IOWA DOT

June 2015

IMPLEMENTATION MANUAL

3D ENGINEERED MODELS FOR HIGHWAY CONSTRUCTION: THE IOWA EXPERIENCE

IOWA STATE UNIVERSITY
Institute for Transportation

National Concrete Pavement
Technology Center
CP Tech Center

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16. Abstract

3D engineered modeling is a relatively new and developing technology that can provide numerous benefits to owners, engineers, contractors, and the general public. This manual is for highway agencies that are considering or are in the process of switching from 2D plan sets to 3D engineered models in their highway construction projects. It will discuss some of the benefits, applications, limitations, and implementation considerations for 3D engineered models used for survey, design, and construction. Note that is not intended to cover all eventualities in all states regarding the deployment of 3D engineered models for highway construction. Rather, it describes how one state—Iowa—uses 3D engineered models for construction of highway projects, from planning and surveying through design and construction.

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About This Manual

This manual is a product of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University. It describes how the state of Iowa uses 3D engineered models for construction of highway projects, from planning and surveying through design and construction. This manual is not intended to cover all eventualities regarding the deployment of 3D engineered models for highway construction. Rather, it describes one state's—Iowa's—approach.

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Mission

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, technology transfer, and technology implementation.

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Table of Contents

Chapter 1: Introduction

Chapter 2: Surveying and 3D Engineered Models

Chapter 3: Designing With 3D Engineered Models

Chapter 4: Application of 3D Engineered Models in Highway Construction

Figures & Tables

Definitions of Important Terms

3D Model

A 3D model is a digital graphical representation of proposed facility/site data consisting of X, Y, and Z coordinates for producing objects in three dimensions to communicate design intent useful for visualization, analysis, animation, simulation, plans, specifications, estimates production, and life-cycle asset management. An accurately designed 3D model will be tied to a defined coordinate system.

4D Model

A 4D model is a digital graphical representation of facility/site data producing object(s) in three dimensions incorporating temporal sequences (e.g., construction activities schedule) and/or temporal dynamic objects (e.g., moving vehicles or pedestrians) progressing over time.

5D Model

A 5D model produces object(s) in three dimensions that incorporate not only temporal sequences progressing over time (schedule), but also costs (budget/cost expenditures).

xD Model

An xD model refers to the concept that new and different aspects of project information can be integrated into the 3D engineered model. Like its cousin, the geographic information system (GIS), the model has significant potential to be used in cross-platform applications.

Automated Machine Guidance (AMG)

Automated machine guidance is a process in which construction equipment is linked directly to the operation of machinery with a high level of precision, improving the speed and accuracy of construction processes. The AMG can utilize the GPS or robotic total stations for positioning information.

Cartesian Coordinate System

The Cartesian coordinate system, often referred to as X, Y, Z coordinates, is a coordinate system that specifies each point uniquely in a three-dimensional space by a set of three numerical coordinates, which are the signed distances from the point of intersection of three mutually perpendicular planes, measured in the same unit of length. Each reference line is called a coordinate axis or just axis of the system, and the point where they meet is its origin, usually at (0, 0, 0).

Civil Integrated Management (CIM)

Civil integrated management is the "collection, organization and managed accessibility to accurate data and information related to a highway facility including planning, environmental, surveying, design and construction, maintenance, asset management, and risk assessment" (Federal Highway Administration, American Association of State Highway and Transportation Officials, American Road and Transportation Builders Association, and Associated General Contractors).

Clash Detection

Clash detection is the process of identifying whether or not two or more objects occupy the same three-dimensional space. The process is also used to determine if objects, such as sewer and water lines, have enough separation to meet code requirements.

Digital Terrain Model (DTM)

A DTM is a digital topographic model of the earth's surface minus objects such as trees, vegetation, and structures that can be manipulated through computer-aided design programs. All elements of the DTM are spatially related to one another in three dimensions.

Global Navigation Satellite System (GNSS)

The GNSS is a network of satellites that provide signals to ground receivers, which may use triangulation to calculate global position.

Global Positioning System (GPS)

The GPS is a subset of GNSS and refers to a specific network of satellites maintained by the United States government. The term "GPS" is also used colloquially to refer to the broader GNSS. The GPS uses a base station unit, a rover unit, and satellites to accurately locate objects using triangulation.

Light Detection and Ranging (LiDAR)

Light detection and ranging is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to an object or earth. LiDAR data can be obtained via ground-based equipment or from airborne equipment such as airplanes, helicopters, or unmanned aerial vehicles.

Point Cloud

Point cloud is the collective term for the millions of data points recorded through the use of laser scanning or LiDAR data collection. The points are defined by a three-dimensional coordinate system.

Surface

A surface, in the context of 3D engineered models, represents an element of design such as existing ground, final grading, or pavement in three-dimensional workspace. All elements of the surface are spatially oriented to one another.

CHAPTER 1: INTRODUCTION

3D engineered modeling is a relatively new and developing technology that can provide numerous benefits to owners, engineers, contractors, and the general public. This manual is for highway agencies that are considering or are in the process of switching from 2D plan sets to 3D engineered models in their highway construction projects. It discusses some of the benefits, applications, limitations, and implementation considerations for 3D engineered models used for survey, design, and construction.

Some of the key points that are highlighted throughout this manual include the following:

- Improved construction documents and communication between the owner, consultant, and contractor.
- Enhanced processes for stakeholder buy-in on projects.
- Enhanced identification and resolution of possible conflicts, issues, and errors before construction.
- Better ability to visualize subsurface features, thereby reducing the risk of utility conflicts.
- Optimized material usage and potentially reduced costs due to greater accuracy of construction.
- Greater productivity and flexibility in the construction process, which leads to lower construction costs and faster schedules.

What Are 3D Engineered Models?

A 3D engineered model is defined as a digital graphical representation of proposed facility and site data consisting of X, Y, and Z coordinates for producing objects in three dimensions to communicate design intent useful for visualization, analysis, animation, simulations, plans, specifications, production estimates, and life-cycle asset management.

The graphic on the following page (Figure 1-1) shows the different elements that make up a 3D engineered model. A complete 3D engineered model includes the base survey data, proposed horizontal and vertical alignments, and proposed features and structures model. The graphic depicts the Interstate 35 and Iowa 92 (I-35 and IA92) interchange project in rural Iowa, which is referenced numerous times throughout this manual.

All of the objects in a 3D engineered model are spatially related in the assigned coordinate system. Because the objects are spatially related, the 3D engineered model can be viewed from various perspectives, such as isometric and elevation views, to assist the designer with visualizing the data. This allows the designer to more easily identify design and constructability concerns prior to the design reaching the field.

When discussing 3D methods, it is important to understand the difference between 3D engineered models and 3D visualization models. 3D engineered models are the product of extensive survey, design, and coordination to develop a computerized model that accurately communicates the existing site conditions and the intent of the designer. The 3D engineered model can be used by the contractor to construct a project with increased accuracy in a short time frame.

On the other hand, a 3D visualization model is more closely associated with presentations and information provided to the public via websites and public information meetings. Figures 1-2 and 1-3 are examples of 3D visualization models created for a nontechnical audience.

3D visualization models convey aesthetics by illustrating how the roadway and bridge design will look for a nontechnical audience, and they generally lack the accurate survey data needed to properly construct the project.

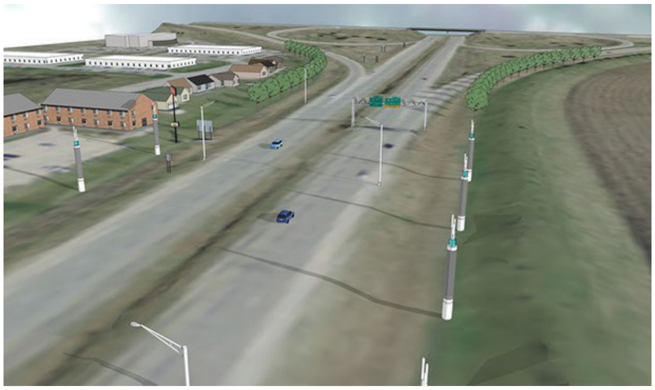


Figure 1-2. 3D Visualization model for presentation purposes.

Figure 1-3. A different view of the same 3D visualization model shown in Figure 1-2.

ELEMENTS of a 3D ENGINEERED MODEL

SURFACE MODEL

The surface model can be the complete grading and pavement surface of the proposed project. Multiple proposed surfaces can be created that are useful to downstream users such as proposed top of pavement, top of subgrade, top of subbase, topsoil strip and respread layers, or any other surface that may be useful for the design or construction of a project. Data from the surface model can be exported to various file formats for use by automated machine guidance equipment for grading and paving operations.

PROPOSED UTILITIES/STRUCTURES

The proposed utilities and structures model can contain structures such as bridges, box culverts, retaining walls, and utility intakes or proposed utilities such as storm sewer, sanitary sewer, water main, fiber optic lines, utility poles, traffic signals, street lights; really anything that may be incorporated into a project. Proposed structures and utilities will be designed in relation to the proposed roadway alignment. When existing and proposed utilities and structures are accurately modeled, designers are able to analyze conflicts or constructability issues that may cause delays during the construction process.

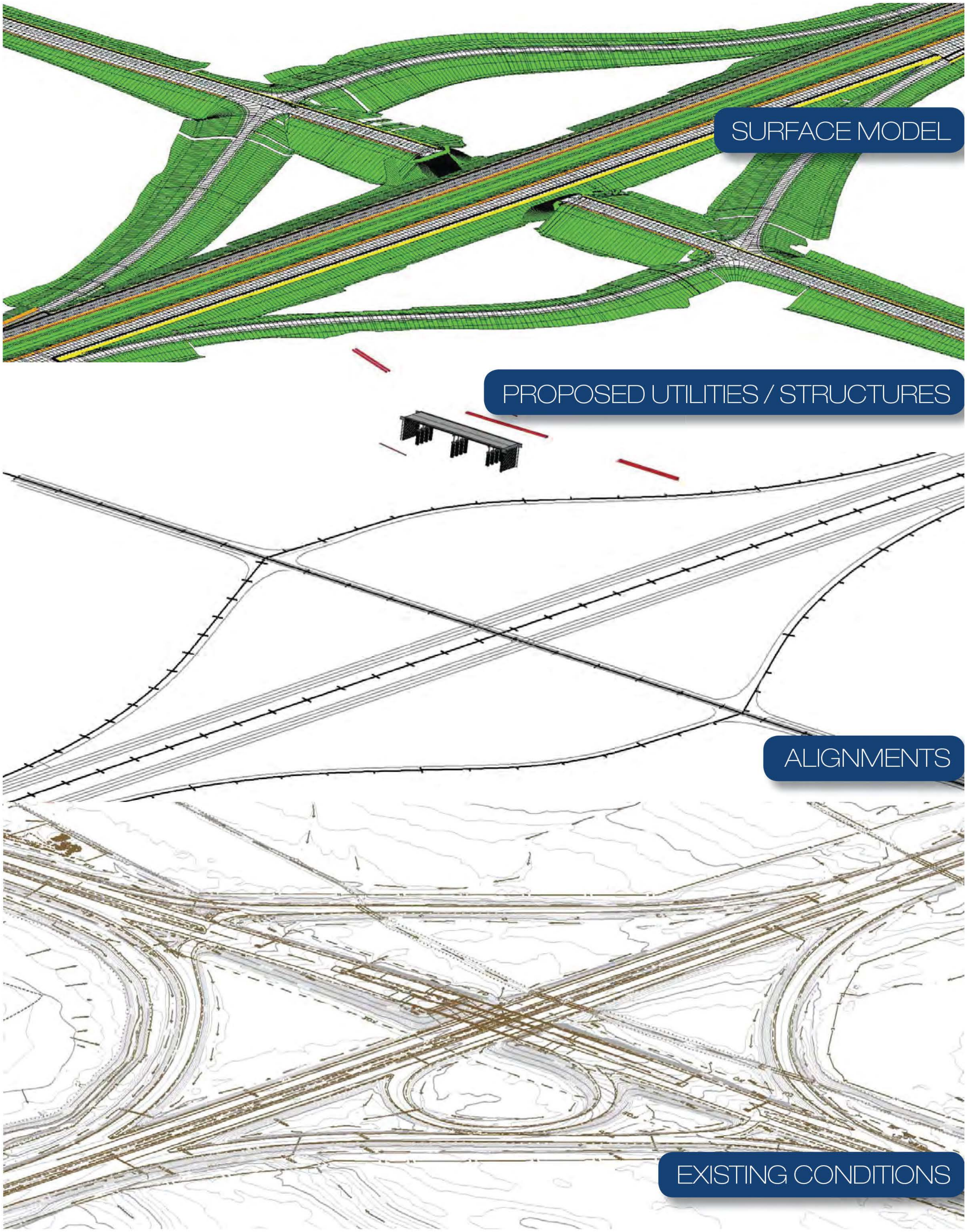
ALIGNMENTS

The horizontal alignment and vertical profile of a roadway is the backbone of any roadway project. The horizontal and vertical alignment of a roadway will be designed to meet agency established design criteria very similar to the way roadways have been designed prior to the advent of 3D methods. Roadway alignments are often determined by the existing topography of an area and therefore rely heavily on the existing conditions model. The horizontal and vertical alignments are vital to the design of the proposed 3D engineered model and can be used by automated machine guidance systems in the construction of the project.

EXISTING CONDITIONS

The existing conditions model is a comprehensive 3D model of the existing site that contains information that is useful to the design team. The existing conditions model can contain topographic survey data obtained by total stations or global positioning systems, point clouds obtained by mobile or terrestrial LiDAR, digital terrain models of the surface or subsurface soils layers, or subsurface utility data that can be used as a base map for the accurate design of a project.

Figure 1-1. Elements of a 3D engineered model.


SURFACE MODEL
PROPOSED UTILITIES / STRUCTURES
ALIGNMENTS
EXISTING CONDITIONS

Organization of This Manual

This manual discusses how the use of 3D engineered models affects all stages of a roadway construction project, from surveying and utility locations to project design to construction.

Chapter 2 covers how 3D technology is being employed in obtaining survey data more quickly and efficiently than ever before. Items and applications such as global positioning systems (GPSs), total stations, digital levels, and light detection and ranging (LiDAR) are discussed. New 3D technology can produce large amounts of survey data in less time. This manual covers how software has the capability to process and manipulate large amounts of data into accurate and detailed models of existing site conditions.

In addition to increased efficiencies achieved through new survey technologies, more accurate underground utility location data can also be obtained. New developments in subsurface utility engineering, or SUE for short, have improved the information of subsurface utility features for 3D engineered models. Chapter 2 also shows how SUE information can be utilized in the 3D engineered model to improve safety and reduce the potential for costly contract modifications.

Chapter 3 describes the creation of 3D engineered models by the design team. 3D engineered models created by the design team provide the ability of the layperson to visualize the plans in a three-dimensional space. This removes a large obstacle to communication that has been common with traditional 2D plan sets. Additionally, they allow trained engineering professionals to eliminate spot or point errors and to analyze what is often quite complex multidimensional data. Chapter 3 discusses how the use of 3D engineered models can improve the accuracy of the finished product prior to construction. The discussion includes the features and benefits of modeling in 3D such as the following:

- Improved accuracy of design surfaces.
- Site grading challenges.
- Staging and constructability issues.
- Virtual drive-through and flyover.
- Parametric modeling.
- Inclement weather analysis.
- Traffic analysis.
- Clash detection.
- Improved earthwork calculations.

