.

Transparent communication and collaboration between the engineer and the contractor are two success factors in using digital data for construction. A preconstruction meeting can establish how a Model of Record will be used to support both AMG and inspection. A construction partnering initiative can facilitate model management. In the absence of construction partnering, a Model of Record should be agreed upon through the Plans and Working Drawings process (FHWA, 2017d).

When 3D models are provided to the contractor, technicians are sometimes able to uncover errors in the original design. Finding errors before construction begins can save a significant amount of time and money; this error checking process is another reason the design and construction teams should agree on a Model of Record before construction commences. The Model of Record may still need to be updated based on design or field changes. Maier et al. (2017b) recommend that the following workflow be used to manage changes and keep the Model of Record current:

1. Receive information of a field or design change
2. Update the 3D data to reflect field or design changes
3. Review revised 3D data
4. Publish the new Model of Record and notify all stakeholders

Governance and Policy Issues

While the adoption of 3D models and technologies for construction can provide many benefits, the risk and liability of errors involved in construction processes do not necessarily shift with digital data. Agencies should give due importance to technical specifications, disclaimer and liability clauses, and risk-sharing mechanisms for 3D data, among others. State DOTs must consider adding language to resolve such issues (O'Brien, et al., 2016).

Lack of clarity and consensus on legal issues for the use of digital signatures and digital deliverables is another critical policy issue. Some specific issues under this category include (O'Brien, et al., 2016):

- Legislation regarding signatures and deliverables preceded the development of model-based drawings and specifications and, therefore, may lack effective provisions for addressing such documents.
- Existing guidelines for encryption tools to protect signatures vary considerably from one state to another.
- Agencies must develop specific guidelines for using digital signatures for various design and construction processes that currently do not have them.

Mitchell et al. (2019) recently examined the use of 3D models as contractual documents, rather than RID. Liability and model ownership were issues that surfaced during the investigation. Respondents to a survey expressed that the following items should be addressed to minimize potential claims (Mitchell, et al., 2019):

- Develop specifications and guidelines for what and how the model will be used.
- Define roles and responsibilities for different actions.
- Establish timeframes for submittals and approvals throughout the process.

Although Iowa DOT has used 3D modeling for roadway projects since 2006, the department still considers the paper plan set as the "signed and sealed" data on many projects. On these projects, electronic 3D files are provided for information only and are not signed by a professional engineer. The contractor is responsible for ensuring the project is constructed in accordance with the signed and sealed plan set (Reeder & Nelson, 2015a). On other projects, Iowa DOT elevates the model above the plans via special provision and identifies the contractual files by name, date, and file size. Iowa DOT still provides 2D plans on these projects, but the plans are for information only.

Governance and policy issues take time, resources, and commitment from various stakeholders to be resolved. Thus, the agencies can try adopting management strategies that promote a cooperative environment when formal guidelines do not yet exist. Partnering is a powerful strategy that can facilitate open communication and improve the quality of the constructed project.

CONSTRUCTION

3D models and their associated technologies have many applications during the construction and post-construction phase. Common uses for 3D models include (Maier et al., 2017b; Mitchell et al., 2019; O'Brien, et al., 2016; Brenner, et al., 2018):

- *AMG:* Uses DTMs and machine-based hardware and software to automate construction operations in the field, including excavation, dirt work, grading, and paving. AMG also enables stakeless operations and increases productivity and site safety.
- *Visualization:* Uses the model to analyze impacts of different construction alternatives and communicate alternative technical concepts. The model can also be used to evaluate constructability, illustrate complex staging, and enhanced graphics for the public.
- *Quantity Take-off:* Contractors are able to compute quantities using a 3D model and survey that has been validated to match field conditions. The methods of earthwork calculation

available through 3D models have significant advantages over the average end-area method still required by some state DOTs, including improved accuracy and efficiency.

- *4D Simulation:* Connects a 3D model to a construction schedule to simulate the sequence of tasks. 4D simulations assist in constructability analysis and planning for complicated construction and identifies temporal conflicts during staged construction.
- *5D Cost Simulation:* Adds cost data to a 4D simulation to visualize the cost impacts of different construction alternatives or to validate interim payments.
- *Inspection and verification* – Inspection staff use a combination of mobile devices (including survey tools) with the model to perform QAchecks during construction. The technology can also be used to record as-built conditions for post-construction.
- *Inter-disciplinary collaboration* – 3D models and associated technology are used to facilitate inter-discipline collaboration and communication during construction.

During construction, contractors use 3D data and models for AMG during earthwork operations and to create stakeout data for other elements, such as structures, guiderail posts, and signs. RTSs or lasers are used to augment vertical accuracy for machine control during fine grading and paving operations. Inspectors can deploy drones for site inspection, progress monitoring, and to estimate of some interim quantities (O'Brien, et al., 2016). 3D models can be uploaded to iPads and laptop computers to allow for easy access to the model and facilitate note taking.

Inspection teams can collect as-built records using mobile survey technology such as rovers and RTSs. The as-built electronic data can be handed over to maintenance and asset management in its native form, which is more durable and interoperable than some processed CAD formats. State DOTs can then archive this digital data from as-built surveys and continue updating it until it becomes available for new project development. 3D data may also be used in asset management applications and the final 3D model could be helpful for some maintenance tasks.

Construction Partnering

Contractor participation and collaboration with the design and inspection teams is a critical component for successfully using 3D models during construction and post-construction. For projects on which a 3D model will be used, the construction department should be involved early in the design process. Many DOTs have found that open communication with contractors during 3D modeling projects proved extremely beneficial to project success. In the past, construction partnering has been a dispute resolution tool to minimize claims. However, the concept has evolved into a scalable collaboration processes between contractors and DOTs. The objectives of construction partnering are to reduce claims and associated costs, provide a framework for improved quality, ensure timely project completion, and reduce or eliminate conflicts, waste, litigation, and budget overruns (FHWA, 2017d).

Successful use of 3D models and field survey equipment requires that all potential sources of measurement error are controlled by using the same control network, survey setup, instrument type, and 3D data. (Maier, et al., 2017a) The design, construction, and inspection teams must collaborate closely to minimize errors that could result from miscommunication.

DOTs and contractors can partner in using the 3D data to perform preconstruction reviews. Risks of quantity differences and constructability challenges can be minimized and mitigated through joint decision-making. Through transparent communication and the use of a single 3D model, the DOT and contractor can avoid the need to exchange data, overcome the disparity in 3D modeling capability, and agree on a set of common 3D data reflecting the design intent for AMG and verification (FHWA, 2017d). The DOT and contractor should work closely to ensure full understanding of modeling expectations including LOD and deliverables. These topics can be discussed in monthly model coordination meetings (Bell, 2018).

More information could be provided to contractors earlier in the project. For example, 3D data should be provided as part of the bidding process, or even before. The DOT could meet with the contractor after award to further refine the needed information for their equipment, as Oregon DOT does. Longer term, the design team should provide intelligent models with embedded pay items to enhance the payment business process (Bentley Systems and Montana DOT, 2016).

Collaboration and partnering applies to all teams involved in the roadway or bridge project, not just between the agency and contractor. A collaborative project delivery process needs to be developed that promotes communication between traditionally isolated pockets of design and construction teams.

Automated Machine Guidance

Perhaps the most popular application of 3D models during highway construction is the use of design files to facilitate AMG (Reeder & Nelson, 2015a; Mitchell et al., 2019). AMG can be applied to highway construction projects to provide efficiencies through enhanced location referencing (FHWA, 2013b). AMG is a process in which construction equipment utilizes onboard computers and positioning systems to provide horizontal and vertical guidance to the equipment operator. (Reeder & Nelson, 2015a) The term “AMG” is used to refer to systems where the operator is merely guided by an onboard computer (e.g. excavation), systems where the onboard computer controls the blades (e.g. grading), as well as systems where the onboard computer also steers the equipment (e.g. concrete paving). Regardless of the level of automation provided by the AMG system, the operators keep close watch on the construction outcomes and make adjustments to ensure a quality product. Many state DOT contractors use sophisticated AMG systems. The following table from Maier et al. (2017b) lists project type and applicable AMG method.

Project Type	Applicable AMG Method
Asphalt mill and pave with ride improvements	2D sonic averaging for milling and paving
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
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
Concrete overlays (incl. ride/drainage corrections)	3D paving
Reclamation	Grading, fine grading, base, and paving
Shoulder and side slope widening or improvements	Grading, fine grading, base, and paving
Lane widening	Grading, fine grading, base, and paving
Reconstruction	Grading, fine grading, base and paving; possibly 3D profile milling and excavation
New construction	Grading, fine grading, base; and paving, excavation

Table 5.12. Project type and applicable AMG method (Maier, et al., 2017b)**.**

In addition to the methods previously listed, AMG is also used for excavation, striping, and slip forming concrete medians and curbs, among other activities. 3D models and sophisticated AMG equipment can automate construction of concrete barriers and retaining walls as well as generate stakeout points for major bridge elements in the field (O'Brien, et al., 2016).

Equipment

Automated machine guidance is often used with grading equipment, excavators, compaction equipment, and milling and paving equipment. Most new equipment can be purchased with AMG hardware installed, and existing equipment can be retrofitted.

Grading equipment such as scrapers, motor graders, and dozers can be fitted with AMG systems that provide the operator with information on the position of the cutting edge with respect to the design surface without the use of grade stakes (Reeder & Nelson, 2015a). Once a 3D models is loaded onto the AMG-equipped grading machinery, the machines reference the position of the blades using a range of positioning hardware (e.g. accelerometers, GNSS rovers, RTS prisms). The onboard computer provides the operator with real-time information. AMG for grading can reduce construction costs, optimize construction schedules, improve quality, and improve the safety of workers. AMG can also greatly reduce the amount of construction staking required.

Excavators equipped with AMG technology utilize the same types of sensors as grading machines to accurately measure slope, reach, and elevation. Operators can see both the design elevation and the elevation of the tip of the excavator bucket. AMG-enabled excavators can grade slopes or hazardous soils without the need for stakes—and even collect as-built records—providing safer working environments for construction crews (Reeder & Nelson, 2015a).

Intelligent compaction places similar technology on rollers (for all stages of pavement construction) to impute compaction from stiffness values in real time. Intelligent compaction differs to AMG in that it is a data collection process only. The data collected by system shows (and stores) the number of roller passes and stiffness values to guide the operator in efficient and effective rolling patterns. The system provides a rich as-built record of the pavement construction.

Milling and paving machinery can use AMG systems to guide the machine vertically and horizontally, creating very smooth, finished surfaces. When the base is constructed using high-accuracy AMG systems, AMG paving also results in very consistent slab or lift depths. AMG systems represent the pavement with much closer data points (e.g. 2 ft) than compared to string line hubs. This provides a smoother edge, as opposed to the series of line segments paved using stringlines. AMG paving also facilitates more precise, consistent paving and improved ride quality. Contractors set string lines with the same data used for AMG operations; using AMG eliminates the time spent setting and removing stringline and diverting traffic around the stringline. One of the most important benefits of AMG paving is the safety improvement avoiding the risk of trips and falls.

Additionally, AMG technology eliminates problems associated with string-controlled technology such as (Reeder & Nelson, 2015a):

- Sag from stringline expansion in hot weather
- Push-up, where improperly tensioned sensors create bumps in the string
- Deviations from loss of sensor contact
- Errors in setting stringline, accidental knocking of stringline, or vandalism
- Bumps created by the sensors catching on knots or splices in the stringline
- Deviations caused from frequent or excessive crew adjustment of the sensor controls

Survey Requirements to Support AMG

While low-accuracy positioning may be sufficient for construction tasks such as recording locations for daily inspector entries and verifying permit compliances, AMG requires high-accuracy, or survey-grade, positioning. Survey-grade positioning is also required for measuring pay quantities and for accepting work for many activities, such as paving and bridge construction (Maier, et al., 2017b). Despite the need for more modern survey techniques, the amount of on-site survey work will decrease as AMG increases, since AMG negates much of the need for construction staking. Bentley Systems and Montana DOT (2016) recommend that a suitable workflow be developed for automating the creation of staking data for direct input into data collectors.

Machine control uses a combination of positioning receivers, a 3D model, and an onboard computer. The positioning receivers include accelerometers, slope sensors, GNSS (including GPS) receivers, RTSs, and laser receivers. The onboard computer processes all the positioning input to determine the position of the blade and adjusts the blade to the target position based on the 3D model. For fine grading and paving operations, the target position will be the proposed surface. For bulk grading operations, or asphalt paving lifts, the target position will often be offset up or down from the proposed surface. When using GNSS, the equipment also needs to receive a correction, which accounts for atmospheric and other interferences to the signal received from the satellites. The correction may come from a base station (which is a GNSS unit set up over a known point within the site), a CORS station, or a RTN.

In the past, with stake-based layout, construction surveyors could adapt in the field to “field fit” and smooth out transitions when the existing ground surface did not reflect the actual site conditions. Differences between the existing ground and the actual field conditions affect the quantities of materials, primarily for grading, but also for more expensive materials in partial reconstruction or slope correction projects. AMG performs real-time layout without the opportunity to adapt quickly in the field. It is important that the design is reviewed against an existing ground DTM that accurately reflects the field conditions before loading the AMG surface. Colorado DOT recommends that the owner conduct this survey and keep control of the survey throughout the project (FHWA, 2013b). Contractors may then generate their bids based on this survey data and the proposed finished grade. Having high confidence in the accuracy of the existing conditions DTM eliminates many uncertainties and reduces errors during construction.

While AMG reduces the risk of operator errors, the operator still controls the equipment and can override the AMG system or apply offsets to the target surface in the cab. Therefore, some contractors and many owners still require placing some stakes at reduced intervals. Stakes are also often used to lay out for utilities, signs, structure layout points, and other features (Reeder & Nelson, 2015a). Location stakes or paint markers also help people orient themselves on the site. Contractors use grade checkers to verify AMG outcomes in the field using the same type of equipment used with the AMG system. Some contractors use a combination of in-house staff and subcontractors to perform these checks.

Control and survey methods should be agreed upon to reduce the chance of errors and inaccuracies. The original mapping control is important for constructing the project in accordance with the design intent. 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 (Maier, et al., 2017b). According to Maier et al. (2017b), 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. 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 re-project to a geospatial coordinate system (Maier, et al., 2017b).

To ensure that field observations are comparable, the contractor and inspector should use the same data collector setup. It may be helpful to have a standard form for agreeing on the construction control and mapping projection or site localization (Maier, et al., 2017b).

Inspection

Inspectors can make use of 3D models and associated technologies to measure and accept completed work. Using 3D models for construction allows inspectors to use GNSS rovers to spot-check elevations and horizontal offsets, or even hand-held GPS tablets to check low-precision horizontal layout such as sign posts and guiderail posts. These technologies can greatly improve QA/QC efficiency compared to traditional stake-based methods of construction inspection. With 3D technology, many inspection tasks become a one-person job. Equipment commonly used by inspection personnel includes:

- Computer hardware and mobile devices such as laptops and iPads
- Surveying instruments such as GNSS rovers, RTS and their respective data collectors.
- Phone hotspots used for remote access to the DOT's network from the field

During preconstruction, quality control for 3D data involves checking the accuracy of the original ground and/or subsurface features and determining the impact and need for design revisions where there are differences. The resident engineer needs to plan how the inspectors will use 3D models and the available survey equipment and network, prioritizing inspection tasks using a risk-based approach. Advance notice may need to be given for some construction activities in order to have the appropriate construction inspectors or surveyors on the job site with the right tools and/or skill set to inspect specific work (FHWA, 2017d). The desired outcome in this project stage is to develop the framework for setting the Model of Record; assess the impacts of differences between the existing ground DTM and actual field conditions; manage the digital data; define the tools and methods for inspection work; identify a source of support for CADD or survey issues during construction; establish the process for measuring and calculating quantities for payment; and determine the needs and formats for 3D as-built records (FHWA, 2017d).

The timing of preconstruction quality control has a significant impact on the ability to control changes to 3D data. Once the contractor has mobilized equipment on the site, the cost impact of delays may exceed the cost savings that might have been possible by using 3D data (Maier, et al., 2017a). During construction, 3D inspection tools enable an objective and transparent construction inspection process through digital documentation and rapid decision-making. Inspectors should take advantage of the available automation processes associated with 3D digital data.

Studies have shown that 3D models and AMG technology reduce time checking grades by 66 percent and staking time by up to 85 percent (Sillars et al., 2018; Mitchell, et al., 2019). When construction inspection staff is equipped with modern surveying equipment and trained on how to use 3D models for verification and quantity measurements, productivity may increase by as much as 50 percent (Sillars, et al., 2018; Mitchell, et al., 2019).

Accessing the Model in the Field

The ability for inspectors to view and interact with the model in real-time while in the field is a critical component to advancing 3D modeling implementation during construction. 3D models can be paired with alternative methods for viewing plans in the field. Inspectors benefit from the use of tablets and laptop computers which can be uploaded with the most current 3D model, giving inspectors access to any design changes that have been updated in the model. Devices such as iPads and other tablets are powerful tools for inspectors working with 3D models. Inspectors can use these tablets to view design data, take photographs for records, take notes, and store information. Cloud-based software allows contractors and inspectors to view and access the 3D model from a device such as an iPad. To avoid errors, inspectors should be working from the same up-to-date model that the contractor is using. Mobile device software that has the following functionalities should be adopted to assist in construction inspection activities (Bentley Systems and Montana DOT, 2016):

- Compatible between platforms (iOS, Windows, Android, etc.)
- Able to use geospatially located 3D models and design features
- Able to markup and redline data
- Able to add field notes, pictures, and videos
- Integrated with a document management system
- Able to run in disconnected mode for standalone functions (i.e. without a data connection)
- Able to locate features based on station/offset and GPS

Michigan Tech Research Institute developed the 3D BRIDGE App for Michigan DOT which allows for tablet-enhanced collecting and locating of defects and repairs in the field. The tool reduces data collection time dramatically by cutting out multiple data entry steps and coordinating any related annotation (Brenner, et al., 2018). The 3D BRIDGE App is used for routine (biennial) bridge condition inspections, but could be used on the initial inspection during construction.

Utility Information

Collecting complete as-built data, including locations of utilities, is an important part of surveying and inspection. Accurate utility information can greatly increase the usefulness of a 3D utility model. There are risks using a 3D model of existing utilities when the model does not communicate the uncertainty associated with the positions (especially elevations) reflected by the model. New inspection technologies have also provided the ability to quickly and accurately obtain utility location information during and after construction.

SUE is a risk management discipline that manages the existing utility records. SUE professionals determine where and when to collect enhanced utility information, e.g. with subsurface exploration techniques or “potholing,” a practice of exposing a utility to capture location information. ASCE 38-02 is the standard used by SUE professionals for the collection and depiction of subsurface utilities. The ASCE 38-02 quality levels may be divided into the following categories (American Society of Civil Engineers, 2002):

- *Quality Level D:* the most basic level of information for utility locations.
- *Quality Level C:* the most commonly used level of information.
- *Quality Level B:* involves the application of appropriate surface geophysical methods to determine the existence and horizontal position of utilities.
- *Quality Level A:* highest level of accuracy available and involves direct observation of the utility, e.g. by potholing.

It is important to recognize that the SUE quality levels are applied to segments of utility line. For example, a water line will be Quality Level A at a pothole location, and Quality Level B on short locations between potholes. The same water line may be Quality Level C on parts of the site that are not affected by high-risk construction activities, and Quality Level D on parts of the site that are not affected by construction activities at all. The SUE professional determines the appropriate Quality Level to depict the utilities based on the risks and consequences of a utility strike. A gas or fiber line has a higher cost consequence in the event of a strike, so a fiber and gas line may be depicted at Quality Level B in one part of the site while the water line is depicted at Quality Level C in the same location.