Chapter 4 covers 3D technology in highway construction. Along with the benefits of 3D engineered models in the phases of survey and design, numerous benefits can be achieved during construction. Perhaps the most important benefit of 3D technology is the improved safety of workers on the construction site. By reducing the need for stringline and grade stakes, workers are spending less time traversing the site while in close proximity to large equipment.

Construction operations can also benefit by reducing the field-to-finish time of a project by utilizing 3D engineered models. Typical construction schedules consist of tight deadlines and expensive penalties if construction is not completed in the time allotted. The use of 3D engineered models can optimize construction schedules by giving contractors the ability to visualize various stages of the construction process and better utilize existing conditions to get the most out of the design.

Additional benefits covered in this manual that are provided by 3D engineered models during construction include the following:

- Increased quality control.
- Less risk of schedule and cost overruns by analyzing staging and constructability concerns prior to breaking ground.
- Optimizing the use of construction materials and providing more accurate quantity calculations.

Lessons Learned in Iowa

This manual also discusses design and implementation considerations that agencies should address when implementing the use of 3D engineered modeling. The discussion includes lessons that have been learned by the Iowa Department of Transportation (Iowa DOT) in its mission for full implementation of 3D technology into the design and construction phase of highway infrastructure projects. A list of the implementation lessons that are discussed throughout the manual includes the following:

- Consistent computer-aided design (CAD) standards are essential.
- Files should be provided to all contractors before bid letting.
- The 2D plan set is the contractual design document.
- The contractor is responsible for making sure the 3D electronic files match the 2D plan set.
- Construction tolerance specifications do not get tighter with the use of automated machine guidance (AMG) construction.
- Do not require contractors to use 3D methods for construction; rather provide it as an alternative method to allow contractors to benefit from efficiencies.
- Surveyors are not eliminated; they are repurposed into a quality assurance/quality control (QA/QC) role instead of construction layout.

Downstream Users of 3D Engineered Models

Not only does the use of 3D engineered models provide benefits in the form of increased efficiency and safety, but the benefits reach far beyond the engineering and construction industry. The concept of data streamlining can be achieved by utilizing 3D engineered models. Downstream users can utilize the engineering data within the model instead of having to regenerate their own model from a 2D plan set. Data streamlining creates less preparation for construction oversight personnel and construction surveyors. 3D engineered models can also be utilized by various other downstream users such as the following:

- Owners.
- Regulatory/review agencies.
- Utility companies.
- Interested public/affected property owners.
- Construction surveyors.
- Contractors.
- Facilities managers.
- Project planners at the next cycle of the project.

This is certainly not a comprehensive list of all the potential users of design data, but it is a representative list of downstream users that are found on a typical roadway project. Downstream users vary in technical skill and background, from having no technical background to having a considerable knowledge base and utilizing the design data to construct the end product.

Owners of Transportation Facilities

Owners of transportation facilities such as State DOTs have the ultimate responsibility to the public to provide infrastructure that moves people and goods safely and efficiently while being good stewards of the public funds. Owners can benefit by the use of 3D engineered models by recognizing improved bid prices from contractors. Contractors can view the 3D engineered models prior to submitting bids to more accurately calculate quantities and look at the constructability of all aspects of construction to recognize where efficiencies can be achieved. The additional information that the model provides to the contractor reduces the risk associated with the project, which can lower bid prices.

Owners can also benefit from the standpoint of reducing the risk of contract modifications during construction. 3D engineered models allow the designer to perform clash detection analysis, which recognizes conflicts associated with the design and existing utilities within the corridor. Traditional 2D design methods may not have recognized utility conflicts until construction was well under way, sometimes creating costly and time-consuming contract modifications to rectify the issue.

Regulatory/Review Agencies

Regulatory/review agencies such as Departments of Natural Resources, floodplain managers, the U.S. Army Corps of Engineers, and numerous others can use the information obtained from the 3D engineered model for floodplain, flood analysis, wetland studies, National Environmental Policy Act permits, and other regulatory information. As shown in Figure 1-4, 3D engineered models can be combined with other graphic software to illustrate flood elevations and how flooding may impact property owners. The 3D engineered model can also be used by bridge designers and hydraulic engineers to determine appropriate elevations for bridges and structures to ensure they remain safe under flooding conditions.

Figure 1-4. 3D modeling can be used to demonstrate flood impacts.

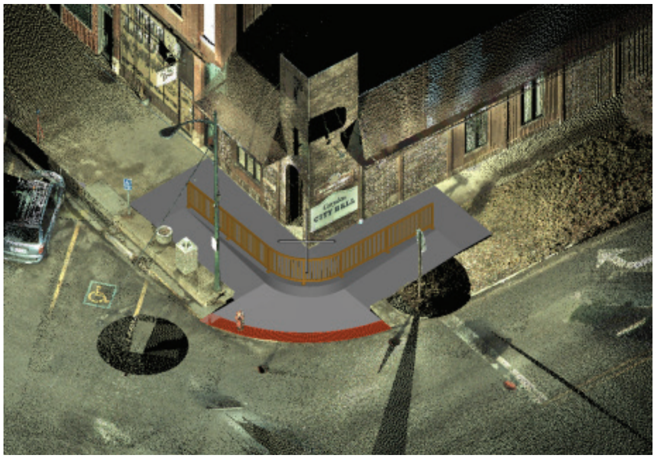
The 3D engineered model has the capability to incorporate wetland studies into the design. For example, designers can delineate potential wetland areas within the corridor and ensure that the design is not impacting the wetland. When the wetland areas are delineated in the 3D engineered model, the contractor also has the ability to make sure that no haul roads or storage areas are placed within the restricted area.

Utility Companies

Utility companies can use the information provided in 3D engineered models to manage their infrastructure through accurate mapping and SUE. Clash detection greatly improves the designer's ability to detect utility conflicts and clashes early, allowing for avoidance or greater time to relocate utilities. This level of accuracy and detail in planning translates to less expense, greater safety to workers and the public, and less delay to the project. Upon project completion, accurate and detailed electronic files can be delivered to the utility operator for inclusion in their geographic information system (GIS) or facilities management database for future use.

General Public/Property Owners

3D engineered models provide a convenient way for the general public and affected property owners to visualize the project prior to construction. Figure 1-5 is an example of how 3D engineered models can be displayed for the general public.



Imageobtained from Iowa Department of Transportation

Figure 1-5. 3D engineered model showing how a pedestrian ramp will impact local businesses.

The existing sidewalk in this graphic was not Americans with Disabilities Act (ADA) compliant, and the city determined this sidewalk needed to be reconstructed with an approved pedestrian ramp. Using traditional 2D methods, it would have been difficult for the designers to illustrate how the intersection would look and function after construction was completed. Prior to seeing this graphic, the public may have had a skewed perception of the project and their initial thoughts may have been negative. However, after the public has a chance to view a graphic of the 3D engineered model that contains known references such as current businesses, traffic signals, street lights, and pavement markings, they may become more comfortable with the proposed improvements.

The following chapters provide an in-depth look at how to implement 3D engineered models in a way that benefits all interested parties.

CHAPTER 2: SURVEYING AND 3D ENGINEERED MODELS

During the survey stage of a project, data are collected using a variety of technologies, filtered and processed, then combined into one comprehensive 3D model that is passed on to the design team. The design team uses the survey information to build the 3D engineered model.

Advances in Survey Equipment and Technologies

Early surveyors relied on survey equipment like that in Figure 2-1, which included rods, chains, staffs, transit levels, compasses, plump bobs, and theodolites. George Washington began work as a surveyor using this equipment in 1748. The technologies have evolved, but the basic principles of surveying are still practiced using newer versions of the same equipment.

Today's surveyors utilize sophisticated equipment such as robotic total stations, high-accuracy GPSs, digital levels, and laser scanners. To understand how 3D engineered models can incorporate the use of new survey technology, it is important to understand the capabilities of each piece of equipment, how it works, and the kind of data it collects.

Terrestrial Mapping Survey Equipment and Technologies

Terrestrial mapping survey equipment includes GPS, digital levels, LiDAR, and total stations. Global positioning systems, digital levels, and total stations are referred to as traditional survey methods throughout this manual. Global positioning systems, LiDAR, and total stations use different technology to measure distance and angles to determine the horizontal and vertical location of existing features to place in a 3D engineered model. Digital levels obtain very accurate vertical information but do not measure horizontal position.

GPS

The power of much of today's survey technology can be attributed to the development of GPSs. The global navigation satellite system (GNSS) is a network of satellites that provides signals to ground receivers, which may use triangulation to calculate global position. The GPS uses a subset of GNSS and refers to a specific network of satellites maintained by the United States government. The United States Department of Defense first began using satellite systems with timing and ranging in the late 1970s. The term "GPS" is also used colloquially to refer to the broader GNSS. Figure 2-2 shows a GNSS receiver unit.

Global positioning systems provide surveyors with many advantages. Before the invention of the GPS, surveyors had to traverse great distances to establish control points and survey baselines. Survey crews often consisted of two or three members to accomplish these tasks. Now, surveyors are able to get GPS satellite corrections at the push of a button and can survey in a fraction of the time. Many crews now are run by a single surveyor doing the work of several people through the use of high-tech equipment.

Understanding how GPS works and its limitations is extremely important. For example, the coordinate quality is affected by the atmospheric conditions, the length of the baseline, the geometric configuration of the available satellites, and other factors.

Figure 2-1. Historical surveying equipment.

Photo obtained from Trimble Navigation Limited

Figure 2-2. GNSS receiver used for surveying.

A GPS uses the following three components:

- A base station unit.
- A rover unit.
- An open view of the sky to receive a satellite correction.

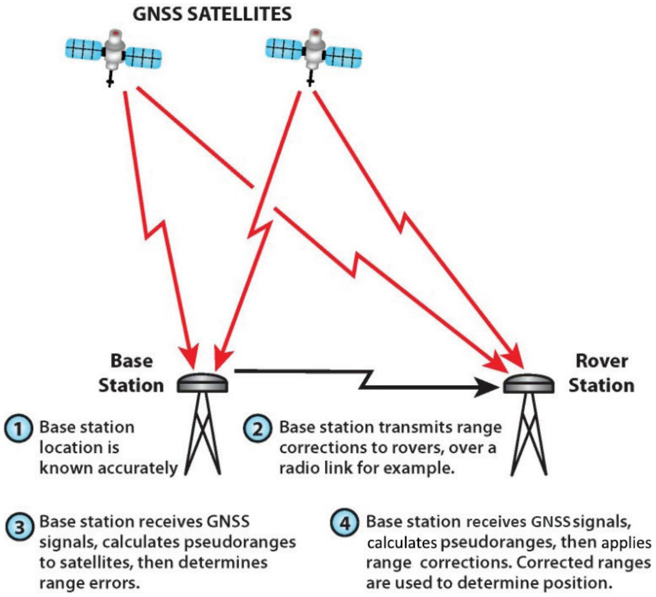
The base station is set up on a known point, commonly referred to as a control point, where the exact location and elevation is known. The base station then transmits data to the rover, where the rover uses its distance and elevation offset from the control point to determine its exact X, Y, and Z coordinates. The rover is the third point for an accurate triangulation. The base station and the rover unit communicate back and forth via a radio link, and thus the user is limited to a range of a few miles with good conditions. Figure 2-3 is a graphic that shows how a GPS rover unit uses a base station for triangulation.

Survey Control Network

The importance of accurate survey control cannot be overstated, especially when using 3D methods. The topo-graphic survey that is obtained on the existing conditions must be correctly linked to the survey control for an accu-rate 3D engineered model. In states with numerous base stations, accurate survey control is not as much of a factor. Some states, however, struggle with obtaining an accurate survey. In states where survey control is inaccurate, 3D models can be off vertically by several inches. This creates issues when calculating earthwork quantities and when tying into existing surfaces. Agencies need to establish accurate survey control prior to implementing the use of 3D engineered models.

Recently, many State governments have begun to set up networks of continuously operating reference stations (CORS), which are permanent base stations to facilitate real-time kinematic (RTK) surveying. The State of Iowa, for example, has developed the Iowa Real Time Network, or IaRTN. These base station networks allow the user to connect remotely via the use of a cell phone modem to the nearest base station to receive range corrections. Some networks like the IaRTN are a free service, but others require users to pay an annual subscription fee to the network operator, as well as a data subscription to a cell phone carrier. The permanent base station network and cell phone modem take the place of a physical base station as well as saving the surveyor the time to set up and take down the base station on each project.

A map of the available base stations located throughout the country is shown in Figure 2-4. The IaRTN base station locations can be seen in Figure 2-5. Figure 2-6 is an example of a permanent base station in the United States.



Graphic adapted from www.blackroc-technology.com

Figure 2-3. How a rover receives signals from the GNSS.

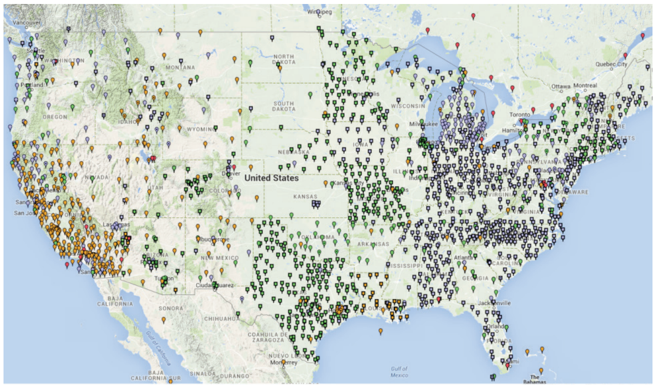


Image obtained from National Geodetic Survey

Figure 2-4. Available GNSS reference stations across the country.

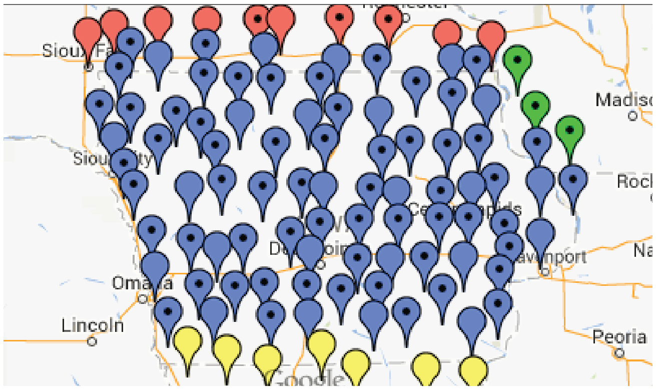


Image obtained from Iowa Department of Transportation

Figure 2-5. The IaRTN base station map. Find permanent base stations in Iowa at www.iowadot.gov/rtn/index.aspx

Total Stations

The modern total station has been instrumental in the improved efficiency of survey crews throughout the nation and the world. The total station, sometimes referred to as a total positioning station (TPS), is one of the most useful pieces of equipment in the surveyor's toolbox. It can measure distances, transfer elevations, stake points, collect topographic data, and much more. In Chapter 4, the use of TPS in AMG control systems in construction equipment is discussed.

Photo obtained from Iowa Department of Transportation

Figure 2-6. Permanent base station.

Essentially, the total station is an electronic theodolite integrated with an electronic distance meter to read distances from the instrument to a particular point. It can take precise horizontal and vertical measurements between the base unit and a prism that is mounted on a portable staff or rod. Modern total stations can be remotely controlled by the surveyor, enabling one-man operation. Modern total station units can be integrated with GPSs. Figure 2-7 shows a modern robotic total station.

Photo obtained from Trimble Navigation Limited

Figure 2-7. Robotic total station used for surveying.