The SUE information will be provided to the contractor and the contractor will usually pothole extensively to improve the Quality Level and minimize their risk of utility strikes. The owner should require 3D position records of all as-built and as-found utilities exposed during construction. Detailed records should also be kept of the status of these utilities; abandoned utilities not removed during construction should be documented as abandoned. Ownership data is also important for subsurface utilities (Utah DOT, 2019). The cost of collecting and storing accurate subsurface utility records during construction is much lower than after the utilities are buried. The accuracy of subsurface geophysical exploration technology is vastly lower than a survey of an exposed utility.

Using handheld GPS devices, inspectors can record the horizontal locations of visible, surface utilities such as fire hydrants, structures, valves, and pipelines. Subsurface utilities should be collected with more accurate instruments like GNSS rovers. This information can then be transferred to the agency's GIS database, allowing the data to be shared among a variety of devices and users (Reeder & Nelson, 2015a).

Virginia DOT and Michigan DOT are on the forefront of developing advanced systems for utility records. Virginia DOT utilizes a radio frequency identification system which uses radio waves to capture and read information stored on tags attached to new and existing utilities. These tags, also called marker balls, are placed at critical points along the utility lines and include retrievable information about the utility owner, type, size, elevation/depth, horizontal coordinates, and reason for the marker (FHWA, 2016a). Michigan DOT has developed a program in which each utility company uses its own methods to collect 3D geospatial data for new and existing utilities. The methods adopted by Virginia DOT and Michigan DOT work well for identifying subsurface utilities. Methods such as lidar can be used to obtain surveys of overhead utilities.

Indiana DOT has experience with 3D modeling for SUE purposes. Indiana DOT has worked with Bentley's SUDA software (renamed to Drainage and Design in Bentley's new Open Roads Designer software) and has provided a best practice guide to the department's Hydraulics and Road Design groups. The department has implemented SUDA/Drainage and Design on an unofficial pilot project for which utility clash detection was the primary goal (Fuller & Pangallo, 2019). The SUDA/Drainage and Design software was used on a small urban structure replacement project with numerous existing utilities. The proposed reinforced concrete box structure was larger than the existing dual pipe arches. The SUDA/Drainage and Design software was able to identify several conflicts including a sanitary sewer, fiber cables, gas lines, and water lines.

Real-time Verification

The purpose of real-time verification is to provide QA/QC checks during construction with minimal interruption and minimal safety risk to inspectors. Using 3D data for real-time verification offers a number of benefits compared to traditional inspection including safety and efficiency improvements, as well as the ability to collect more accurate, consumable, and repeatable measurements. However, real-time verification also presents a significant change for inspectors, requiring new survey equipment and methods.

To realize the benefits of using survey equipment for real-time verification, inspectors must understand their role and be able to effectively use the rovers in conjunction with 3D data. To perform real-time verification, and inspector loads 3D data onto a data collector and selects the appropriate survey tool to check the tolerances of the specific construction activities (Maier, et al., 2017a). Table 5.13 lists the measurement tolerances for tools and example activities for which the tool is appropriate. In the table, H means "horizontal" and V means "vertical."

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

Table 5.13. Tool selection guidance inspectors. (Maier, et al., 2017b)**.**

The inspector is able to verify the following:

- Primary acceptance factors such as slopes and material depths
- Dimensions such as lengths and clearances
- Elevations such as inverts and beam seats
- Pavement horizontal locations and grades
- Correct use of safety devices, and
- Erosion prevention and sedimentation control device compliance.

Real-time verification observations can be made and stored in a data collector in seconds, but must then be processed to appended to the inspection daily report. GNSS rovers have sufficient accuracy to verify grade and capture length, count, and pay area quantity measurements. A RTS is needed to verify structure grades and to compute some high-precision pay quantities (McDaniel & Wheeler, 2014). Contractors use RTS rovers to verify pavement construction because of the depth precision requirements, not the grade precision requirements. Concrete paving pay factors use ¼ inch bands to compute depth pay factors. (Maier, et al., 2017b)

Implementation Recommendations for Construction

Construction must undergo significant policy changes and workflow changes during the transition from 2D to 3D. The following flowchart (Figure 5.7) from Maier et al. (2017b) shows a recommended workflow for managing construction and inspection with 3D technology:

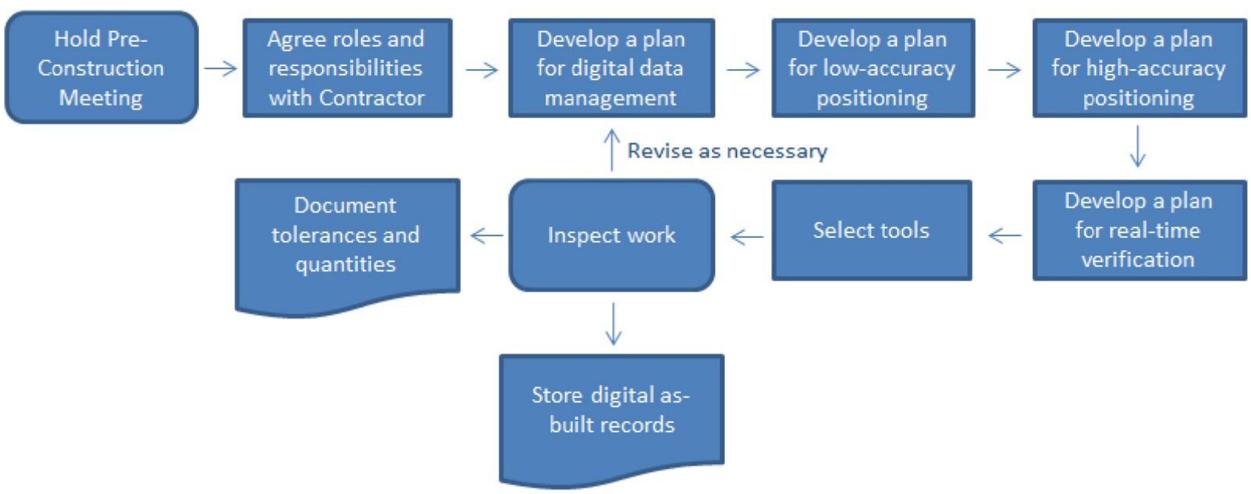

Figure 5.7. Managing construction with 3D technology (Maier, et al., 2017b)**.**

Construction Partnering

Contractor participation and collaboration with the design and inspection teams is a critical component for successfully adopting 3D modeling techniques during construction and post construction. For projects on which a 3D model will be utilized, construction should be involved as early as possible in the design process. Many DOTs have found that open communication with contractors during 3D modeling projects proved extremely beneficial to project success. Construction partnering has been utilized successfully by leading DOTs to reduce claims and associated costs, provide a framework for improved quality, ensure timely project completion, and reduce or eliminate conflicts, waste, litigation, and budget overruns (FHWA, 2017d).

Collaboration and partnering applies to all teams involved in the roadway or bridge project, not just between the agency and contractor. A collaborative project delivery process needs to be developed that promotes communication between traditionally isolated pockets of design and construction teams.

Project Delivery

Many DOTs have found that open communication with contractors during 3D modeling projects is an important factor for project success. Therefore, along with construction partnering, several DOTs have used project delivery methods that are conducive to communication and cooperation when piloting 3D modeling in construction. For example, both Utah DOT and Colorado DOT have used CM/GC delivery for 3D modeling projects. Utah DOT recommends starting with low-complexity projects and then expanding to test more complex projects in the CM/GC environment.

Constructability Analysis

The purpose of a constructability analysis is to refine a project's design and increase its construction efficiency. PennDOT currently requires that constructability reviews be conducted by teams at various stages throughout project development. Procedures should be created for design reviews and constructability analysis using the 3D model, including:

- Visual inspection of the design components and features accomplished by view zoom and 3D rotation in CADD
- Reviewing triangles, fine contours (0.1 interval), and flow arrows of the proposed DTM to look for blade shudder
- Conflict resolution using "Clash Detection" routines
- Use "drive-through" or "walk-through" functions in OpenRoads/OpenBridge

Construction Inspection

Construction inspection is an essential part of a department's QA program. Inspectors can make use of 3D models and associated technologies to measure and accept completed work. The following are tools used by leading DOTs during the inspection process:

- GPS rovers
- RTSs
- Handheld GPS tablets
- Devices used to access the 3D model in the field
    - Laptop computers
    - Tablets

- Software that facilitate access to the 3D model in the field

Agencies are exploring and developing alternative methods for viewing CADD and GIS data in the field, including through augmented reality. Each agency should find software that works best for its workforce and institutional data needs.

Inspectors and construction personnel must be properly trained and equipped with the relevant tools to be able to make effective use of 3D technology for inspection. Guidance should also be developed for field crews on how to document various surface measurements. Utah DOT recommends that the guidance cover (Lukes & McDowell, 2017):

- The method for using rovers on the construction network to verify constructed surfaces
- The method for processing design surfaces into rover surfaces
- The method for processing collected rover points into easy-to-use deviation/acceptance reports
- Criteria for inspecting surfaces as they are constructed
- The method for documenting inspected and accepted surfaces

FHWA recommends the following workflow to be used when using 3D data for construction inspection (FHWA, 2017d):

1. Select tool
2. Select reference data from Model of Record
3. Check into control point and make observations
4. Document field conditions and pay quantity measurements
5. Check into control point
6. Repeat from Task 1

Verification observations should only be stored if they are a meaningful as-built record, document an issue that needs to be resolved, or are part of a pay quantity measurement. Additionally, observations and measurements taken should be repeatable within the instrument tolerance, and inspectors should take advantage of the available automation processes (FHWA, 2017d). Inspectors need guidance or judgement to determine what 3D data is required for documenting construction in accordance with the specifications, versus measuring quantities. This judgment can be developed through experience and training.