Some manufacturers have incorporated laser scanning capabilities into TPS units. An automated reflectorless mode enables the total station to collect tens or even hundreds of thousands of points in rapid succession. This allows the surveyor to collect even the most intricate details of a particular feature, so much so that the resulting point cloud resembles a photograph of the object. Laser scanning and point clouds are discussed in more detail later in this chapter.

Some total stations have the ability to take photographs as well. When the user selects a particular area to scan, the instrument captures multiple photographs of this same area and stitches them together. As long as there are multiple viewpoints (images) of the same target from at least two different setups of the TPS unit, the user is able to literally pick a point in the photograph and the instrument can calculate a coordinate value and elevation for it.

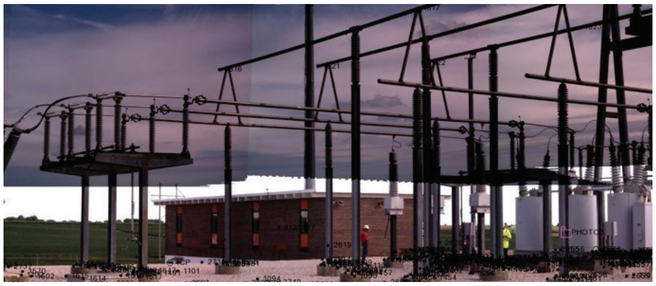


Figure 2-8. A substation survey that was performed using laser scanning technology. The total station captured images and placed the survey points on top of the image.

Figure 2-8 illustrates the image-capturing abilities of a total station. This is a substation survey with the points depicted on top of the images captured. The surveyor took panoramic images from three different locations around the site while performing the survey. The total station's software was able to triangulate positions and elevations on the points shown above from the images taken by the total station. This allows data to be added to the model without the expense of an additional trip to the project site.

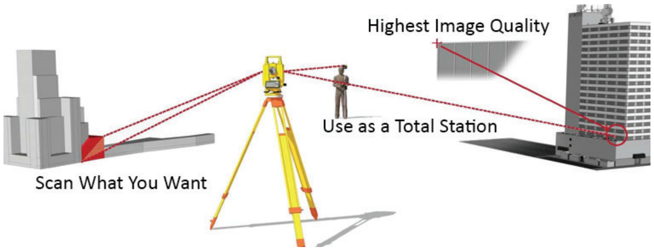


Figure 2-9. Modern total stations can be used to gather data using laser scanning (left), traditional ground shots (center), or ortho corrected images (right).

Figure 2-9 illustrates how a modern total station could be used to gather data in several different ways on a job site. A small scan could be done on an intricate area (left), traditional ground shots could be taken using the remote control (center), and orthocorrected images can be captured to cover other areas for future data extraction (right). All of these items can be performed with a one-person survey crew taking advantage of high-tech equipment.

Digital Levels

Digital levels are another important tool that surveyors can use to obtain topographic information. Modern digital levels (Figure 2-10) allow surveyors to accurately transfer elevations across project sites. Digital levels read a barcode on a level rod, as opposed to the traditional optical method of sighting the rod through a scope. Today's best digital levels are capable of transferring elevations over half a mile using double-run leveling and an invar staff with a vertical accuracy to less than 0.01 ft.

LiDAR

One of the newest forms of technology available to surveyors is the laser scanner. Whereas the equipment itself is known as a scanner, there are actually several types of laser scanning. The scanning data are collected with a technology known as LiDAR. There are three types of LiDAR scanning: terrestrial, mobile, and aerial.

Terrestrial LiDAR

A single scanner mounted on a tripod (Figure 2-11) is used for terrestrial LiDAR or static scanning. The scanner spins 360 degrees from its fixed position and gathers reflectorless measurements at a specific density. The scanner's range depends upon the specific model, but many current scanners can measure 3D position more than 100 ft in any direction with accuracy to within 0.02 ft. These scanners are capable of collecting thousands of points every second.

When it is necessary to have the data in the correct location or project datum, the scanner can be set up in between several known points (control points) that can be easily seen in the point cloud.

Targets are placed over these points to make them easily identifiable in the scan. These targets are typically arrows, spheres, or globes that show up well in the scan (see Figure 2-12). Several scans are required from various angles to accurately scan an object or a particular area and collect information on all sides of an object. The common control points are then used to properly align, or register, the point cloud data to be spatially accurate. Figure 2-13 shows the location of the targets that were used on the I-35 and IA92 project.

Mobile LiDAR

When collecting scan data on a long corridor such as a roadway project, it becomes less cost effective to set up a static terrestrial scanner many times in order to gather all necessary data. Mobile LiDAR was developed for this

Photo obtained from Trimble Navigation Limited

Figure 2-10. Digital level used for transferring elevations across a project site.

Photo obtained from Trimble Navigation Limited

Figure 2-11. Terrestrial scanner.

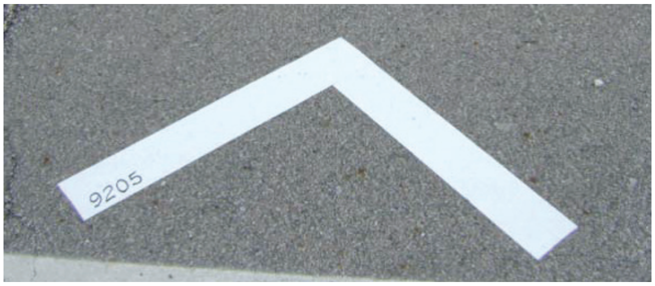


Photo obtained from the Iowa DOT

Figure 2-12. This photo shows a control point target that was used on the I-35 & IA92 interchange project.

Graphic obtained from the Iowa DOT

Figure 2-13. Control point locations on the I-35 and IA92 interchange project. The control points are delineated by triangles on this map.

application. The mobile LiDAR vehicle shown in Figure 2-14, with several laser scanners on board, drives through a corridor and the overlapping scan data from the scanner array collects the data needed while the vehicle and scanner are in motion.

Figure 2-15 is a simple graphic that shows how a typical mobile LiDAR vehicle collects data. Several variables are introduced with this system. Since the scanners are not sitting over a known point, GPS is integrated into the system to gather positional data for the vehicle. In addition, the vehicle is twisting and turning as it drives along. Sensitive inertial measuring units, or IMUs, keep track of the pitch, roll, and yaw of the vehicle while it is in motion. Finally, high-tech computers with sophisticated software take the data received from the scanner(s) and, using the IMU and the GPS sensor information, estimate and adjust the data trajectory and combine it all into a usable point cloud.

Digital cameras are also integrated into the system. The cameras capture images and video of the corridor as the vehicle travels through it. This can be used to create an overlay for the point cloud. The pixels in the images are spatially related to the scan data, so the user can point to a specific point in the photo or video and the software can identify the corresponding point in the point cloud.

The graphic on the left of Figure 2-16 shows the mobile LiDAR data that were collected on the I-35 and IA92 interchange project. The photo on the right of Figure 2-16 shows the mobile LiDAR vehicle at the same location as depicted in the graphic on the left.

Aerial LiDAR

Another useful tool in surveying is aerial LiDAR. It is similar to mobile LiDAR, but the scanners are mounted on an aircraft rather than a truck. Mobile LiDAR units are obviously restricted to areas they can physically drive to, but an aircraft is not subject to those same limitations. The aircraft can fly in overlapping patterns and collect vast amounts of data from the air in a short amount of time. Typically, surveyors set a network of ground control monuments prior to the LiDAR flight. These targets are often large X-shaped targets that can be easily seen from the air. The surveyor obtains precise horizontal and vertical data on each of the targets and supplies those data to the LiDAR crew.

The graphic in Figure 2-17 illustrates how aerial LiDAR data are collected.

After the LiDAR flight, the scan data can be rotated and scaled into correct coordinate space using the targets. This process, known as orthocorrection, creates spatially accurate imagery that can be very useful in project planning. Because the scanner is much further away from the ground than it is

Image obtained from Michael Baker International

Figure 2-14. Mobile LiDAR vehicle used for obtaining survey data.

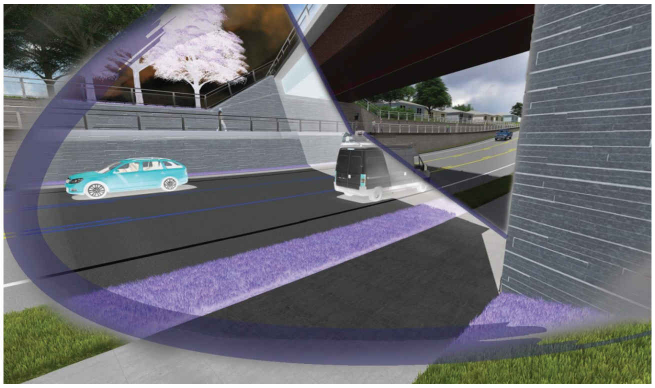


Figure 2-15. Mobile LiDAR vehicles use scanners to collect accurate survey data on pavement surfaces in a short timeframe.

Image obtained from the iowa DOT

Image obtained from the iowa DOT

Figure 2-16. Top: Point cloud data on the I-35 and IA92 interchange as it would appear on a computer screen. Bottom: The same location as depicted in the point cloud.

in terrestrial or mobile LiDAR, the accuracy is diminished. On hard surfaces such as roadways or parking lots, many LiDAR providers can get data accurate within a few tenths of a foot (10 cm), depending upon the altitude of the flight. Ground surfaces with vegetation are less accurate, often showing errors of from 1 ft (30 cm) or more to several feet.

Figure 2-18 shows an overhead viewpoint of how LiDAR data appear to the user in a heavily forested area. In Figure 2-19, the scanner collected many data points on the canopy of the trees, while certain measurements penetrated through to the ground level. Careful filtering of these data can yield a ground surface that is relatively accurate.

These aerial-based LiDAR surfaces provide designers with a quick and easy tool to begin the planning stages of projects. Some states have aerial LiDAR data available for free to download from various public universities. These data are typically broken down into tiles for ease of downloading because of large file sizes containing millions of points.

LiDAR Data

Often, a detailed survey is the only way to obtain sufficiently precise data to design a project. In some cases, a detailed survey can be used for the critical areas, and LiDAR data can be used as a supplement for open areas or additional areas outside of the original project limits.

LiDAR Accuracy

The level of accuracy varies greatly between different types of LiDAR. This variation is due to a large number of factors, including the type of scanner being used, the site conditions, the distance between the object being scanned and the scanner, and other factors.

LiDAR surveys for use in 3D engineered models can require equipment and data acquisition methods with 1A and 1B levels of accuracy. A 1A level of accuracy can be defined as LiDAR data measured at 100 ft or less tightly constrained to ground control targets. A 1B level of accuracy can be defined as LiDAR data measured at 100 ft or less loosely constrained to ground control targets. When 3D modeling is required over larger areas more than 200 to 300 ft in length where correct drainage flow and grade elevation changes are critical, 1A level accuracy is required. When 3D modeling is needed only in a smaller area or at independent intermittent areas on a project, 1B level of accuracy can be sufficient.

Loosely constrained LiDAR can be precise and relatively accurate in a small area, but as the area of the model increases the relative accuracy to other areas in the model decreases. In a tightly constrained model, the precision and relative accuracy are maintained in every area. Loosely constrained LiDAR acquisition cost is about a third of

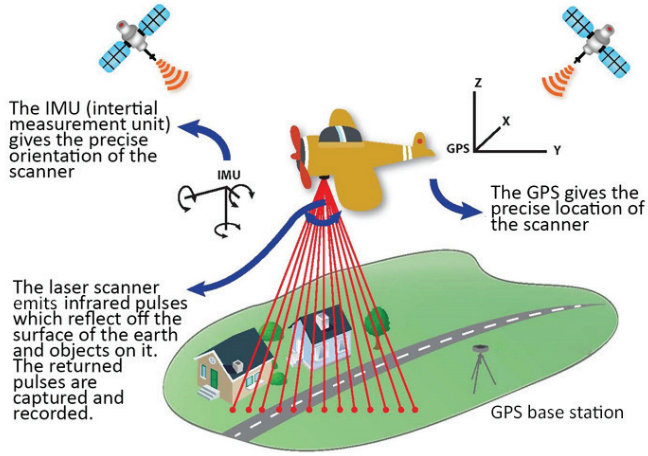


Figure 2-17. Aerial LiDAR uses GPS to determine the exact location of the scanner.

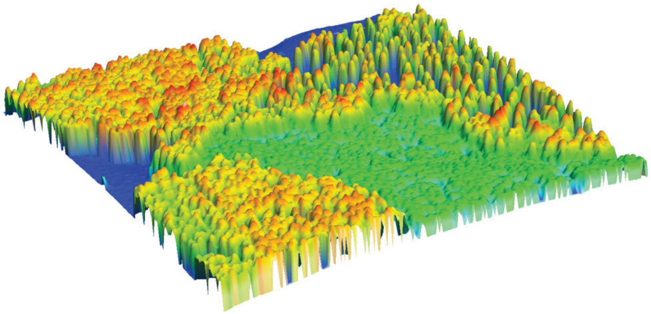


Image obtained from USDA Forest Service

Figure 2-18. A tree canopy that has been surveyed using aerial LiDAR technology.

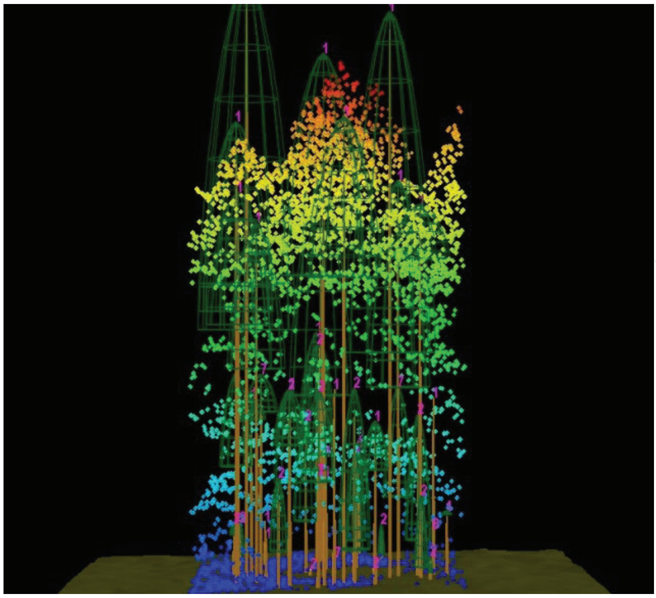


Image obtained from Aleksandra kazakova, Remote Sensing & Biospatial Analysis Laboratory of the Precision Forestry Cooperative

Figure 2-19. Aerial LiDAR is limited by its line of sight. When aerial LiDAR flies over a tree canopy, the user must filter out the points on the vegetation and use only those points that reached the ground surface.

that in which data are tightly constrained because of the control survey and data adjustment cost incurred for tightly constrained LiDAR data.

Data Management

With the use of laser scanning or LiDAR, data management and warehousing become extremely important. The collection of millions of data points for each project can cause electronic file sizes to become very large very quickly. These data, collectively known as a point cloud, allow engineers and designers to grab as little or as much data as they may need from the cloud in order to create their design. There are several software products that aid designers in the manipulation of this point cloud data. These products allow the user to bring in scan data with varying levels of manipulation, registry, filtering, and exploration.

The point cloud on the I-35 and IA92 interchange is shown in Figure 2-20. This point cloud was gathered by mobile LiDAR.

Aerial Photography

Aerial photography can be used as another method for acquiring survey data for which accuracy is needed within a few inches. Aerial photography, also called aerial photogrammetry, utilizes large-format imagery and ground coordinate information to effectively recreate the geometry of a portion of the earth in a virtual environment. In this virtual environment, reliable horizontal and vertical measurements can be made and recorded (or compiled) directly into a geospatial data file.

Accurate measurements can be recorded from aerial photographic images by using traditional methods only when the following conditions are met: (1) stereoscopic image pairs (two or more overlapping photographs) cover the object to be analyzed; (2) accurate X, Y, and Z coordinates are known for at least three defined object points in the overlapping photographs; and (3) a calibrated mapping camera is used to take the photographs.

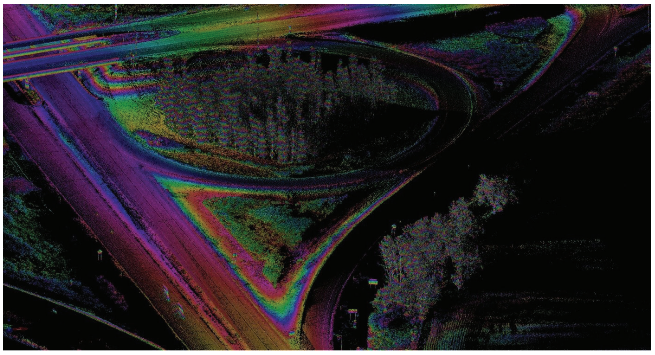


Image obtained from the Iowa DOT

Figure 2-20. Screenshot of point cloud data at the I-35 and IA92 interchange.

The compilation of planimetric features (such as roads and streams) and topographic information (topographic contours) from the photographic sources is accomplished through the use of digital stereoscopic instruments. Digital, or softcopy, photogrammetric workstations require specialized software and hardware for viewing a pair of stereo images. In this virtual environment, an experienced operator can link the images with the ground control to collect precise horizontal and vertical coordinates for a point, line, polygon, or surface. The photogrammetric workstation recreates the geometry of the field subject through a series of mathematical operations. These procedures require a high level of expertise and repetition to maintain the operator's skill.

Subsurface Utility Engineering (SUE)

Subsurface utility engineering is a branch of engineering practice that involves managing certain risks associated with existing subsurface utilities. It involves mapping utilities at appropriate quality levels, coordination with utility companies, design of relocated utilities, utility condition assessment, and implementation of utility accommodation policies. This definition is adapted from the Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data, CI/ASCE 38-02, from the American Society of Civil Engineers published in 2002.

This new ASCE standard did several things for the industry. The first was to put a formal definition to the practice of SUE. Another significant piece of this standard was the definition of quality levels for existing utility information. Because designers obtain their utility information from so many sources, the information has varying degrees of reliability. The standard defined quality levels A, B, C, and D to associate with this information, with QL-A (quality level A) being the highest. These quality levels provide a way for the designer to qualify the level of certainty of the location of the lines shown on the plans.

Subsurface utility engineering provides 3D location data (alignment, elevation, and thickness or diameter) to the 3D model for underground project elements such as pipelines, footings, piers, and structures. With traditional two-dimensional plan sets, utilities were often shown in plan and profile view, oftentimes with different items being shown on separate plan sheets. Being able to verify or detect accurate cover, separation, or even outright clashes between improvements was difficult. The creation of a 3D model defining locations of existing and proposed underground utilities together with proposed surfaces and other underground improvements such as footings or piers gives the designer a much more efficient method of determining the potential for a conflict or clash between existing utilities and proposed improvements. Being able to visualize these improvements in the same three-dimensional space, from different angles and at different stages of construction, reduces the potential to overlook these problems.

Quality Levels for SUE

There are four quality levels for SUE data.

Quality Level D

Quality level D (QL-D) information is typically from maps, old records, or even verbal accounts of existing infrastructure. Its usefulness is limited overall. Quality level D is the most basic level of information for utility locations. It comes solely from existing utility records or verbal recollections, both typically unreliable sources. It is useful primarily for project planning and route selection activities.

Quality Level C

Quality level C (QL-C) information is obtained when a surveyor surveys visible appurtenances on the surface, such as fire hydrants and valves, and then uses a map to connect the dots between these points. The information is accurate for the above-ground features, but it may contain some inconsistencies for the unseen portions. Quality level C is probably the most commonly used level of information. It involves surveying visible utility facilities (e.g., manholes and valve boxes) and correlating this information with existing utility records (QL-D information).

Quality Level B

Quality level B (QL-B) information is achieved via the use of surface geophysics. One such example is the use of a pipe and cable locator. The utility locator hooks a transmitter up to a tracer wire and induces a signal onto the wire. That signal is then traced from the surface and paint or flags are placed on top of the signal. If done well, this can yield quite accurate information about the horizontal location of buried infrastructure. Quality level B involves the application of appropriate surface geophysical methods to determine the existence and horizontal position of virtually all utilities within the project limits. This activity is called “designating.”

Locating vs. Designating

When a utility company has a technician mark the existing utilities in the field with paint or flags, it is called “desig-nating.” A surveyor who records the position of the utility company’s paint marks or flagging is “locating” the utilities for depiction on the plans.

Quality Level A

Quality level A (QL-A) data are typically gathered only at specific points. It adds a third dimension to the QL-B data, and that is the precise elevation of the utility. Most often this is obtained via the use of test holes, or “potholing” as it is sometimes referred to. Once the horizontal location is known, a particular utility can be excavated at the point of a potential conflict to record its elevation. This gives one specific point at which the engineer knows exactly where the utility is located. Some people incorrectly use the idea of digging these test holes as doing SUE, when in fact it is the whole science and methodology of getting to this point that is the main idea behind SUE. Quality level A, also known as “locating,” is the highest level of accuracy presently available and involves the full use of the SUE services.

Shown in Figure 2-21 are condensed versions of the Federal Highway Administration’s definitions of the various utility quality levels. A typical SUE project contains a mix of utility data falling into all four of these categories. As the quality level of information increases, so does the corresponding cost to obtain it.

Quality level A data points are the most expensive to obtain. The benefit of the higher quality level data are weighed at each stage of the project to determine the appropriate level of expenditure to collect data.

Figure 2-22 illustrates the typical correlation of balancing the benefit of gathering the higher-quality data with the cost of collecting the data on existing utilities. In the early stages of a project, utility mapping alone, or QL-D information, is sometimes enough. For example, if an engineer knew nothing more than the fact that the existing infrastructure was all on the west side of a road, that might be enough to know that he should design his new storm sewer to go in on the east side of the road to avoid expensive relocations. As the design advances, more detail is necessary, thus physical marking of utilities in the field is often necessary to further refine the plans.

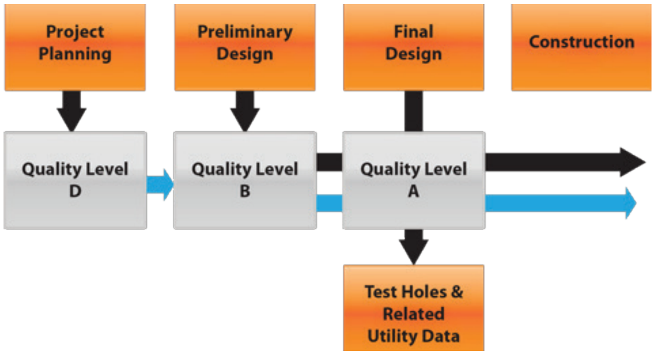


Image adapated from the American Society of Civil Engineers Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data (38-02)

Figure 2-21. Standard guidelines used to describe quality levels for utility locates.

When deciding how much money to spend on SUE, a project owner must consider his overall risk exposure. In cases in which there are not a great deal of utilities in a project corridor, or the ones that are there are easily moved, it does not make sense to invest much money on SUE. But as the complexity and sensitivity of the utilities increases, so does the need for quality, accurate information. Usually, as the cost of the data collection and SUE increases, the owner's risk decreases, and vice versa.

Data Incorporation

If all known utilities are able to be designated using geophysical tools and located using survey-grade equipment, the results could yield a very accurate 3D model, such as the one shown in Figure 2-23. If this level of detail is known about the existing underground infrastructure, the potential for conflicts during construction and redesign is greatly reduced.

Although the model is three dimensional, the plan sheets for the project are shown in a 2D or plan-view environment. Linework is added in computer-aided design and drafting (CADD) that represents the underground utilities. Some information comes from reliable sources like GPS survey shots. Other data, such as mapping received from utility owners, are still valuable to the design team and may be simply drawn in CADD with QL-D attached to the lines. This tells the project designers that, while there is most likely a utility in the vicinity, its location is known with lower confidence in the 3D model. By associating quality levels to all of the data, the designer is able to make more informed decisions and limit risk exposure at the same time.

SUE Data Collection Tools and Equipment

In order to accurately designate underground infrastructure, SUE technicians rely on a vast array of sophisticated equipment. Many firms employ geophysicists who are experts in the technologies and their applications. Some firms even work to develop new technologies for the express purpose of mapping subsurface infrastructure.

Ground-Penetrating Radar

The ground-penetrating radar unit (Figure 2-24) projects radar waves into the ground, which are blocked by existing utilities or other buried obstructions. These blockages are depicted on the display as parabolic waves at varying depths. The operator deploys the unit in a grid pattern over the site, and postprocessing software is able to trace the blockages or utilities in a linear fashion and depict them on a map. By adhering to a spatial grid or using surveying equipment to track the instrument's position, the utility lines are able to be plotted accurately in a design file.

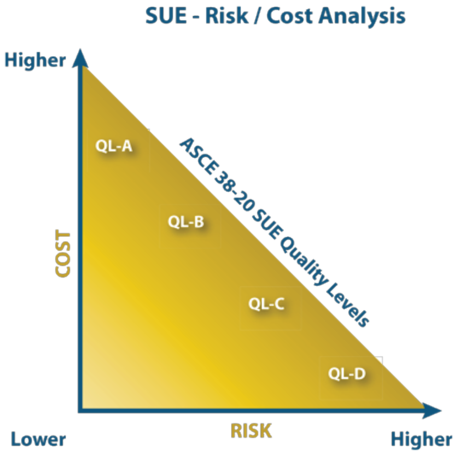


Image obtained from the American Society of Civil Engineers Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data (38-02)

Figure 2-22. SUE-risk/cost analysis. Although the cost increases with higher quality levels of subsurface utility engineering, risk is greatly reduced.

Image obtained from Bentley Systems, Inc.

Figure 2-23. A 3D representation of subsurface utilities in an urban setting.

Photo obtained from Utility Mapping Services, Inc.

Figure 2-24. Walk-behind ground penetrating radar system.

Electromagnetic Equipment

Electromagnetic equipment works in a similar fashion to ground-penetrating radar. It projects a signal into the ground and senses a return signal from another metallic object, typically a buried utility.

Other examples of equipment include pipe and cable locators, thermal and acoustic sensing equipment, magnetic locators, cameras, sondes, and more.

Air and Hydro Excavation

After the design is substantially completed, it may be determined that a number of QL-A data points, or test holes, are required to resolve potential conflicts between existing infrastructure and proposed improvements. This requires more equipment in the form of air- or hydro-excavation tools (Figure 2-25). These tools are usually seen mounted to a truck for the purpose of excavating utilities. Both types use a pressurized media, either air or water, to safely expose utilities. They have an onboard compressor and a corresponding vacuum to remove the loosened soil from the hole. Either method provides a nonintrusive way to expose sensitive utility lines and gather the necessary information without damaging the lines.

Image obtained from Utility Mapping Services, Inc.

Figure 2-25. Hydro excavation operation to locate underground utilities.

Benefits of SUE

Safety

The most important benefit of SUE is increased safety. Encountering an unforeseen gas main or electrical line in an excavation can be very hazardous not only for citizens who live near a construction project, but also for workers who are working on the project. It is very important for designers and contractors to understand and communicate not only the existence, but also the best information on location of all utilities, especially very hazardous utilities.

Design Applications

Subsurface utility engineering has useful applications in modeling the subsurface improvements in critical or very complex situations. Congested corridors, potentially hazardous utility lines, or utilities that are vital to the health and safety of a community may require the use of more complex modeling systems over traditional plan and profile methods.

Examples include the following:

- Utilities to critical facilities, such as hospitals.
- Potentially hazardous utilities such as high-pressure gas mains or major electrical lines.
- Facilities that are difficult or expensive to relocate such as fiber-optic duct banks.
- Areas with abandoned or buried structures.
- Factories, industrial plants, and hospital facilities with private utility lines.

Savings

The potential project savings are numerous as well. These savings can be in the form of time, costly change orders, redesign costs, or even insurance claims if there were to be an accident. Some costs are hard to quantify, such as the economic impact of a major shutdown. Several studies have been performed analyzing the costs and benefits realized by utilizing SUE. One such study conducted by Purdue University in 1999 suggests that an estimated savings of $4.62 per dollar spent was realized. This study analyzed 71 DOT projects from Virginia, North Carolina, Texas, and Ohio. A more recent Penn State University study shows a potential savings of up to $22 per dollar spent on SUE, based upon 10 random projects performed by the Pennsylvania DOT.

From this, it is estimated that 10 percent to 15 percent of this cost can be saved utilizing sound SUE practice as follows:

- Administrative (2 percent).
- Engineering (0.5 percent).
- Utility relocation (5 percent).
- Construction (2.25 percent).
- Cost overruns (5 percent).

Implementation Considerations

With so many tools at their disposal, surveyors are often faced with the decision of which one is the most appropriate for a given project. This decision considers several variables. Each site presents challenges, and often physical features are constraining. A site with many aerial obstructions such as trees or tall structures, for example, is not suited for GPS. This would then also rule out mobile LiDAR, because it relies on GPS position data in order to orient the point cloud. This type of a site is better suited to a total station, or a combination of a total station and a terrestrial scanner. A control point network can be established with the TPS unit, and the scanner could then use control points for spatial orientation.

Technology Improves Safety

One of the biggest hazards to a surveyor is traffic. Not only does traffic impede the surveyor's ability to physically take the necessary measurements, it may also put him or her in danger while doing so. Surveyors are often very vulnerable to the hazards of inattentive drivers or other roadside hazards.

Often, lane closures are the only way to get the critical information needed to develop the base mapping for a project. Although effective, lane closures require careful planning and considerable expense.

Alternatives that take the surveyor out of this dangerous position include the use of aerial, terrestrial, or mobile LiDAR. This greatly reduces the need for personnel in traffic zones.

Site and project constraints dictate which type of survey technology is best suited for the task. It is important for the engineering and surveying teams to work together to consider the following factors:

- *Design intent*: Who will be the end user of the data being collected? What is this person or team of people doing with the data? How will the data be used?
- *Level of accuracy and detail needed for design*: Certain projects only require a bare minimum of data to achieve the desired results, whereas others need complex point clouds.
- *Safety concerns*: Will one type of equipment provide the crew with a greater degree of safety than another?
- *Satellite reception*: Is the corridor congested? Is the satellite window obstructed? Does vegetation obscure any areas of the site? Is GPS a viable option?
- *Traffic*: Can lane closures be used? Which specific shots are needed in the roadway?
- *Time of year of survey collection*: Will seasonal weather patterns need to be accounted for? Leaves on the trees or snow?
- *Control survey needed*: Is horizontal/vertical survey control needed?
- *Budget*: How much staff time and resource time can be allocated to collecting this data?
- *Schedule*: When are the data needed? Is there time for cleanup of raw shots to create usable deliverables?
- *Availability of staff*: How many surveyors are available to complete the survey? What is the appropriate number based upon the type of equipment being used?