For roadway construction, Iowa DOT recommends that inspectors take random spot checks with GPS rovers to make sure the site is being graded properly. Pole-mounted GPS equipment can compare the currently graded elevations to the proposed design surface at all locations within the 3D model's limits. Inspectors should also spot-check elevations behind the paver to ensure the equipment is set up and working properly. The inspection technology associated with 3D models allows inspectors to quickly and easily spot-check elevations, thus improving the QA process.

On bridge projects, the use of 3D models for routine maintenance and inspection has been well-established by several leading state DOTs. Inspectors use tools associated with 3D modeling to significantly reduce data collection times and improve safety by reducing the number of inspectors required in the field. Interactive inspections allow the workforce to collect and report condition data at the component element level and for broader audiences to query results right on the 3D model (Brenner, et al., 2018).

Utilities

SUE must be considered when implementing 3D models for design and construction. Subsurface utility location and relocation within the right-of-way constitute leading causes for delays for highway and bridge construction projects (Maier, et al., 2017b). Subsurface utilities can be included in 3D models, but it is important to communicate the SUE designation of existing utilities to convey the uncertainty associated with the depiction in the model. With digital delivery, it is possible to use color to communicate the SUE quality level visually. (It is important, however, to use a color scheme that differentiates the colors for people with colorblindness and line styles that differentiate if printed in black and white.)

Pipes and utility structures are relatively easy to model using modern CADD software, which enables following functionalities:

- Automatic creation of spatially located 3D utilities in CADD
- Automatically show utility elements on profiles and cross sections
- Locate the 3D utility elements with respect to the 3D design models and terrain models
- Attribute the 3D utility elements and display, report, and search on the attributes
- Perform conflict detection on the drainage, utility, and other design elements
- Export and import utilities to GIS

The following figure 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.

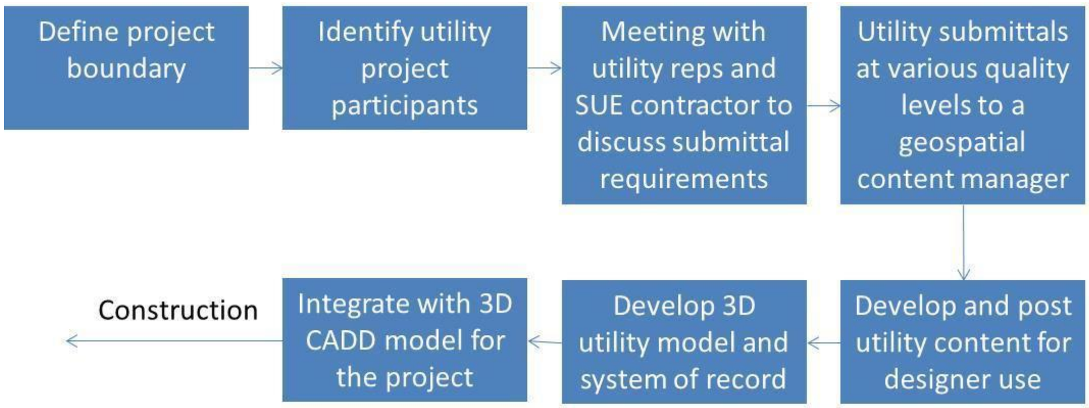

Figure 5.8. Integrating 3D utility data into 3D model or project plans (Maier, et al., 2017b)**.**

Michigan DOT has developed a statewide utility as-built program known as Geospatial Utility Infrastructure Data Exchange. In the initiative, it is a condition of the permit that utility companies document the utilities continuously as they are being installed. Existing utilities are also documented as they are encountered. This utility survey data is then shared with Michigan DOT.

The 3D models of subsurface utilities should be organized to distinguish the different quality levels for plans production and clash detection. It is also 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. This practice can significantly improve SUE mapping and reduce uncertainty on future projects.

POST-CONSTRUCTION

Construction completion is not the end of the usefulness of the information contained in a 3D model. Once construction is complete, 3D models can be used to create final as-built records, export information for maintenance and asset management. The 3D model can be stored in a digital archive, but currently these models are in proprietary formats that are not interoperable—sometimes even unreadable by later versions of the same software product.

As-Builts

As-built records represent the project as it was constructed, which may be significantly different from the initial design. (Note: significant changes are documented through a design review or change order process; with digital delivery these changes should propagate to the Model of Record.) The as-built conditions should be reflected in the final 3D model delivered for acceptance following certification protocols for accuracy and completeness, providing reliable and trusted data for long-term documentation and asset management records (FHWA, 2017d).

With traditional 2D plan-based contract documents, record drawings are developed based on memory, hand-written documentation, or PDF mark-ups. If these records are not properly maintained throughout construction, there is a risk that the final record drawings will be inaccurate. As-built information must sometimes be obtained using surveys to create the record drawings. Real-time verification enables inspectors to capture surveyed as-built information as they verify construction, which can then be used to create the as-built records; while processing the survey data and updating models in CADD is more onerous on the inspector than marking up plans in ink or PDF, the digital information is significantly accessible and valuable if stored appropriately.

A 3D model can be updated quickly and easily via a mobile computer system as progress is made and changes take place, assuming someone with the CADD skillset is available on-site or as remote support. Once construction is complete, the 3D model becomes the record drawing without the need to obtain additional as-built survey. The as-built information, including utility information, will have been continuously added to the model as construction progressed and inspection was completed. Capturing as-builts with 3D technology can greatly enhance the efficiency and safety of inspectors on site, 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 (Maier, et al., 2017b).

The workflow for as-built records needs to incorporate updated 3D models and associated information. This data should be searchable by geospatial location for as-built information (Bentley Systems and Montana DOT, 2016), rather than buried in a document-based storage system organized by the construction Project Identification Number. Additionally, further discussions are needed for the requirements of the ultimate users of the as-built information. The as-built 3D models are too burdensome for maintenance and asset management users; Minnesota DOT has developed as-built requirements that require data formatted ready for the maintenance and asset management business systems for priority assets. (Minnesota DOT, 2017)

At Michigan DOT, the responsibility for creating as-built plans is dependent upon which party performed the staking. For projects where the contractor directs the layout, they are responsible for updating the as-builts. Likewise, for projects in which Michigan DOT performs the layout, agency construction staff is responsible for documenting as-built conditions (Mitchell, et al., 2019). The responsible party for recording as-built conditions should be equipped with the necessary tools and training to proficiently collect the data. Mitchell et al. (2019) recommend that the data dictionary for each model element being recorded be established ahead of time in coordination with the asset inventory staff. Once data is collected, it should be validated against the requirements and specifications to ensure data quality. Once validated, the data can be accepted and stored.

Ohio DOT requires the contractor to maintain and submit an as-built 3D model to the department. The as-built 3D model is to be a transmittal of all utility spot locations, and if applicable, a digital 3D model. The as-built model information is to be submitted to Ohio DOT with a sealed letter from a professional surveyor or professional engineer. The professional surveyor or engineer must have participated in the as-built model creation and implementation (Ohio DOT, 2015).

Capturing As-Built Data

A range of as-built data is 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 (Maier, et al., 2017b). Field survey tools such as total stations, GNSS rovers, digital levels, and laser augmented GNSS rovers may be used as well. Once verified by an inspector, this as-built data can be used as a resource for verifying compliance with the specification or measuring completed work. Lidar, both aerial and ground-based, is also a popular method of collecting final as-built surveys. Lidar can capture a wide area in a short period of time but requires more intensive data processing than does field survey data. Compared to more traditional methods, lidar has the potential to realize significant cost and time savings when capturing as-built data. For example, it has been estimated that Washington State DOT could save $800,000 per cycle by collecting only bridge clearances with survey-grade mobile lidar (Brenner, et al., 2018, Yen, et al., 2011). Post-processing tools enable extraction of existing inventory and condition data. On bridge projects, for example, it enables measurement of clearances or detection of cracking and spalling concrete.

The term “Scan to BIM” has emerged for bridge construction projects and refers to the process of capturing existing or mid-construction conditions via lidar and then generating idealized model geometry based on extracted features. Scan to BIM can be used at any time, for instance to create existing condition models prior to design, or to capture as-built in-progress construction. It could also be used to verify the screed information if there is support to responsively register and process the data (Brenner, et al., 2018).

Maintenance

Accurate and detailed record information is critical to facilitate maintenance once needs develop along the roadway or bridge. The 3D model is useful after construction for purposes such as a base map for future maintenance or reconstruction projects, accurate data in a GIS database, or to update asset management systems (Reeder & Nelson, 2015a). Asset information models may be used to view and organize monitored data across multiple assets in real-time. Off-site access to such information can help management teams detect safety issues before they become critical (Brenner, et al., 2018).

State agencies should consider engaging personnel from maintenance for review during detailed design. Some of the data needs for the life cycle from maintenance and asset management can be incorporated into the early stages of a project. DOTs can consider assigning identification number to project elements that hold references to important document and data-based information (O'Brien, et al., 2016). Maintenance personnel benefit from this strategy because they will have access to pertinent data as needed, without having to know the last construction project identification number to locate the information.

Guidelines must be developed that define which parties are responsible for managing the model post-construction. The final as-built model can be stored in the DOT’s digital data archive to allow access for maintenance activities. Asset identification needs, considered during planning and integrated during design, improve the objectivity in the decision-making process for asset management. Maintenance personnel can have timely access to the accurate data they require to carry out their tasks (O'Brien, et al., 2016). During the operations phase, state agency maintenance departments will manage the majority of the roadside assets, while pavements and bridges are maintained according to FHWA requirements.