The surveyor must understand equipment capabilities and limitations as well as site and project constraints to make the best decision. This decision-making process begins at the onset of a project, often with the surveyor. With so many tools at the surveyor's disposal, it is important to choose wisely and to maximize the efficiency of the particular equipment being used. The end user is also often the determining factor in the equipment decision. Budget, schedule, safety, and weather also influence the equipment decision. Taking all of these factors into account and selecting the appropriate equipment for the job is often the first step toward a successful project.

Table 2-1 shows approximate accuracies and costs for the equipment that has been discussed in the previous pages. The cost/mile column assumes a 1-mile segment for a rural two-lane roadway. It should be noted the information contained within Table 2-1 is approximate and various factors could impact these numbers, including equipment tolerances, site constraints, weather conditions, etc.

To better understand how a project team can determine which type of survey technology to utilize, the process used to select survey methods on a typical project should be studied. At the start of a project, the design team would sit down with the survey department to determine what type of survey technology would work best for the design team, surveyors, and budget. The main priority is the safety of the surveyors and how they should work around high traffic volumes on the interstate. Not only is safety a concern, but the use of traditional survey methods would require lane closures, which would take a large bite out of the available survey budget.

The project team would also look at the accuracy requirements of the survey that needed to be obtained. 3D

Table 2-1. Approximate Accuracies and Costs of Survey Equipment.

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

engineered models are used for a wide variety of applications in construction. As such, they have varying requirements from an accuracy standpoint. Fine-tuning of a 3D engineered model can be quite time consuming, so knowing the design team's plan for the model is very important.

Using traditional equipment, such as total stations and GPS units, a surveyor would likely only take shots on 15- to 30-ft intervals along the corridor. Similarly, the cross-section sheets from the construction plans would likely only show cross sections on 50-ft intervals. If the decision was made to use a mobile or terrestrial scanner for surveying this project, it would not have been prudent to set the equipment to take shots at 0.01-ft intervals, because doing so would create hundreds of thousands of points that are unnecessary. Choosing a higher threshold would make much more sense, and the resulting base file would be much more manageable while still fulfilling the accuracy requirements of the project.

At this step in the planning phase, it is important to point out that each jurisdiction has different accuracy requirements. At the beginning of each project, it is important to be aware not only of what the design intent is for the survey you are performing, but also for whom you are working. Review accuracy standards for the project area to be sure chosen survey and corresponding modeling methods conform to local requirements.

In this example project, the team may also discuss how the project corridor is located in rural Iowa with few large trees to obscure the satellite window of GPS equipment. In this situation, GPS would work fine and there should not be any concern about large buildings or tree canopies affecting the GPS signal.

The survey team would describe the equipment and survey options that could be used on the project. Traditional survey equipment with a rod-mounted GPS rover would work well for this site. There was a safety concern for the surveyors, however, and multiple lane closures would have been necessary to obtain the survey. The surveyors also point out this type of survey would take significant time and man-hours to obtain an extensive topographic survey for multiple miles of mainline pavement, the entire interchange, and ramps. In addition, the design team would like a very detailed level of survey, which would have increased the number of survey shots required.

The survey team also discussed the use of mobile LiDAR to obtain the topographic survey on the project corridor. The most important benefit of using mobile LiDAR was the improved safety for surveyors along the busy roadway. Additional benefits included the elimination of lane closures and the significant amount of survey shots that could be obtained along the corridor in a short amount of time. The design team would also benefit from having scan data on the existing bridge to assist in the creation of the 3D engineered model.

After discussion among the team members, it was decided to utilize mobile LiDAR on the corridor to collect a majority of the survey data. Since the mobile scanner was constrained by the available line of sight, its use was supplemented with traditional survey methods in areas that could not be adequately scanned by the scanning equipment. Figure 2-26 shows the point cloud that was captured by mobile LiDAR on the I-35 and IA92 interchange.

Building the 3D Engineered Model: Existing Conditions

After the base mapping, SUE data, and topographic survey data have all been gathered, these data are merged into a comprehensive existing-conditions 3D model for use by the design team.

Processing the Survey Data

The raw survey data may have come from several different sources. Some of these sources may include TPS survey raw data, GPS survey raw data (Figure 2-27), LiDAR sources and subsurface utility data. The raw data may have to be processed or filtered before they can be exported into the 3D model.

Typically, data gathered on both TPS and GPS can be exported directly in a format that is usable by most CADD software packages. In some cases, there may be postprocessing or editing of these raw data that has to be done before the data can be used. This is typically handled in a proprietary software package provided by the equipment manufacturer. Examples of current processing software include Leica's Cyclone, Technodigit's 3D Reshaper, Trimble's Realworks 3D Bentley Cloudworx, Geomagic Studio, Rapidform XDR, VR Mesh Studio, Terrasolid Terrascan, Geomatics VG4D, LP 360 for ArcGIS, and Certainty 3D TopoDOT. This software enables the user to manipulate the

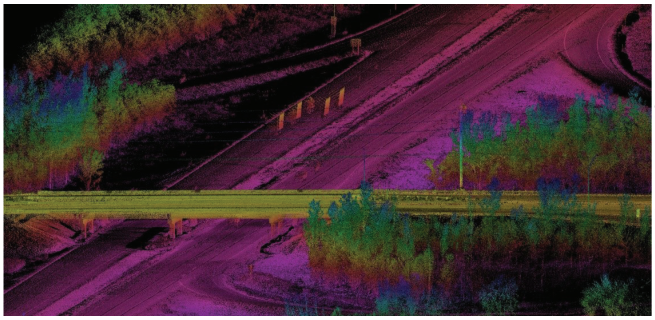


Image obtained from the Iowa DOT

Figure 2-26. Mobile LiDAR data gathered at the I-35 and IA92 interchange.

data to exchange coordinate systems, process level loop data, or filter out any measurements taken with poor coordinate quality.

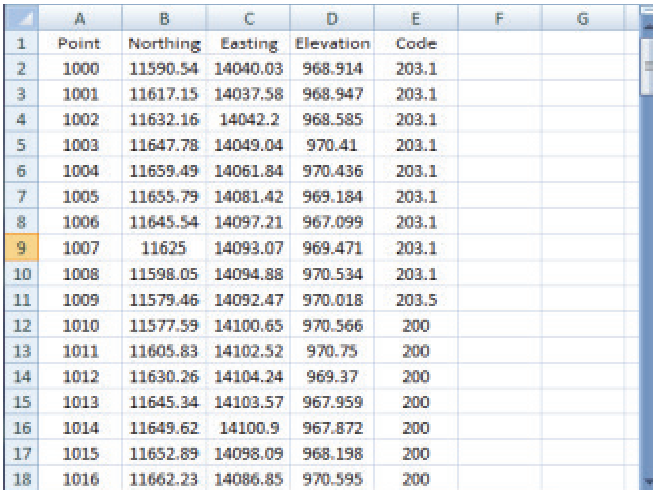
Terrestrial, mobile, and aerial LiDAR raw data are in the form of a point cloud. These raw data typically needs to be filtered before use. For example, on a roadway project, there may be cars driving by while the LiDAR scan is being performed. The point cloud needs to be filtered to remove these sorts of extraneous data points, or "noise," from the target survey data.

In Figure 2-28, the arrows are pointing to an example of noise in the I-35 and IA92 point cloud that needs to be removed by filtering. The noise in this graphic comes from a vehicle traveling along the interstate that was surveyed by the mobile LiDAR unit. There are typically automated routines that the user can run that simplify this process.

Aerial LiDAR data typically come into the model fairly simply, because the shots can be filtered to include ground surface shots only. This creates a surface file or a digital terrain model (DTM). In situations where aerial LiDAR is used, the main work associated with using the data takes place when it is to be merged with other forms of raw survey data. Often data must be manipulated when stitching together surfaces from different sources.

Figure 2-29 shows the raw DTM file that was used on the Interstate 35 and IA92 interchange project with data from multiple survey technologies. The blue lines and dots represent the field survey, utilizing traditional survey methods and mobile LiDAR. The triangulation in this figure came from aerial photogrammetric data to supplement the field survey. The aerial photogrammetric data were included to represent the general land shape over a larger area to show the boundary of the drainage area for this particular watershed.

In this example, the information outside of the traditional survey boundary was absolutely necessary for the hydraulic modeling, but it did not need to have a high degree of accuracy. This example could easily use LiDAR data instead of photogrammetry to supplement the traditional survey. The LiDAR contour data could be quickly merged with the field data. This demonstrates an appropriate use of technology that provides accurate answers quickly and inexpensively.



	A	B	C	D	E	F	G
1	Point	Northing	Easting	Elevation	Code		
2	1000	11590.54	14040.03	968.914	203.1		
3	1001	11617.15	14037.58	968.947	203.1		
4	1002	11632.16	14042.2	968.585	203.1		
5	1003	11647.78	14049.04	970.41	203.1		
6	1004	11659.49	14061.84	970.436	203.1		
7	1005	11655.79	14081.42	969.184	203.1		
8	1006	11645.54	14097.21	967.099	203.1		
9	1007	11625	14093.07	969.471	203.1		
10	1008	11598.05	14094.88	970.534	203.1		
11	1009	11579.46	14092.47	970.018	203.5		
12	1010	11577.59	14100.65	970.566	200		
13	1011	11605.83	14102.52	970.75	200		
14	1012	11630.26	14104.24	969.37	200		
15	1013	11645.34	14103.57	967.959	200		
16	1014	11649.62	14100.9	967.872	200		
17	1015	11652.89	14098.09	968.198	200		
18	1016	11662.23	14086.85	970.595	200		

Figure 2-27. Raw survey data in the form of .csv file.

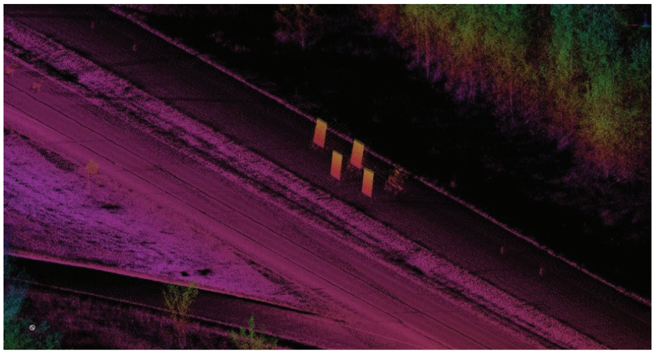


Image obtained from the Iowa DOT

Figure 2-28. Screenshot of point cloud data at the I-35 and IA92 interchange. Arrows show "noise" from a car that was captured during the survey operations.

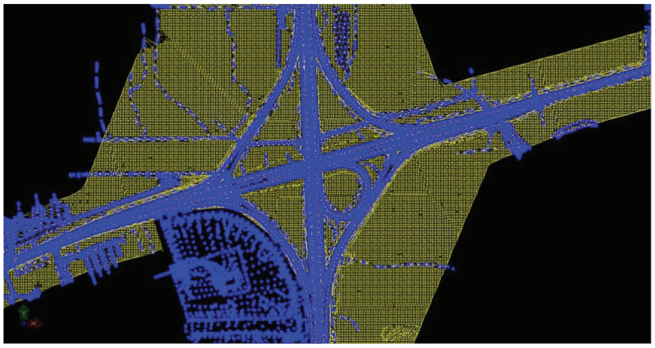


Figure 2-29. Survey data on the I-35 and IA92 interchange. The blue linework represents field survey and mobile LiDAR data. The triangles represent photogrammetric data that were supplemented into the model.

DTM

The DTM serves as the base for the 3D design model. In essence, it is a 3D representation of the surface of the ground in a given area. The existing DTM is derived from data from various sources such as aerial LiDAR contours and raw survey shots.

Compiling the data from these sources into one surface file yields a continuous surface that can be visualized with triangles between the data points or with computer-generated contours draped over the whole surface.

Difference between DTM and Surface

Digital terrain models are sometimes inaccurately used synonymously with surfaces when discussing existing and proposed feature models. A DTM is a representation of the ground surface for a specified area and it also includes multiple surface layers and features such as subbase, subgrade, and pavement. Surfaces, on the other hand, typically only include a single ground surface or another surface such as pavement.

Sometimes, choosing a combination of both triangles and contours gives the viewer a good way to check for inconsistencies in the data. Deleting long triangles and swapping the triangulation between various data points are common ways to clean up or smooth out the surface. Most of these edits are performed in a 2D, or plan view, environment. Figures 2-30 and 2-31 illustrate the same area on a project site. Both show the I-35 and IA92 interchange, but Figure 2-30 depicts it with traditional survey line work and Figure 2-31 shows what it looks like through the use of a triangular network.

For a quick quality assurance check of the completed surface, using a 3D visualization tool quickly and easily shows spikes or holes in the surface that might not have been obvious in the plan view. These errors are typically in the form of bad data points, such as a point that is recorded with an elevation value of zero or a point recorded with an incorrect reflector height on the total station.

Some 3D visualization tools have various rendering options that allow the user to view elevations based on color for added effect. These tools also help identify problems with the DTM. Figure 2-32 shows the same location on the I-35 and IA92 interchange with colors used to visualize elevations. The dissimilar colors help visualize where significant elevation changes occur such as the ramps and drainage channels.

The next step in the development of the existing-conditions 3D model is the inclusion of underground infrastructure. Doing this in a 3D environment has several benefits. The designer can typically plan around existing infrastructure much more successfully when precise information is obtained via a thorough subsurface utility investigation.

A typical urban intersection could include a large number of underground utilities such as storm sewer, gas main, water main, sanitary sewer, electrical utilities, etc. In order to have precise information similar to what is shown in Figure 2-33, a substantial number of test holes have to be performed to obtain accurate data about the size and depth of the existing infrastructure.

Additional Survey Equipment Information

For additional information on the survey methods discussed in this chapter, the links below provide up-to-date product capability, specifications, and pricing for popular brands of surveying equipment in the United States.

- http://www.landsurveyors.com/resources/land-survey-pricing
- http://www.trimble.com/survey/index.aspx

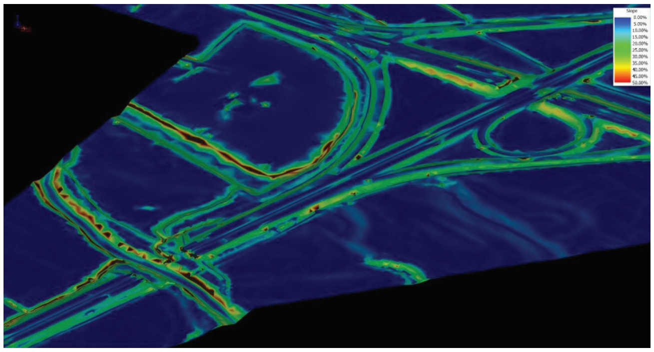


Figure 2-32. Existing site conditions at I-35 and IA92 interchange. This model has rendering options turned on to assist the user in identifying elevation changes based on colors.

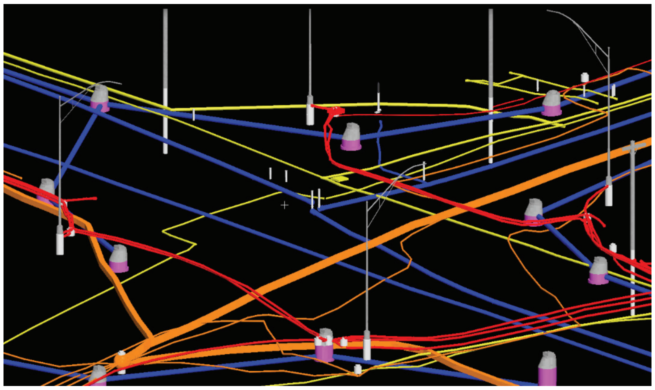


Image obtained from Utility Mapping Services, Inc.

Figure 2-33. A 3D engineered model of an urban intersection with SUE.

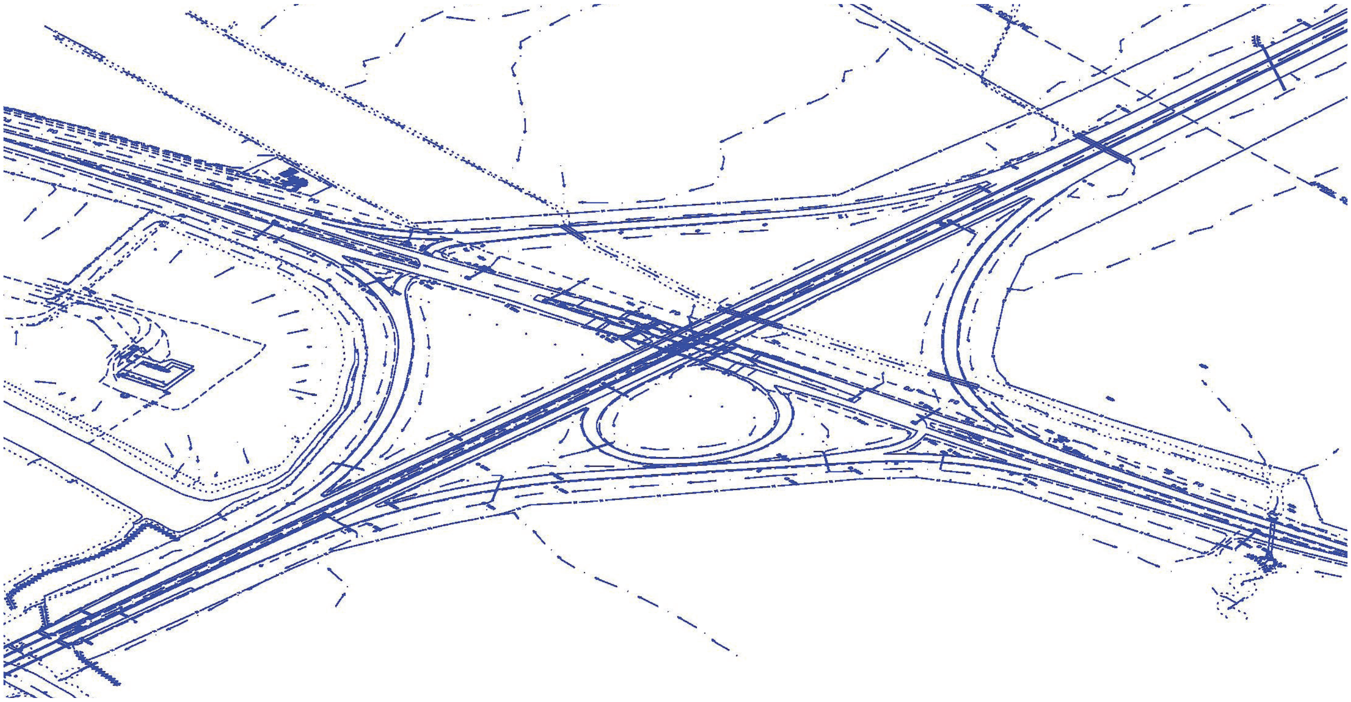


Figure 2-30. Survey linework on I-35 and IA92 interchange obtained from traditional survey methods.

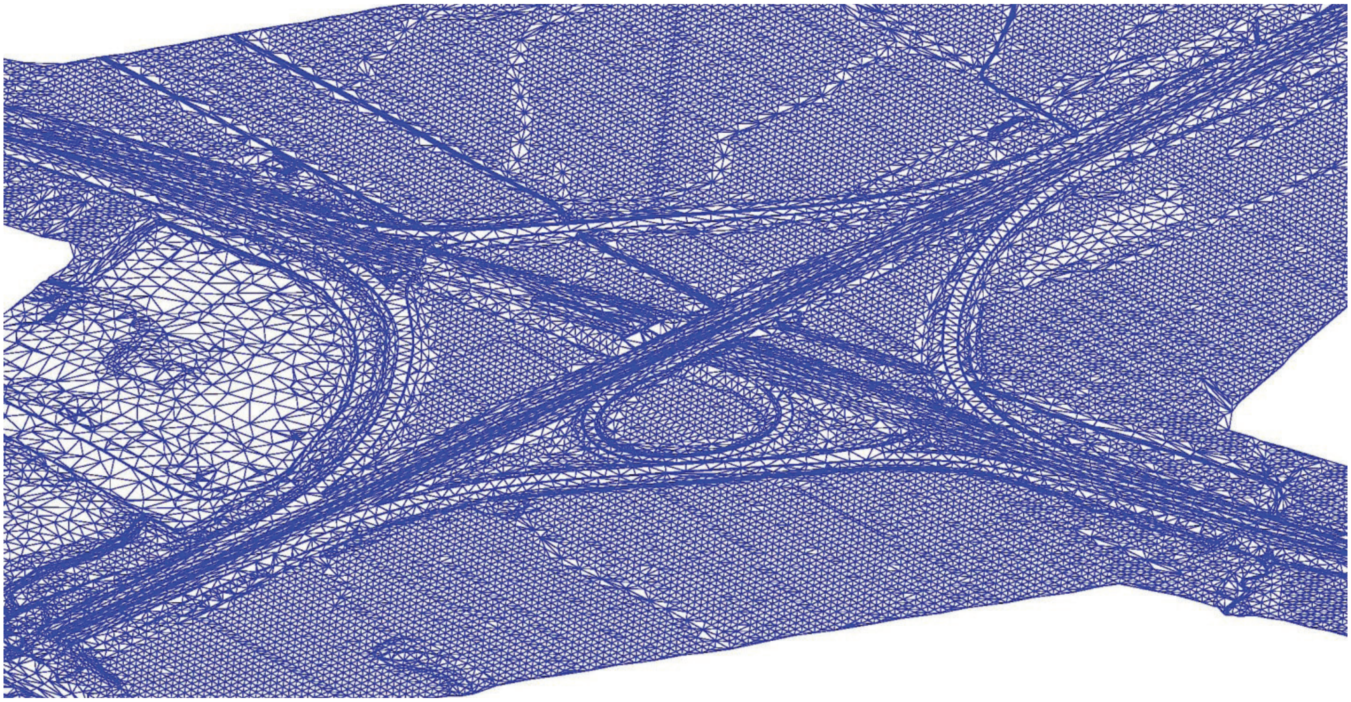


Figure 2-31. Triangulation view of existing site conditions at I-35 and IA92 interchange.

- http://www.leica-geosystems.us/en/Products_885.htm
- http://global.topcon.com/products
- http://us.sokkia.com/products

Each brand has qualities and functions that make their equipment unique, so it is important to do research and find the equipment that works best for the type of work that the surveyor will be doing, as well as the particular region and site conditions where work will take place. With the increasing level of complexity of surveying equipment, sometimes having good technical support or a good local product representative can be just as important as the particular brand that is selected to purchase. With more and more competition in the industry, sometimes adding another piece of equipment to your toolbox allows you to pursue different types of business or enter into a new segment of the market entirely.

Training and Product Updates

No matter which brand of equipment is selected, continuous training and updates are a necessity. Manufacturers periodically send out firmware updates for equipment to address glitches found by end users. Trade shows, vendor shows, and exhibitions continually display the latest advances in surveying equipment. It is important to keep up with these meetings to stay up to date on advances in technology.

Equipment suppliers typically include some form of formal training when you purchase new equipment. It is important to take advantage of this training to ensure that the equipment is being used to its full capabilities. After some initial training, the only way to really test out the equipment is to use it in the field. Once one is familiar with the equipment operation, online forums and user groups often provide a good resource or sounding board to bounce ideas off of other users and obtain advice.

CHAPTER 3: DESIGNING WITH 3D ENGINEERED MODELS

3D engineered models are instrumental for a more accurate and cost-effective method of roadway design. This chapter covers how 3D technology can assist the design team with improving project communication, contract deliverables, and quality assurance. Implementation considerations are also discussed to provide information to agencies that are considering the use of 3D engineered models.

The successful completion of a project relies on strong communication from the earliest planning stages. At the start of a project, it is important to understand what the final project deliverables will be. For instance, is this a large-scale roadway project containing grading, utilities, pavement, and bridges? Or is it a project that only contains grading and utility installation? The scope of the project can indicate what software is best suited to complete the design.

The 3D engineered models provide unmatched graphic representation of a project to the public, the owner, and the affected property owners. Plan views and cross sections are difficult for the lay person to interpret. Roadway prism grading, drainage issues, and underground utilities are difficult for professionals to visualize accurately, and they are very challenging for the general public to interpret. The 3D engineered model takes the "picture is worth a thousand words" adage to a new level.

3D engineered models are used during all phases of a project and are capable of numerous benefits that are not possible with traditional 2D methods. During the design phase, the designer needs the ability to translate a 2D plan view into a completed 3D model in their mind to properly visualize how the project should look after construction.

Design Product Creation and Delivery

To examine how 3D engineered models are created and used during the design phase, let's walk through a typical project development scenario.

Scoping/Planning Phase

During the initial scoping phase of a project, the owner determines the project goals and constraints, providing specific requests and specifications that need to be met. The owner may also provide critical information about the existing site or adjacent areas that could be an important aspect that needs to be analyzed by the engineer. Public information meetings similar to the one shown in Figure 3-1 can be held during the initial scoping phase of a project to garner public support and receive input from local property owners and the affected public. At this point in the project delivery phase, aerial LiDAR can be a very efficient way of looking at the existing topography at a macro scale. Aerial LiDAR can be used to compare alternative routes, seek preliminary right-of-way needs, and calculate rough earthwork quantities for comparison purposes.

Typically LiDAR data are used to make project planning decisions. Figure 3-2 shows aerial contour data adjacent to an existing town. Job-specific survey data would likely take days, if not weeks, to gather via traditional survey methods. In contrast, publicly available LiDAR mapping can provide a contour map of reasonable accuracy of the area in a matter of hours or even minutes. This level of accuracy is often sufficient to make educated decisions on how to proceed with the preliminary design of a project.

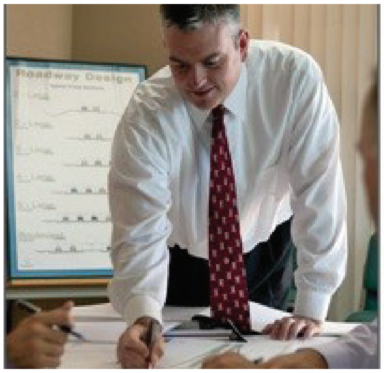


Figure 3-1. A public meeting between engineers and local residents during the early stages of a project is critical for obtaining public approval.

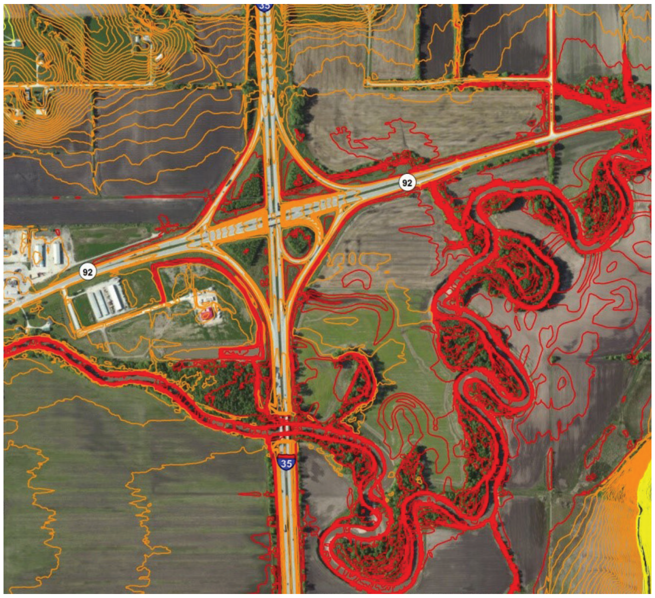


Figure 3-2. Elevation contours created using aerial LiDAR data.

At this stage of the design process, it is important for the designer to consider the goals of using a 3D engineered model. A clear understanding of the agencies' objectives helps guide the design team to making decisions about the level of effort required for 3D modeling. Some examples of goals that agencies are seeking with 3D engineered models include the following:

- 3D engineered models for public information and presentations.
- Increased design quality assurance.
- SUE.
- Earthwork quantity calculations.
- Providing contractors with 3D files for grading or paving.

Survey Phase

After the public input process has been completed, the scope of the project has been determined, and a route has been selected, survey information is obtained on all of the existing features along the project corridor. As discussed in Chapter 2, survey information, including SUE, can be obtained via 3D methods.

Roadway Geometrics/Layout Phase

After survey information has been collected and incorporated into the 3D engineered model, the designer develops the preliminary roadway geometrics and lays out important features. The Iowa DOT uses civil design software from Bentley Systems, Inc., to create 3D engineered models. The use of 3D engineered modeling has a major benefit during early design stages versus traditional 2D methods because 3D technologies can easily make alignment and profile modifications without the need to manually compute earthwork, right-of-way impacts, and other design elements. The 3D engineered model can also save the designer time by allowing the information created during the preliminary design phase to be updated and efficiently used for final design purposes.

The backbone of any major roadway project is the horizontal alignment and vertical profile of the roadway. 3D engineered models have the ability to integrate all aspects of the design into one complete "on-the-fly" model. Traditional 2D methods required the designer to develop the roadway alignment in plan view and then create a separate profile to assign elevations to the horizontal alignment. After the horizontal and vertical alignments had been determined, the designer would calculate intersection, driveway, sidewalk, backslope, and foreslope grades for the entire corridor.

One of the advantages of utilizing 3D engineered models is that design changes are implemented quickly and seamlessly. With traditional 2D methods, sometimes significant design changes such as a profile adjustment, an alignment adjustment, a typical section adjustment, a cross section adjustment, or the implementation of additional survey information could become a time-consuming process that could cost weeks of work.

Early in the design stage, the 3D engineered model can be used to facilitate coordination with utility companies that have services located within the project corridor. Traditional utility coordination between designers and utility providers often consisted of multiple phone calls and plan sheets being sent back and forth in an effort to resolve utility conflicts prior to construction. Even with the extensive coordination between parties, there was still a risk of utility conflicts that could be discovered during construction and create costly contract modifications and schedule delays. The 3D engineered model can improve communication and visualization for utility companies located within the corridor.

Final Design Phase

After the preliminary alignment and profile have been developed, the design team can proceed with final design. Final design includes a review of all survey information to ensure the proposed features can tie into the existing surface.

As with most large roadway projects, there are multiple design disciplines involved in the creation of a quality plan set. Many diverse specialized engineering disciplines can harness the power of the 3D model to make their work more efficient and accurate. These designs can also be incorporated and integrated into the model.