When inventory mapping is performed with modern survey methods such as lidar and imagery, it can meet the data needs for asset management and maintenance (O'Brien, et al., 2016). State DOTs at high levels of 3D modeling proficiency build up and regularly update a digital data archive that can inform decisions about managing existing facilities and developing new projects. (FHWA, 2016b)

Establishing agency-specific object standards enables models to be generated with pre-populated asset information needed for maintenance and asset management systems. The maintenance and collection of asset/maintenance management systems information is a difficult task that involves collecting paper-based design and construction information or locating the assets to collect their attributes (Brenner, et al., 2018). Some systems that receive the asset data (more prominent in building management) can maintain the link to the 3D model which allows for visualization by the facility team and enables live updates of repairs and equipment replacements.

The US Army Corp of Engineers developed the Construction Operations Building Information Exchange (COBie) which facilitates the data transfer from the model to downstream target database systems (Brenner, et al., 2018). COBie transforms information in paper documents into data that can be used throughout the electronic design/build/operate process. COBie has been created primarily for building projects, but there are ongoing efforts to extend the COBie data structure to better support linear infrastructure projects.

Implementation Recommendations for Post-Construction

The ability to more quickly and accurately capture as-built information is one of the most significant advantages of using 3D models for construction and post-construction. The following workflow can be used to prepare as-built records (Maier, et al., 2017b):

1. Receive notification of a completed construction activity
2. Request as-built data from the contractor
3. Take observations and process in CADD to review as-built data
4. Publish the as-built records and notify all stakeholders

DOTs should develop guidance and contract language for specification of as-builts by the contractor. Utah DOT guidance includes (Lukes & McDowell, 2017):

- Developing a method for integrating accepted surfaces into design models for as-builts,
- Developing a method for incorporating as-builts into a usable format, and
- Investigating attribute conversion software.

One of the most important issues an agency must consider with regard to data management is the heterogeneity in the as-built information. Information from construction sites or as-built data collection efforts comes in a variety of formats – paper or PDF mark-ups, 3D electronic, and 3D point clouds, among others. DOTs can consider developing processes to mine this information to meet the needs of maintenance, asset management, and future project development (O'Brien, et al., 2016).

GIS is often used to manage asset inventories. Examples of GIS collection tools include Collector for ArcGIS, Survey 123, and Feature Manipulation Engine. These collection tools can be customized with standard forms that easily integrate the data with the GIS database. Collector and Survey 123 are used to capture as-built information in the field (e.g. by Utah and Iowa DOTs, amongst others) whereas Feature Manipulation Engine is used to extract asset information from 3D models. Feature Manipulation Engine is a core part of Utah DOT's digital delivery strategy.

TRAINING

Training is crucial to the development and efficient use of 3D modeling; it is also one of the most cited barriers to implementation (Maier, et al., 2017b; O'Brien, et al., 2016; Bentley Systems and Montana DOT, 2016; Reeder & Nelson, 2015). Training is not only needed for designers and design reviewers/managers, but also for inspectors and surveyors. FHWA developed several categories of outreach, education, and training products during the Every Day Counts rounds 2 and 3 deployments of 3D Engineered Models. These products included:

Informational/Training Webinars

- Two series of 90-minute informational/training webinars.
- Topics included overviews and specific applications of 3D models.

Web-based Training

- Developed five web-based training modules, which are stored on the AASHTO website.
- The modules are available for free on AASHTO's website (https://store.transportation.org/Training?type=free):
  - 3D Engineered Models for Construction
  - Introduction to 3D Engineered Models for Highway Transportation
  - Surveying and 3D Engineered Models
  - 3D Engineered Models in Highway Design
  - Develop web-based training for 3D modeling and AMG operations

Document Success Stories

- Two series of case study documents were developed for a variety of 3D modeling topics.
- Case studies are available on the FHWA website (https://www.fhwa.dot.gov/construction/3d/case_studies.cfm)

Guidance Documents

- Two series of guidance documents were developed for a variety of 3D modeling topics.
- Guidance documents are available on the FHWA website (https://www.fhwa.dot.gov/construction/3d/guidance.cfm)

Return on Investment Research

- Michigan DOT commissioned research, conducted by Mitchell et al. (2019) to determine the return on investment for their RID documents.

- Additional research into the return on investment for lifecycle uses of BIM for infrastructure is being conducted via NCHRP project TFRS-02, which was initiated in early 2020.

Workshops and Peer Exchanges

- FHWA conducted two series of workshops hosted by 22 different DOTs to assist them in defining their goals and plan to implement 3D Engineered Models. PennDOT hosted one of these workshops in June 2014.
- FHWA also conducted ten online peer exchanges to assist states to overcome specific challenges to their 3D modeling implementation. Recordings of three of these peer exchanges are available on the FHWA website (https://www.fhwa.dot.gov/construction/3d/workshops.cfm)

Quality Assurance Training

- FHWA has provided an additional series of workshops and webinars specifically focused on using 3D Engineered Models in Highway Construction and Quality Assurance.

Iowa DOT recommends "Just in Time Training," which refers to information delivered to learners at the moment and location they need. This practice ensures that trainees immediately apply what they have learned to a scenario or project. Iowa DOT has cited studies that show that information retention is reduced to 25% after 5 weeks if personnel are unable to apply what they have learned.

Designers

Hands-on, instructor-led classroom training is generally seen as the most effective training method for 3D modeling software. However, hands-on training should be supplemented by additional sources. For example, Iowa DOT has created designer resources that include documentation and videos outlining how to perform certain tasks. The DOT has developed a video library to supplement its training effort. This video library may be found on Iowa DOT's website (https://iowadot.gov/design/VideoIndex). New York State DOT has created several short instructional videos for Bentley software. The videos begin with the basics of getting started with the software and progress to more in-depth design.

Ohio DOT has also created an extensive training guide which may be found under the training section of its website (http://www.dot.state.oh.us/Divisions/Engineering/CaddMapping/CADD_Services/Training/Pages/Guides.aspx). The site includes both survey and design training for OpenRoads Designer and GEOPAK V8i. Ohio DOT training provides PDF guides for a wide range of topics including data processing, corridor modeling, templates, project management, and geographic coordinate systems. These guides may be accessed by anyone and may be downloaded individually or as a full download. Ohio DOT has also created a YouTube channel that provides training videos (https://www.youtube.com/channel/UCo-lOt5L4GHSDbSkKWPeWAw/videos).

Some DOTs have developed multi-stage training programs for 3D modeling. Texas DOT, for example, has held one-day introductory training for 3D modeling as well as more in-depth 3-day courses for 3D design. Florida DOT also held multiple training sessions when transitioning to a 3D modeling workspace. As with Texas DOT, the training began with an introductory course and moved to an advanced 3D modeling training session in which participants learned to use the Bentley OpenRoads software tools in the Florida DOT workspace. For advanced training, it is recommended that the training takes place over several days. In-depth training for OpenRoads and OpenBridge is also available through Bentley for users to learn and practice on their own time.

While training is crucial, it is also beneficial to have experienced staff to assist with any questions or issues regarding the 3D design process. These staff may be in the office or on site. Michigan DOT realizes there may be a significant learning curve when implementing 3D modeling. Therefore, it is suggested to have experienced Department staff or engineering consultants on site to verify grades. Brenner et al. (2018) recommend a number of training methods for both roadway and bridge design including handouts, Bentley trainings/LEARNserver, YouTube channels, and training built into the modeling software.

Brenner et al. (2018) created training materials for Michigan DOT's structural designers that provided guidance for directly using the software for producing bridge models to support visualization, structural analysis, basic plan production, and reporting. The training material was used during an initial interactive "over-the-shoulder" session for a select group of power users who had been identified as bridge design leadership. The outline for Michigan DOT's 3D bridge design course was as follows (Brenner, et al., 2018):

- *Training Course #1: Virtual Kickoff Training* – A kick-off webinar was held on February 20, 2018 to set expectations and provide information to meet pre-requisites for the interactive training session. Intended audience: Project Managers and Structural Designers.
- *Training Course #2: Michigan DOT 3D Bridge Modeling for Project Managers* – This course was delivered on March 19, 2018. The materials for this course include a handout that follows Michigan DOT's training template and provides a general overview of 3D modeling for bridges, and contract that is specific to Michigan DOT. Intended audience: Project Managers
- *Training Course #3: Michigan DOT 3D Bridge Modeling for Structural Designers* – This course was delivered on March 28, 2018. The materials for this course include a handout that follows Michigan DOT's training template and provides technical guidance for developing 3D bridge models using Bentley's OpenBridge Modeler using Michigan DOT specific CADD workspace. Intended audience: Structural Designers.

Construction and Inspection Teams

People and processes are equally important to 3D modeling implementation as software and technology. To increase proficiency with 3D models and technology, transportation agencies should create a specific training program for construction and inspection staff. The training will help fill the gap between design and construction. The program should be consistent with position descriptions to develop skills required for model-based construction engineering and inspection (Mitchell, et al., 2019). Sustained proficiency with 3D technology (both models and the survey technology to use the models on site) can be realized through regular use of skills and recurring training opportunities that build advanced skills in line with new technology.

Construction and inspection personnel must receive thorough training and proper guidance to harness the full potential of 3D data and technology. Valuable data is collected in the field, so inspectors must be trained on how to utilize that data. Perhaps most importantly, inspectors should be trained on the tools and processes required to perform quality assurance and verification tasks (Mitchell, et al., 2019). For inspectors, training should develop skills for importing 3D data into data collectors, collecting measurements in the field, and exporting the data from the data collectors back to product. Training should also educate inspectors on all the applications of 3D models for construction inspection.

The following are key knowledge areas for inspectors (Mitchell, et al., 2019; Maier et al., 2017a):

- *Surveying Basic Concepts:* General overview of mapping fundamentals. It may be beneficial to work with local colleges to develop a basic online course.
- *Mapping Fundamentals:* Coordinate systems, transformation and project-scale factors, site localization.
- *Data Management:* Instructions for managing data files, including version control, review and validation of data, and collaboration tools.
- *Survey Hardware and Software Skills:* Instructions for using modern surveying equipment and associate software programs including mobile applications, CADD software, and databases.
- *Survey Tool Selection:* Understanding equipment tolerances, ability to choose tools for different activities.