Structural Design

The structural engineer's design can be incorporated into the 3D engineered model to help the roadway designer understand where to place utilities and how to grade the bridge berms. Figure 3-3 shows the 3D engineered model on the I-35 and IA92 interchange project with the bridge incorporated into the master model. The 3D bridge model is also valuable because it provides a quality control tool to make

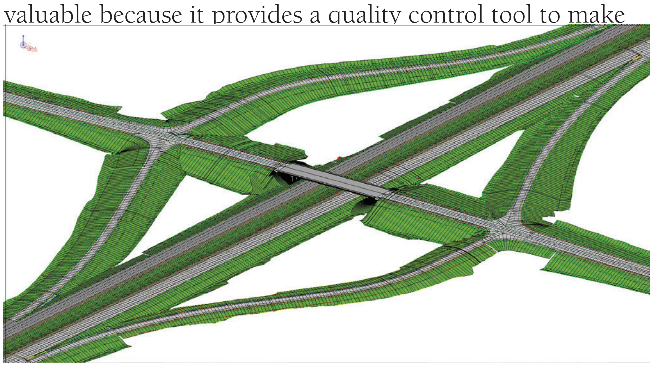


Figure 3-3. The I-35 and IA92 interchange including the bridge designed in 3D.

Hydraulic Design

Hydraulic engineers can also benefit from the ability to incorporate the structural drawings into the 3D engineered model. The hydraulic engineer can use the model to accurately calculate the volume of unobstructed flow that can bypass the bridge structure. Hydraulic analysis can also be used to assist in calculating the buoyancy of structures that have the potential to be exposed to flooding conditions. Hydraulic information such as flood elevations can be incorporated into projects to assist designers in making sure the design functions according to the specification requirements. Figure 3-4 shows how flood information can be incorporated into a 3D engineered model.

Geotechnical Design

Geotechnical information can be incorporated into the 3D engineered model as well. Information obtained from soil borings can be implemented into the model that can include soil types, rock ledges, water tables, etc. Computer-aided design and drafting software today has the ability to display soil layers in different colors to assist the designer in evaluating geotechnical information (Figure 3-5). This information can help the designer make more informed decisions and calculate quantities more accurately compared with traditional 2D methods.

The geotechnical information contained within the model can also be used to help designers determine where unsuitable soils may be encountered within the corridor. Unsuitable soils, especially under pavements, may need to be removed to ensure a firm base for proper construction of the pavement. With the additional information that the 3D model can provide in terms of geotechnical information, there is less risk of encountering unsuitable soils that may need to be removed and replaced by competent material.

Figure 3-4. Discharge and elevation data from a hydraulic model can be shown on a digital terrain model developed from LiDAR data to accurately demonstrate impacts of different flood events.

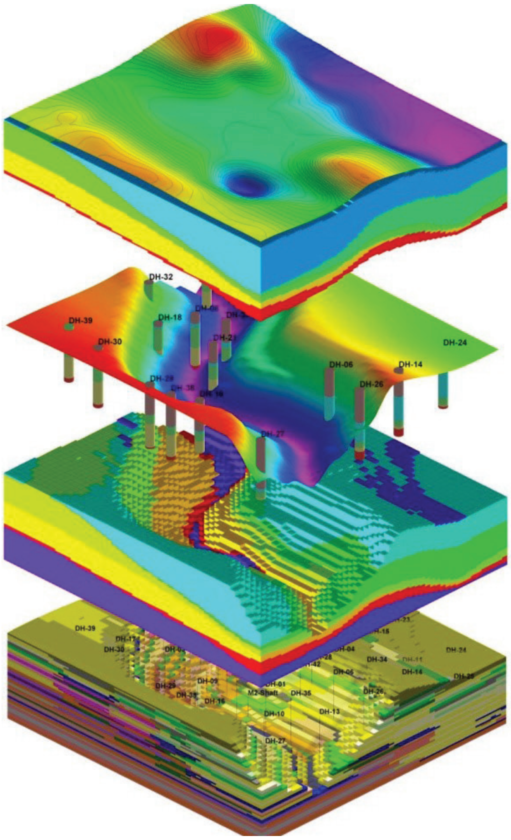


Image obtained from RockWare, Inc.

Figure 3-5. Geotechnical 3D model showing above-ground surface and geological layers.

3D Design and Analysis Tools

The final design stage also includes engineering analysis on various elements of the design to ensure the project meets specifications and reduces the potential for design omissions. Some of the 3D modeling tools that are available to assist designers with engineering analysis include virtual drive-throughs, flyovers, parametric modeling, constructability analysis, sight distance calculations, traffic analysis, inclement weather analysis, and clash detection.

Virtual Drive-Through and Flyover

Using 3D techniques, designers can perform a virtual drive-through of the entire corridor prior to commencing construction. The virtual drive-through feature of CAD provides a level of quality control that was not possible with traditional 2D methods. The virtual drive-through enables designers to identify any irregular bumps, dips, alignment errors, holes, or “busts” in the design model. This can also assist in sight distance reviews and checking for adequate signage. These types of model animations can also help communicate design objectives to the public for informational meetings and demonstrations.

Similar to a virtual drive-through of the corridor, flyovers can also be used in the design phase to facilitate engineering analysis. Figure 3-6 shows an example of a flyover on the I-35 and IA92 interchange project.

Parametric Modeling

3D engineered models can also assist the designer by providing a process called parametric modeling. Parametric modeling uses factors such as dimensions or specifications to define a model that can be modified later. To understand how parametric modeling is used, a retaining-wall example will be explored. In the case of a retaining wall designed using parametric modeling, as dimensions and various other constraints are selected and modified, the retaining wall model will automatically update. The retaining wall model can automatically adjust footing sizes and wall thicknesses as the height and type of the wall change to ensure it meets applicable specifications and standards. Figure 3-7 shows a screenshot of a retaining wall parametric model.

Parametric modeling can also be used for bridges, manholes, intake structures, and many other components of construction. By using parametric modeling, the designer can ensure the individual structure or "part" meets safety and specification standards and allows it to adapt to new conditions or dimensions. Parametric modeling improves efficiency and provides a layer of quality control by ensuring the design meets specifications.

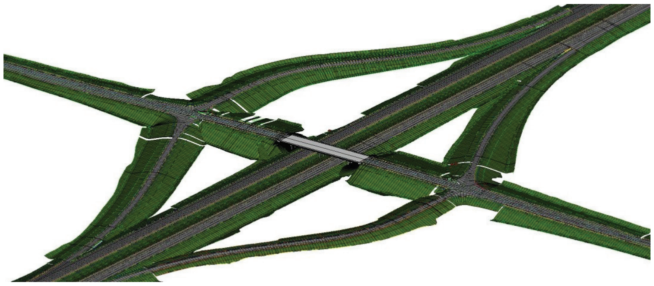


Figure 3-6. How a flyover appears to the designer on the I-35 and IA92 interchange.

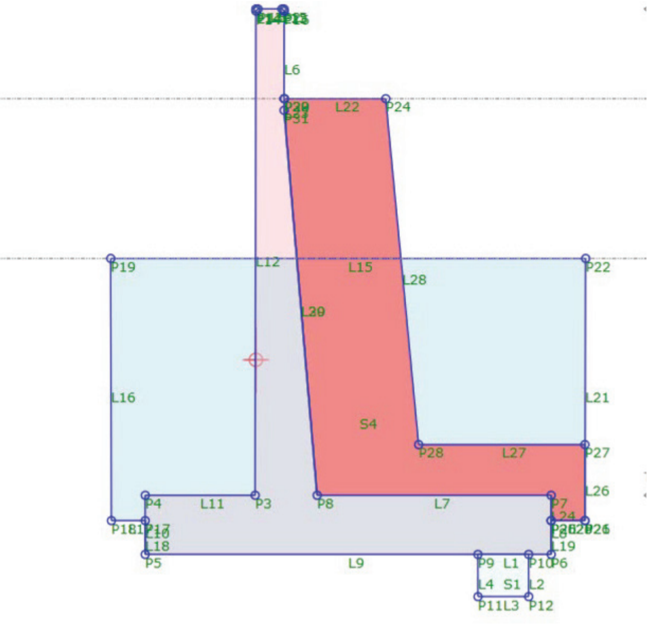


Figure 3-7. Screenshot of a parametric model of a retaining wall.

Image obtained from Sundt Construction

Constructability Analysis

3D engineered models provide designers with the ability to analyze the constructability of all aspects of the project prior to the model leaving the designer's office. The 3D engineered model can show important items such as grading limits, vertical clearances, and utility conflicts that could create costly contract modifications if not identified prior to construction. The 3D engineered model can also be used to identify areas that may be difficult to construct such as utility installation in congested urban areas. Figure 3-8 is an example of a project in which 3D engineered models can be instrumental in visualizing the staging on complex roadway construction.

Sight Distance Analysis and Clear Zones

3D engineered models give designers the ability to quickly and accurately check driver sight distance and clear zones, which improves the safety of the traveling public. Traditional 2D methods of checking clear zones and sight distance specifications required the designer to run through numerous equations to ensure the design met all applicable safety standards. While traditional equations should still be used to double-check results, new 3D technology allows the designer to calculate sight distance requirements as soon as a roadway alignment and profile have been created. If the safety requirements are not satisfied, the design can be modified quickly and easily. Figure 3-9 shows a 3D engineered model of a bridge project in which vertical clearances can be checked by the design team.

Traffic Analysis

3D engineered models can be used by designers to visualize traffic patterns and traffic flow using powerful modeling software. Typically, the 3D engineered model is developed with CADD software and includes intersection geometrics, turning lanes, traffic signal placement, and pedestrian crosswalks. The 3D engineered model can be used with traffic analysis software in which the designer can input traffic counts and turning movements based on current or forecasted volumes along the corridor. Once the designer has imported the 3D engineered model and traffic volumes, the traffic analysis software can simulate how the intersection/interchange will function and provides information on important features such as vehicle delay, queue lengths, turning movements, traffic flow, and pedestrian safety.

The designer can also use traffic analysis software to provide a video simulation of how traffic might flow with proposed improvements (Figure 3-10). This could be particularly helpful when proposing an innovative traffic configuration such as a roundabout, J-turn, or diverging diamond interchange. This type of communication can be instrumental in helping gain public acceptance of innovative intersection designs.

Inclement Weather Analysis

3D engineered models assist the designer in analyzing how the corridor will function in inclement weather. In areas that experience snowy weather (Figure 3-11), new developments in 3D engineered models provide the capability for designers to analyze the effects of blowing and drifting snow throughout the corridor. Traditional 2D design methods have limited capability in analyzing drifting of snow, and traditional methods often rely on the experience and lessons observed from previous projects. New methods in 3D engineered models allow designers to simulate blowing snow and blizzard events in the design phase. Based on the results of the simulation, a roadway corridor can be adjusted to reduce the potential of drifting snow.

Clash Detection

The 3D engineered model can assist the designer by identifying utility conflicts prior to the design reaching the field. In addition to SUE, when proposed features of the project—including storm sewer, water main, sanitary sewer, electrical conduit, and all other subsurface utilities—are incorporated into the 3D engineered model, the engineer can quickly identify conflicts. The 3D engineered model allows the designer to view all areas of the project in various views, including isometric. Looking at the project from different 3D views provides more information than would be available with traditional 2D plan views.

Utility conflicts can occur in two ways: between existing versus proposed utility conflicts and proposed versus proposed utility conflicts. Existing versus proposed utility conflicts are those in which a proposed feature such as a storm sewer pipe, water main, sanitary sewer, or bridge footing will be in conflict with an existing utility within the corridor. A proposed versus proposed utility conflict is one in which a proposed feature will be in conflict with another proposed feature. An example of this would be if a proposed storm sewer intake structure would be in conflict with a proposed bridge column footing. Accurate subsurface utility information is important, but the 3D engineered model offers powerful methods of visualizing or detecting the clashes.

Figure 3-8. 3D engineered models can assist designers with visualizing important staging concerns in complicated projects.

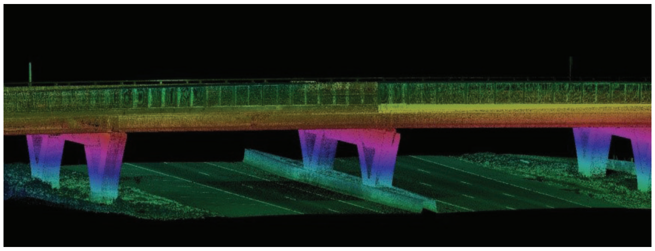


Figure 3-9. 3D engineered models allow the design team to calculate clear zones and vertical clearances to improve the safety of the traveling public.

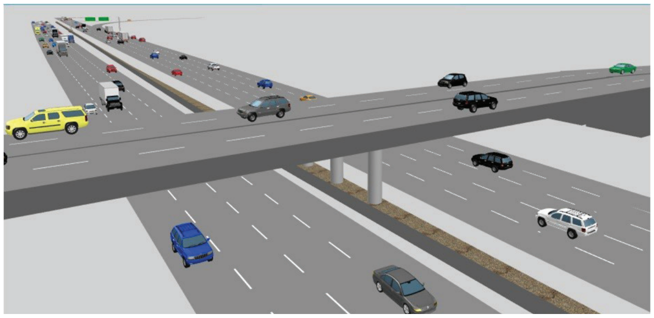


Figure 3-10. 3D engineered models can be imported into traffic simulation software to perform traffic flow analyses.

Image obtained from the Iowa DOT

Figure 3-11. 3D engineered models have the capability to perform snow drift analysis throughout a corridor.

3D engineered models have the capability to automatically detect clashes between utilities and other features within the model using a process called clash detection. The software can alert the designer when utilities or other elements are in conflict with one another. Clashes can be "soft" clashes or "hard" clashes. Soft clashes are sometimes called clearance clashes because they refer to objects that require certain tolerances or buffers to adequately be constructed. When soft clashes occur, the utilities or other features are not physically in conflict. Rather, they are within the geometric tolerances that are required for safe and practical construction of one of the elements. For example, a specification requires that water main pipe needs to have a minimum clearance of 2 ft in any direction from a storm sewer pipe. The 3D engineered model detects that a portion of the proposed water main is only 1.3 ft from the proposed storm sewer. Even though the pipes are not physically touching, the water main does not meet specifications because of its proximity to the proposed storm sewer. Soft clashes can be analyzed by the designer to determine if the conflict requires one or more of the elements to be relocated. Figure 3-12 shows a screenshot of a soft clash detected within a 3D engineered model.

Hard clashes, on the other hand, occur when two elements occupy the same space and, therefore, are in direct conflict. For example, an existing water main pipe would be running directly through the middle of a proposed storm sewer pipe. Figure 3-13 shows an example of a hard clash.

Staging conflicts when installing underground utilities can also be analyzed using the 3D engineered model. For example, a large water main is to be installed in conjunction with an interchange reconstruction project in a northern state that experiences extremely cold weather during the winter months. Because of the complexity and large size of the project, construction will take two years to complete. The water main is designed to have a minimum of 6 ft of cover over the top of the pipe when final grade has been achieved to ensure it would be below the frost line. Because of staging and traffic control during construction, however, the water main will be exposed approximately 3 ft above the existing ground surface during the winter months until grading operations can fill over the top of the pipe in the spring. A staging conflict similar to this could be identified during the design phase with a 3D engineered model and appropriate adjustments could be made.

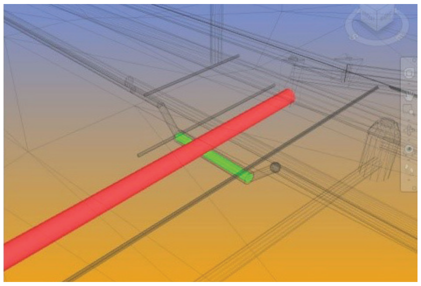


Image obtained from Autodesk, Inc.

Figure 3-12. This screenshot shows a "soft clash" utility conflict within a 3D engineered model.