Developing a training program in these core knowledge areas is a key success factor for implementing 3D models for construction inspection. Training delivery methods should include a variety of options to meet the needs of a diverse workforce, including traditional instructor-led, train-the-trainer, hands-on, short how-to documents, and videos (FHWA, 2017d). Many inspectors indicate that trained expert assistance is more helpful than written guidance alone.

Bentley software training is offered through the Bentley LEARN subscription program. However, the training may be too in-depth for inspectors who would benefit more from a tailored curriculum and inspection-specific training for relevant software and equipment. The Bentley-developed online training may be adequate for design personnel but may be overwhelming for construction staff (Mitchell, et al., 2019). A potential solution to this problem is to create a specific Bentley LEARN path for inspection work to be followed by DOT-specific training.

Training should be thought of as a process rather than a one-time event. While information sessions and one-day workshops can help acquaint personnel with 3D modeling concepts, continuous training efforts play a major role in the skill development process (O'Brien, et al., 2016). Cross-discipline training may also prove beneficial to understand the various processes and uses of digital information. Inter-discipline collaboration and data sharing will likely increase with 3D implementation maturity.

Implementation Recommendations for Training Programs

Developing an effective training program is a key success factor for implementing 3D modeling. Training is not only for designers, but also for inspectors and surveyors. DOTs should consider developing hands-on, instructor-led classroom training for 3D modeling software. Hands-on training should be supplemented by additional sources.

A multi-staged training program has proved effective in several state DOTs. Such a training program often begins with short introductory sessions followed by several days of progressively more in-depth training. These types of training sessions allow users to get hands-on experience in a setting devoted to new users. For advanced training, it is recommended that the training takes place over several days. In-depth training for OpenRoads and OpenBridge is also available through Bentley for users to learn and practice on their own time.

It is also beneficial to have experienced staff to assist with any questions or issues regarding the 3D design process. These staff may be in the office or on site.

FINANCIAL IMPACTS

Clevenger et al. (2014) examined the impact of BIM on bridge construction for two case studies. BIM utilizes 3D modeling and advanced construction management techniques to improve the process of building construction. The results of the case studies indicated that first implementation of BIM for bridge construction may incur significant costs depending on the type and complexity of the project. Conversely, for one of the projects examined (the I-70 Bridge), the implementation of BIM may have contributed to the reduction of the number of requests for information and change orders and, potentially, a decrease in project schedule and elimination of rework, compared with traditional construction methods.

Specifically, Clevenger et al. (2014) found that metrics related to requests for information and change orders decreased in the ranges of 12-87 percent and 22-89 percent, respectively. In addition, total costs for change orders and rework represented a 6% increase over the original estimate for the baseline project versus only a 1% cost increase overestimate for the BIM-enabled project. Such a finding suggests that BIM may have provided approximately 5% cost savings during construction by contributing to reduced change order s and rework. Furthermore, when total costs for change order s and rework are compared with the standardized project costs of both projects, analysis suggest a 9% cost savings. (Clevenger, et al., 2014).

According to the contractor and owner, implementing BIM on the I-70 Bridge project allowed the project team to deliver a bridge that otherwise could not have been built according to the required time and space constraints. Specifically, the ability to provide accurate and realistic visualizations of the project to the public prior to construction enabled the level of public engagement and support necessary for success (Clevenger, et al., 2014).

Mitchell et al. (2019) performed an extensive Cost Benefit Analysis study on Michigan DOT's use of providing 3D models as RID and documented the subsequent results. During discussions with contractors regarding their use of 3D models, the authors found that the cost of 3D models for AMG typically fall between 0.5% and 3% of the overall construction contract value, favoring the lower end of that range. It is uncommon for the cost of a model to surpass 3% of the construction contract value. Some contractors may pay up to $40,000 to develop what they consider a good model. However, the improved quality of the RID 3D models has made a significant difference in what contractors are paying for developing an estimating and AMG model. One contractor estimated that RID 3D models are currently saving them between 25% to 50% of the time it takes to create AMG models. Additionally, estimators spend substantially less time in performing quantity take-offs during the bidding process. This improved quality of the RID 3D models allows the contractors to have a better understanding of the design intent and creates estimates faster and more accurately. This results in contractors not having to inflate their bids as much to account for unknown risks. Overall, contractors are significantly more confident in the RID files than they have been in the past.

In the Mitchell et al. (2019) study, contractors also indicated that AMG reduces the number of workers that once were dedicated to placing string lines for paving. One contractor indicated that in the past, a 4-person crew was needed for placing string line for every day of paving (compared to one or two operators of the RTSs in the AMG system), which equates to approximately $10,000 per paving day just in operational cost. These savings in operational cost do not account for the gained efficiencies between string line method and AMG trimming and paving. Earthwork contractors noted that machine grading saves 30% to 40% on production cost compared to traditional construction methods. For example, savings are realized in cost of equipment and operator time, which ultimately impacts unit bid prices (Mitchell, et al., 2019).

Wisconsin DOT conducted an ROI analysis for CIM. O'Brien et al. (2016) summarized the analysis. WisDOT found that a considerable portion of a project's construction change order expenditures could be reduced by using a 3D model and clash detection. The department also estimated that if 3D models had been used for the Mitchell Interchange Project, $9.5 million (or 3.7% of the project's budget) could have been saved. WisDOT determined that CIM investment has the potential to reduce future overall program costs (O'Brien, et al., 2016).

WisDOT has created robust 3D models at a significant upfront expense to provide to contractors for their digital models. Although the initial cost is very high, the department has found that the investments easily pay off by creating lower bid prices.

6: IMPLEMENTATON STRATEGIES

This section of the report provides strategies to implement the recommendations of this report that will assist PennDOT with the Digital Delivery Directive 2025 initiative.

IMPLEMENTATION OBJECTIVES

The initial vision of the Digital Delivery Directive 2025 is that by 2025, PennDOT will have the ability to design projects using 3D engineered models and deliver the design intent to construction using 3D engineered models as the primary document of truth. This comprehensive vision for digital delivery—involving changing the medium of communicating project information from document-based to 3D model-based throughout project delivery—touches each stakeholder that needs to access project information. The success of the initiative rests on being able to create a solution that makes the information stakeholders need more accessible than it is with the current, document-based approach. This involves guiding the implementation through a set of clear requirements to ensure that solutions meet the needs of all stakeholders. The primary objectives of the implementation are to establish the requirements for the solution and to build and scale the core capabilities to implement that solution.

Requirements

One of the first steps for implementation should be to establish clear and measurable requirements to guide the solution development. The requirements establish the end-user needs for a successful solution. Once the requirements are defined, the policy, technology, and workforce development solutions can be developed that meet these requirements.

Attributes of the digital delivery solution that end-users need include:

- *Accessible:* they can access the information when they need it.
- *Verifiable:* they can verify authenticity of the information they access.
- *Dependable:* the information is always fit for purpose.
- *Predictable:* the information is in the form that they expect.
- *Durable:* the information can be accessed and used over the lifecycle of the asset.
- *Transparent:* they can verify the provenance of the information.
- *Reliable:* the information is always the same quality.
- *Repeatable:* the information is the same every time they access it.

In order to achieve all of these attributes, the digital delivery solution needs to fulfill four primary requirements:

- *Secure:* data is protected from being modified unintentionally.
- *Standardized:* data conforms to a set of rules.
- *Interoperable:* data can be read and written by a variety of software products.
- *Open:* the standards and procedures for accessing the data are published.

These four requirements also core elements of a data governance framework. Other data governance elements to consider are stewardship and risk management.

Components

The three components of a digital delivery solution are policy, technology, and workforce. All three need to advance in a coordinated manner to incrementally implement the solution.

Policy

The policy components of digital delivery include:

- *Statutes:* These are the laws the govern digital data in Pennsylvania, including digital signatures, digital seals, record retention, open access, etc.
- *Manuals:* These are PennDOT publications that provide requirements for the creation, use, and delivery of digital data, including design manuals, CADD manual, inspection manual, etc.
- *Specifications:* These are the legal terms for construction, including how digital data is used to for communication between the contractor and PennDOT representative, how digital data is used in computing payment quantities, etc.
- *Guidelines:* These are publications that provide instruction on workflows and procedures that are not contractual requirements.

Technology

The technology components of digital delivery include:

- *Hardware:* These are the physical devices used to create and consume digital data, such as servers, networks, personal computers, smart phones, tablets, and survey equipment.
- *Software:* These are applications loaded on the hardware through which users create, view, edit, and exchange digital data, such as design software, construction survey software, AMG software, spreadsheets, word processors, etc.
- *Business Systems:* These are enterprise-scale hardware and software systems that host and serve the digital data, such as PPCC, ECMS, and asset management systems.

Workforce

The technology components of digital delivery include:

- *Skills and Knowledgebase:* These are the competencies to develop to facilitate digital delivery workflows, including 3D modeling skills, construction survey skills, knowledge of procedures and requirements, etc.
- *Roles and Responsibilities:* These are new positions or responsibilities for staff related to digital delivery, such as the digital delivery program manager, data stewards, model authors, and model managers.

GAP ANALYSIS OF PENNDOT STANDARD PRACTICES

Chapter 3 summarized PennDOT's efforts to date to implement digital delivery. Chapter 4 summarized efforts from PennDOT's peer agencies. While no DOT has implemented a comprehensive digital delivery solution to date, the purpose of this gap analysis is to identify areas of the solution that other agencies have refined so that PennDOT can capitalize on those lessons learned to more quickly close those gaps.

Policy

Insights from peer agencies can accelerate progress in the following policy areas:

- *Digital Signatures and Seals:* Many states have institutionalized digital signatures and some (e.g. Iowa, Utah, New York) have created procedures to fulfil the requirements to sign and seal 3D model-based contract documents.
- *Survey Requirements:* Lead DOTs (e.g. Utah) have updated their survey manual to ensure that the existing conditions are captured based on control and accuracies needed for 3D design and AMG.
- *3D Design Modeling Requirements:* Lead DOTs have developed detailed 3D model requirements for design using the same software that PennDOT is currently deploying.
- *Bid Package 3D Model Requirements:* PennDOT's current 3D modeling deliverables relate to software that PennDOT is replacing. Other agencies have implemented OpenRoads Designer software, which provides insights for PennDOT to update the bid package 3D model deliverable requirements.
- *As-built Deliverable Requirements:* Some states (e.g. Michigan, Minnesota) have developed digital as-built requirements. While these states' solutions are tailored to their own business systems, the approach they followed can provide insights to PennDOT.
- *Level of Development Definitions:* Lead DOTs (e.g. Utah, Michigan) have developed preliminary LOD definitions for roadway and bridge model elements.
- *Specifications:* Lead DOTs have developed special provisions or updated their specifications to facilitate 3D model-based contract documents and to streamline the contractor's use of evolving construction technology (e.g. AMG, Intelligent Compaction).

Technology

Insights from peer agencies can accelerate progress in the following technology areas:

- *OpenRoads Designer Workspaces:* Some states have developed workspaces and components for 3D modeling both for roadways and bridges. Some elements of the workspaces would not be transferable (e.g. level naming conventions), but some (e.g. parametric bridge and roadway component definitions) may be applicable.
- *Document Management Systems:* A number of states have experience using a wide range of different solutions to host 3D data for design and construction. Their procurement

specifications can help PennDOT evaluate the current business systems and inform procurement planning if needed.

- *Digital Signatures:* Requirements for digital versus electronic signatures, particularly in construction, vary from state to state. If PennDOT determines that digital signatures are needed, there are examples from several states (e.g. Florida, Michigan) on establishing the public/private key and certificate validation resources.
- *Hardware & Software Requirements for Construction Inspection:* Lead DOTs that have piloted 3D model-based contract documents can provide insights into viable solutions for PennDOT to begin piloting the use of 3D models in construction inspection.

Workforce

Insights from peer agencies can accelerate progress in the following workforce areas:

- *Design Software Training:* Some states have developed training materials to augment generic software vendor training for roadway and bridge design software. Some elements of the training (e.g. state-specific standards and workspaces) would not be transferable, but would provide insights on which aspects of the training to customize.
- *3D modeling workflows:* Some states have developed guidance documents that document effective workflows for roadway and bridge design and bid package production.
- *3D model Review Checklists:* Several states have developed checklists to review 3D models at design milestones and/or at bid package submittal.
- *Construction inspection workflows:* States that have piloted 3D model-based contract documents have experience developing workflows for construction inspection.

PRIORITIZED AREAS FOR DEVELOPMENT

This section provides some of the first steps that PennDOT can take to build on its existing capability for digital delivery and prepare the foundations for a more comprehensive solution.

Policy

Any policy change that requires legislative action will take time to achieve through the legislative cycle:

- *Digital Signatures and Seals:* PennDOT should evaluate the legislative requirements to sign and seal 3D model-based contract documents to determine what—if any—legislative action is required.
- *Survey Requirements:* The accuracy of the control established prior to base mapping is a limiting factor on the accuracy of the existing ground used for design. PennDOT should evaluate the current design survey standards to ensure that newly-surveyed projects will have existing conditions captured based on control and accuracies needed for 3D design and AMG.

- *Specifications and Special Provisions:* PennDOT should work with contractors to review the Specifications and identify and prioritize areas that need to be modified for digital delivery.

Technology

Technology development includes the hardware, software, and data specifications. It takes time to program, fund, and procure technology infrastructure needs. Priorities include:

- *Hardware & Software Requirements for Construction Inspection:* The requirements for construction inspection hardware and software need to be established so that they can enter the procurement cycle while the details of the solutions are developed.
- *As-built Requirements:* The first step in developing as-built requirements that serve the needs of maintenance and asset management is to document the technical requirements for the existing maintenance and asset management business systems and the priorities of these department to receive asset information from construction.

Workforce

It is difficult to develop the workforce when the policy and technology are not yet in place, however the following are actions that PennDOT can take quickly:

- *3D model Review Checklists:* Designers are already producing 3D models; having a checklist to review their models helps to build their modeling skills and knowledge and provides confidence in sharing those models as part of bid packages.
- *Design Software Training:* Design software is the primary tool for designers; proper software training enables designers to make effective use of the software and realize efficiencies in the design process.

STRATEGIC PARTNERSHIPS

The State DOTs that are most advanced with their digital delivery implementations have done so by partnering with their local industry to plan and prioritize their implementation. Each industry partner has knowledge and expertise to lend to the implementation. A full transition to planless digital delivery requires a solution that works for all parties that must access project information; this means catering to the lowest common denominator. The implementation pace needs to meet industry's capacity to absorb the change and invest in enabling infrastructure and workforce development if PennDOT is to maintain a competitive environment for design and construction.

American Council of Engineering Companies of Pennsylvania

The American Council of Engineering Companies of Pennsylvania (ACEC/PA) is the appropriate avenue to engage consultant stakeholders. ACEC/PA represents large and small consulting firms, including disadvantaged business enterprises (DBEs). ACEC/PA has three subcommittees that PennDOT can collaborate with to advance Digital Delivery Directive 2025:

- *Diverse Partnerships:* This subcommittee is concerned with the relationship between prime firms and sub-consultants. The subcommittee can identify and resolve issues related to digital delivery needs of small sub-consultants, including DBEs, who may have less capacity for procuring the enabling hardware and software infrastructure and training for workforce development.
- *Innovative Delivery:* This subcommittee is concerned with enabling innovative delivery methods through identifying legislation changes, emphasizing successes, and addressing concerns. The subcommittee can provide input to potential legislative changes (e.g. digital seals) and can help deploy digital delivery across the consulting community.
- *Construction Services:* This subcommittee is concerned with construction inspection issues. The subcommittee can help develop and deploy 3D model-based inspection practices.

Associated Pennsylvania Constructors

Promoting quality, safety and innovation are one of three core elements of the Associated Pennsylvania Constructors (APC). Many of APC's activities are intended to provide better partnerships with PennDOT and to develop the highway construction workforce. APC holds spring liaison meetings with PennDOT's Districts, a fall seminar, and winter schools in each District. APC also has two committees that PennDOT can collaborate with to advance Digital Delivery Directive 2025:

- *EEO/DBE:* This committee works with the PennDOT Bureau of Equal Opportunity to make sure the DBE Program remains fair to all contractors. The committee can identify and resolve issues related to digital delivery needs of DBE contractors, including those that may have less capacity for procuring the enabling hardware and software infrastructure and training for workforce development.
- *Information Technology:* This committee works with PennDOT to identify, apply, and enhance technologies for communicating bid information and increasing project management efficiency. The committee can provide input to help guide how digital data is shared between the contractor and PennDOT and provide feedback on the usability of the digital solutions to ensure that efficiencies are fully realized.

Other State DOTs

Many of PennDOT's peer agencies are simultaneously working on their own digital delivery solutions. There is a clear opportunity to capture the lessons learned from other agencies and incorporate them into PennDOT's digital delivery solution.

The three primary avenues for collaboration with other DOTs on digital delivery are:

- AASHTO Committees,
- Transportation Research Board Committees, and
- The Highway Engineering Exchange Program.

AASHTO Committees

The two most active AASHTO committees working to advance digital delivery are the Joint Technical Committee on Electronic Engineering Standards and the Committee on Bridges and Structures, specifically, the T-19 subcommittee on software and technology.

- *Joint Technical Committee on Electronic Engineering Standards:* This committee will identify the data needs, information requirements, and industry standards to assist the transportation industry effort to transition from traditional 2D plans to 3D information models. This committee is working on addressing significant gaps to digital delivery for highways, including LOD standards and the IFC standard for roads. PennDOT is currently represented on this committee by a non-voting member.
- *Bridges and Structures Subcommittee on Software and Technology:* This committee led the creation of a Transportation Pooled Fund study for BIM for Bridges and Structures. The committee is currently involved in advancing the IFC standard for bridges and structures and in solving the digital delivery challenges for bridges. PennDOT is currently not represented on this subcommittee, but is a member of the related Transportation Pooled Fund study.

Transportation Research Board Committees

The two most active Transportation Research Board committees working to advance digital delivery are the BIM for Infrastructure subcommittee of the Visualization Committee (AED80) and Construction of Bridges and Structures Committee (AKC40). These two committees organize webinars and workshops on BIM for Infrastructure (the latter focused specifically on bridges and structures) and the subcommittee holds quarterly meetings and drafts research needs and synthesis statements. PennDOT is not represented on either committee.

Highway Engineering Exchange Program

The Highway Engineering Exchange Program holds an annual conference that caters to DOT personnel involved in programmatically implementing digital delivery within their agencies. The organization is divided into five regions; PennDOT is in Area 1 (northeast) and is represented by the chair of the regional group. PennDOT hosted the annual conference in 2015. The next annual conference will be September 2021 in Hartford, CT.

Neighboring States and Regional Agencies

Regional cooperation on policy frameworks can accelerate the rate at which competencies scale across industry. While business systems will be closely tailored to each agency's unique needs, regional cooperation on technology requirements (that do not limit competition) can accelerate the rate at which industry adopts new technologies. For example, if regional states have common requirements for inspection technology that multiple vendors can serve, industry partners do not need to procure different solutions for each state. Further, if regional agencies (e.g. PennDOT and the Pennsylvania Turnpike, large city agencies, and neighboring states) have a common requirements framework, then skills developed from one owner's project transfer to PennDOT projects, accelerating the rate of regional workforce development and industry's capacity to adopt digital delivery. Examples include the bid package deliverables, signing and sealing, construction inspection procedures, as-built requirements, and 3D modeling workflows.

Secondary and Tertiary Education

PennDOT's near-future workforce is currently in secondary and tertiary education. These institutions need to prepare future PennDOT employees for digital delivery. While the so-called "digital native" generation brings many digital skills to the workforce, they also bring expectations for usability and an affinity for crowdsourced information. It is important that the secondary and tertiary education institutions address the critical skill gap for construction surveying and prepare students for the digital delivery workforce, including an appreciation for data governance and security, the foundations of parametric 3D design and geospatial data.

CONCLUSION

PennDOT is well placed to advance its Digital Delivery Directive 2025. This report has provided insights on the enabling policy, technology, and workforce development needs for a comprehensive digital delivery solution. Chapter 4 and Chapter 5 provide examples of lead state DOTs that can provide insights to PennDOT as it develops its own digital delivery solution. The implementation strategies in this chapter have provided additional insights on strategies, actions, and partnerships for PennDOT to accelerate its development of digital delivery and scale the digital delivery competencies across industry.

7: REFERENCES

AASHTO, 2019. *Adoption of Industry Foundation Classes (IFC) Schema as the Standard Data Schema for the Exchange of Electronic Engineering Data*, Washington, DC: American Association of State Highway and Transportation Officials.

American Society of Civil Engineers, 2002. *Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data (38-02)*, Reston, VA: American Society of Civil Engineers.

Atkins, 2012. *High-Definition Surveying*, s.l.: Atkins Global.

Bell, P., 2018. *Civil Integrated Management and the Use of 3D Data Models for Construction Inspection*, Albany, NY: New York State Department of Transportation.

Bentley Systems and Montana DOT, 2016. *3D Study and Implementation Plan*, Helena, MT: Montana Department of Transportation.

Brenner, J. et al., 2018. *Development of 3D and 4D Bridge Models and Plans*, Lansing: Michigan Department of Transportation.

Causseaux, J., 2019. *Florida DOT Implementation of Data Governance*, Tallahassee, FL: Florida Department of Transporattion.

Clevenger, C., Ozbek, M., Mahmoud, H. & Fanning, B., 2014. *Impacts and Benefits of Implementing Building Information Modeling on Bridge Infrastructure Projects*, Fargo, ND: Mountain-Plains Consortium.

Crawley, B., Squire, J. & Farr, C., 2015. *Peer Exchange on e-Construction: Oregon and Michigan Departments of Transportation*, Washington, DC: Federal Highway Administration.

Crudele, B., 2019. *Model Based Contracting at NYSDOT*, Albany, NY: New York State Department of Transportation.

Danforth, V., 2016. *QC the Model: 3D Modeling Tips for Deliverables*, Tallahassee, FL: Florida Department of Transportation.

FHWA, 2013a. *3D Engineered Models for Construction*, Washington, DC: Federal Highway Administration.

FHWA, 2013b. *Automated Machine Guidance with Use of 3D Models - Techbrief*, Washington, DC: Federal Highway Administration.

FHWA, 2016a. *As-Built Utility Surveys: A Tale of Two State Transportation Departments*, Washington, DC: Federal Highway Administration.

FHWA, 2016b. *Geospatial 3D As-Found Surveys: A Key Component of Utah's Integrated Asset Management Program,* Washington, DC: Federal Highway Administration.

FHWA, 2016c. *The Oregon Coordinate Reference System: A Surveying Approach for Supporting Geospatial-Based Technologies in Transportation Applications,* Washington, DC: Federal Highway Administration.

FHWA, 2017a. *3D Engineered Models for Bridges and Structures,* Washington, DC: Federal Highway Administration.

FHWA, 2017b. *Determining the Return on Investment for Using 3D Engineered Models in Highway Construction,* Washington, DC: Federal Highway Administration.

FHWA, 2017c. *Optimizing Survey Data for 3D Design,* Washington, DC: Federal Highway Administration.

FHWA, 2017d. *Using 3D Engineered Models for Construction Engineering and Inspection,* Washington, DC: Federal Highway Administration.

Florida DOT, 2018. *Roadway Design and 3D Modeling,* Tallahassee, FL: Florida Departmenet of Transportation.

Fuller, M. D. & Pangallo, A., 2019. *INDOT Intelligent Design and Construction,* Indianapolis, IN: Indiana Department of Transportation.

Georgia DOT, 2018. *3D Modeling Best Practices & FAQ,* Atlanta, GA: Georgia Department of Transportation.

Guo, F., Turkan, Y., Jahren, C. T. & Jeong, D., 2014. *Civil information modeling adoption by Iowa and Missouri DOT,* s.l.: International Conference on Computing in Civil and Building Engineering.

Krot, E., 2018. *PennDOT Uses Photogrammetry to Measure Up.* [Online]
Available at: https://www.penndot.gov/PennDOTWay/Pages/Article.aspx?post=151
[Accessed 4 September 2020].

Lukes, G. & McDowell, J., 2017. *Intelligent Design and Construction Guidance Document,* Salt Lake City, UT: Utah Department of Transportation.

Maier, F. et al., 2017a. *Utilizing 3D Digital Design Data in Highway Construction - Case Studies,* Washington, DC: Federal Highway Administration.

Maier, F. et al., 2017b. *Automation in Highway Construction Part II: Design Guidance and Guide Specification Manual,* Washington, DC: Federal Highway Administration.

McAuley, G. W., 2013. *Three Dimensional (3D) Computer Aided Drafting and Design (CADD) Models,* Harrisburg, PA: Pennsylvania Department of Transportation.

McDaniel, R. E. & Wheeler, T., 2014. *Construction Inspection with Stakeless Technology 3D Modeling Technology QA/QC using Rovers,* Sterling, VA: Federal Highway Administration.

Minnesota DOT, 2017. *As-Built Special Provision 2011.601,* St. Paul, MN: Minnesota Department of Transportation.

Mitchell, A., 2014. *Challenges Delivering 3D Data to Construction at a DOT - Webinar.* s.l., Federal Highway Administration.

Mitchell, A. et al., 2019. *3D Highway Design Model Cost Benefit Analysis,* Lansing, MI: Michigan Department of Transportation.

New York State Department of Transportation, 2017. *NYSDOT Bridge Manual,* Albany, NY: New York State Department of Transportation.

O'Brien, W. et al., 2016. *Civil Integrated Management (CIM) for Departments of Transportation, Volume 2: Research Report*, Washington, DC: National Academies of Science, Engineering, and Medicine.

Ohio DOT, 2015. *Special Provision for 3D/4D Modeling for CRS: FRA-71-5.29 PID 84868,* Columbus, OH: Ohio Department of Transportation.

Ohio DOT, 2018. *Guidelines for Electronic Design Deliverables,* Columbus, OH: Ohio Department of Transportation.

Oregon DOT, 2015. *2012 ODOT Highway Design Manual*, Salem, OR: Oregon Department of Transportation.

PennDOT Bureau of Project Delivery, 2016. *Design Manual, Part 3 Plans Presentation March 2015 Edition Change No. 1,* Harrisburg, PA: Pennsylvania Department of Transportation.

PennDOT Bureau of Project Delivery, 2018. *Design Manual Part 1X Appendices to Design Manuals 1, 1A, 1B, and 1C November 2015 Edition, Change No. 1,* Harrisburg, PA: Pennsylvania Department of Transportation.

PennDOT, n.d.. *BIM Virtual Meeting Summary.* s.l., Pennsylvania Department of Transportation: SharePoint.

Proctor Jr. , M., 2017. *3D Design Implementation.* s.l., Texas Department of Transportation.

Reeder, G. D. & Nelson, G. A., 2015a. *Implementation Manual—3D Engineered Models for Highway Construction: The Iowa Experience,* Ames, IA: Iowa Department of Transportation.

Reeder, G. D. & Nelson, G. A., 2015b. *3D Engineered Models for Highway Construction: The Iowa Experience,* Ames, IA: Iowa State University and National Concrete Paving Technology Center.

Reihart, D., 2016. *3-Dimensional Modeling at PennDOT.* s.l., Pennsylvania Department of Transportation.

Sankaran, B. & O'Brien, W. J., 2015. *Establishing the Level Of Development (LOD) Requirements for Modeling in Highway Infrastructure Projects.* Tokyo, Japan, Osaka University.

Schneider, C. & Weisner, K., 2017. *e-Construction Peer-to-Peer Exchange: PennDOT and AlDOT.* s.l., Federal Highway Administration.

Sillars, D. et al., 2018. *Advanced Technology: Return on Investment at the Oregon Department of Transportation,* Salem, OR: Oregon Department of Transportation.

Singh, R., 2008. *Engineering Automation: Key Concepts for a 25 Year Time Horizon.* [Online] Available at: http://www.oregon.gov/ODOT/HWY/GEOMETRONICS/docs/engautokeyconcepts.pdf

Turkan, Y. & Shane, J., 2016. *Modernizing Road Construction Plans and Documentation*, St. Paul, MN: Construction Management and Technology Program and Minnesota DOT Local Road Research Board.

Utah DOT, 2019. *UDOT Digital Delivery.* [Online]
Available at: https://digitaldelivery.udot.utah.gov/
[Accessed 5 September 2020].

Virginia DOT, 2018. *VDOT CADD Manual: Electronic Deliverables,* Richmond, VA: Virginia Department of Transportation.

Vonderohe, A., 2013. *3D Technologies Implementation Plan,* Madison, WI: Wisconsin Department of Transportation.

Wisconsin DOT, n.d. *3D Design in WisDOT Projects.* [Online]
Available at: https://wisconsindot.gov/Pages/doing-bus/eng-consultants/cnslt-rsrces/tools/civil3d/3dprojects.aspx
[Accessed 4 September 2020].

Yen, K. S., Ravani, B. & Lasky, T. A., 2011. *LiDAR for Data Efficiency,* Olympia, WA: Washington State Department of Transporrtation.

Zogg, J., 2013. *3D Technologies Implementation Plan,* Madison, WI: Wisconsin Department of Transportation.