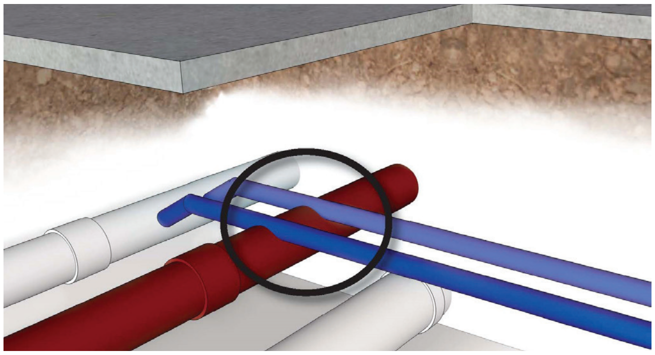


Figure 3-13. This screenshot shows a "hard clash" utility conflict within a 3D engineered model.

3D Engineered Model Quality Assurance

Final design also includes quality assurance prior to the plans being sent out for the bidding process. One of the most important benefits of utilizing 3D engineered models is the level of quality assurance that can be performed during the design phase. 3D technology can reduce errors and lead to a higher quality of construction. Traditional 2D quality control methods were limited by the reviewer's ability to visualize 2D plan drawings in a three-dimensional workspace. The reviewer had to rely on plan views, cross sections (Figure 3-14), and construction details to be able to visualize what the project was intended to look like after construction had been completed. This level of quality control could vary widely because visualization often had to combine information from different plan sheets, visualizing complex information. The traditional method of quality control did not take into account all aspects of the design because cross sections were typically cut every 25 or 50 ft along the corridor. The engineer or reviewer had to "connect the dots" between cross sections to interpret how the paving and grading operations should look and function at intermediate locations.

The reviewer also had to rely on 2D plan views of grading contours and flowline elevations to ensure that the site would drain as intended. With the 2D plan views, it was also difficult for the reviewer to verify that the site grading plan could adequately match the existing ground at the grading limits.

3D engineered models allow the designer to look at the project in isometric views at various angles to detect any

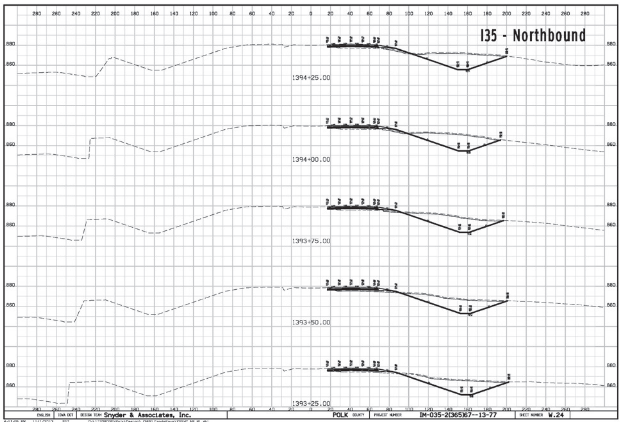


Figure 3-14. Traditional cross sections used to assist designers with visualizing how the roadway should be graded.

surface irregularities such as "spikes" or "holes" that need to be corrected. The designer can also look at the surface triangles of the model to help identify errors.

A drainage analysis tool is used to assist the designer in determining the direction of flow on existing or proposed surfaces. Some drainage analysis tools also have the ability to delineate drainage areas based on existing and proposed 3D surfaces in the model. This tool provides a level of quality control by allowing the designer to locate drainage problem areas on a computer screen. Accuracy of the existing and proposed 3D model is very important when using the drainage analysis tool because any unintended "spikes" or "dips" in the 3D surface can greatly affect its performance.

3D engineered models can adjust the horizontal and vertical exaggeration of elements to assist the designer in detecting errors. With traditional 2D methods, vertical exaggeration could typically only be achieved in the cross section view. The limited use of exaggeration with traditional methods helped the designer and reviewer detect errors at every cross section. Any areas between cross sections, however, would not be detected with the use of exaggeration tools.

Unlike traditional 2D exaggeration tools, 3D engineered models allow the designer to exaggerate the entire surface to assist in detecting even the slightest errors in the model's surface. The exaggerated surface can be rotated and viewed from multiple angles along the entire corridor to identify any surface imperfections. The exaggeration tools are a major benefit in quality control and help designers and reviewers identify and correct errors that likely would have been overlooked using traditional 2D design methods.

Most errors that are detected during the QA/QC process can be quickly and easily corrected in the 3D engineered model prior to supplying the model to the client, owner, or contractor.

Agencies are encouraged to develop a quality assurance process to check 3D engineered models prior to providing the files to contractors. One of the ways this can be done is creating a checklist for individual components of the design that should be double-checked. Items on the checklist should include, but are not limited to, the following:

- Visualize either contours or the triangles in a 3D file. Look at it from the top and front, side, and isometric view. This gives the designer a pretty quick idea if there are any irregular dips or spikes or if the software created a void in the surface when it made the XML file. Designers should also look at the triangles on top of the proposed design file. Triangles should not cross obvious breaklines such as centerlines, edges of pavement, edges of shoulders, etc.
- The contour interval should match the tolerance of the purpose. For example, if the model is intended for grading and the specification is 0.1 ft, the contours should be created at that interval. If contours are cut at too large of an interval, "chatter" may be hidden in the model.
- Cut a profile of the XML surface down the centerline (and edges of pavement if profiles have been created for them). Visualize this XML profile on top of the design profile from the plan and profile sheets. The lines should lie on top of each other. The designer can also have the software print elevations on both the design profile and the XML profile at even stations and compare them side by side in a spreadsheet for an additional quality control measure.
- Cut the surface that has been imported from the XML on top of the design cross sections. When navigating through these sections, the lines should lie on top of each other. Pay particular attention to areas of superelevation and ditch grades. Many times the designer discovers an error that does not appear correct at this stage.
- Look at visualized contours or flow arrows from the XML surface. The low points should line up with the proposed drainage structures. This is also a good opportunity to check other structure flowlines to ensure they match the proposed surface.
- Check the horizontal alignment of the corridor and compare it to available survey control information.
- If agencies have access to the same software that is used by local contractors to view the 3D engineered model, the design team should load the model into this software to assure it looks as intended.

The previous steps are all things that a designer can run through pretty quickly to see if there are obvious problems. More often than not, the surfaces are fine where the typical section is consistent. Special attention should be given to spot-checking nontypical areas such as intersections, foreslope transitions, bridge berms, superelevation transitions, etc. These are the areas in which inconsistencies are most likely because they may have required some hand modifications by the design team.

Implementation Considerations

To properly implement 3D engineered modeling, agencies, owners, and designers must take into account various design considerations prior to full implementation of 3D techniques. Changes to current CAD modeling standards will need to be made to allow for the efficient and effective use of 3D engineered modeling.

Complete 3D Model

Traditional methods of design create an incomplete and, sometimes, inaccurate model. An example of this is when a contractor requests a 3D model of a grading or pavement surface when the design was completed in two-dimensional space. Traditionally, contractors could take it upon themselves to create 3D models for their purposes based on the 2D cross sections created by the engineer and contained in the plan set. Although this method does create a 3D model of grading or pavement surfaces, the model does not account for the areas between the cross sections. Typical cross sections are cut every 25 or 50 feet; therefore, the model is correct at the exact station where a cross section has been cut. A lot can change in terms of topography over 50 ft of an alignment, however, and high and low points within the vertical alignment may not be depicted. This method produces an inaccurate model by using a "connect the dots" approach to interpret grading between each individual cross section.

Alternatively, when 3D engineered models are created by the design team, a complete 3D surface is created for all areas within the proposed project boundaries. The 3D engineered model takes into account special grading areas and topography changes at all locations, not just at individual cross sections cut every 25 or 50 ft along a corridor. More accurate earthwork quantities can be calculated by knowing the exact cut/fill distance at all locations within the model boundaries instead of interpreting quantities between cross sections. Earthwork quantities can be calculated by comparing proposed surfaces to existing surfaces instead of the average end-area method. The surface-to-surface earthwork calculations can be performed on a station-to-station range to provide a level of comfort for the design team and contractor. This can reduce the risk of underestimating earthwork quantities, which can provide a cost savings for contractors and owners. If required or preferred, cross sections can still be created, but they would be based on the 3D engineered model and could be cut at any interval.

3D engineered models should not contain gaps or void spaces within the model boundaries. Traditional design methods have gapped difficult areas such as bridge berms and intersection radii. This caused contractors to spend time and money to fill in the gapped areas and also created difficulties for construction personnel in interpreting design intent. Misinterpretation by construction personnel can lead to errors and costly rework. Agencies need to strike a balance, however, between the level of model completeness and how much effort is required by the designer. For example, the Iowa DOT determined it was too labor intensive to model ADA-compliant pedestrian ramps when contractors would likely not be using the 3D model to construct them. Whether or not to model intricate details such as this needs to be decided by the agency before implementing 3D engineered modeling. A fully designed 3D engineered model may contain all features of the proposed project such as the following:

- Topographic survey information.
- 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.

Through several years of successful 3D implementation, the Iowa DOT determined that it is not necessary for designers and consultants to spend a great deal of time merging side-road models and other features into a single "master" model. Contractors will take whatever information they can get and have the ability to merge information on their own to match specific staging operations. Additionally, designers should not expend effort trimming 3D models into more manageable sizes. Most software programs that contractors utilize have the capability to trim files into their desired area.

3D engineered models should contain the appropriate beginning and ending of transitions for key geometric features. Beginnings of vertical curves and ends of vertical curves should be included within the model. Intersection radii and intersection grading should also be modeled to clearly communicate the drainage patterns and design intent of the project.

CAD Standards

One of the questions that agencies need to address prior to implementing 3D engineered modeling is if the agency wants to perpetuate what they do now with a new process. States that have implemented 3D engineered modeling have discovered that several of their historic construction details were very difficult to model in 3D and construct in the field. The agencies' Standards Group should work closely with the 3D CAD group to modify details to make the modeling process easier. This process is a great opportunity to review historical details.

Agencies need to review their individual CAD standards to determine whether or not changes need to be made to their internal design process to make implementation of 3D engineered modeling easier. Computer-aided design standards should include appropriate level symbology and intuitive naming for 3D line strings to clearly indicate what each element within the model represents. Designers need to ensure they use consistent symbology and naming conventions for each line string because the level names dictate the information used by construction personnel. Designers should avoid creating custom level symbology and naming conventions to avoid confusion by contractors who will be utilizing the 3D engineered model.

To fully implement the widespread use of 3D engineered models, roadway typical sections, sometimes referred to as templates, should be developed that have standard setups and individual components. The State of Iowa is one of the nation's leaders when it comes to statewide use of 3D engineered modeling. The Iowa DOT has developed several CAD templates and individual components that can be accessed by designers performing work for the DOT.

The templates and individual components have been set up with the appropriate level symbology and naming conventions that are consistent with the required design standards. If the project does not match one of the templates, designers have the ability to select a template that most closely resembles their own roadway typical section and modify the DOT template to fit his or her individual project.

If a roadway template is modified by a design team, the template needs to use the appropriate point setups as specified by the State DOT. To fully understand how point setups are an integral part of a compatible design file, it is important to know how CAD templates are built. A template is made up of multiple "points" that represent individual components of the roadway such as edge of pavement, subbase, shoulders, etc. Figure 3-15 shows a template that has been modified by the designer for use on an Iowa DOT project. Each point is represented by a red "plus" symbol and has a unique name. These points are compatible with the Iowa DOT design standards.

Table 3-1 shows a few of the point names and which component they represent. The point names need to match the agency design standards to ensure the files are compatible among agencies, consultants, and contractors.

It should be noted that agencies should not let the lack of CAD standards prevent the use of 3D design and construction. Although CAD standards are helpful, as long as designers clearly communicate what each layer and line type represent, contractors can successfully utilize the 3D model. Computer-aided design standards can be developed over time.

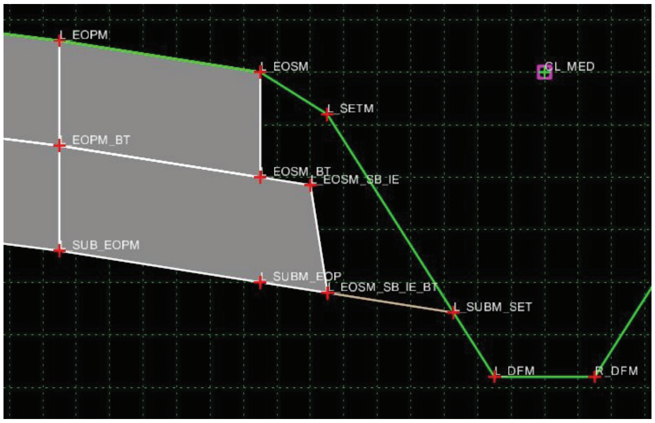


Figure 3-15. Templates with specific point names are critical when creating 3D engineered models that are compatible among agencies and contractors.

Table 3-1. Example Point Names and Corresponding Components for Roadway Templates.

Point Name	Component
L_EOPM	Left Edge of Pavement Median
L_EOSM	Left Edge of Shoulder Median
R_DFM	Right Ditch Front Median

Interval Spacing

The files that are available for AMG also need to be designed at the correct interval. The interval refers to the lateral distance between X, Y, and Z coordinates that make up a 3D surface. The interval can also be used interchangeably with the term "template drop."

The Iowa DOT initially chose 10 ft as the interval for creating machine guidance surfaces, which was adequate for grading but insufficient for paving purposes. After discussions with the construction industry, the DOT implemented a 5-ft minimum interval for pavement surfaces. The industry indicated that intervals greater than 5 ft caused cording in the surface that the paver could not span. The result was poor pavement smoothness. Designers can go down to intervals of 2.5 ft or even closer to ensure a smooth surface, especially through horizontal and vertical curves. To balance the additional effort and keep file sizes in check, however, 5-ft interval spacing is recommended for pavement surfaces and 10-ft interval spacing for grading surfaces.

Design teams should also use an appropriate interval frequency for different stages of plan development. The Iowa DOT uses 25-ft intervals for the preliminary design stage since the project would not be constructed from the model and accuracy requirements are not as stringent. When right-of-way needs are being investigated, designers should use a maximum interval of 5 ft to minimize the opportunity for irregularities between template drops. A maximum interval of 5 ft is recommended for later stages of design as well, including final design. This shorter interval improves the accuracy of the model and reduces the potential for errors within the project limits.

Software Capabilities

Agencies are encouraged to discuss software capabilities with vendors prior to implementation of 3D design and construction. Some designers and agencies are unaware of the capabilities that are provided by software currently on the market. Designers must understand how the 3D information they provide to contractors can be used. New software capabilities allow contractors to use and manipulate the 3D model for their own purposes. Contractors can use the model for activities such as crane locations to determine pick distances or for deep-trench excavation limits. Because of contractors' abilities to manipulate the 3D model, accuracy and quality assurance are essential unless specifications state each file's intended use.

Bid Letting

The 3D engineered model can be provided to contractors during the bid preparation process. This allows the contractor to review the files prior to submitting a bid to the agency. Agencies that have implemented 3D engineered modeling have discovered that contractors are interested in all applicable files that can be provided to them.

The agency should provide all files that will be used by the contractor for construction purposes prior to the bid letting. Because of the lengthy bidding process, sometimes two to three months can pass between completing final design and awarding the contract. 3D-savvy DOTs have discovered that it takes a fair amount of time and effort to gather relevant construction files for the contractor after the design team has been away from the project for this length of time. It is more efficient to provide the files immediately after final design has been completed while the project is still fresh in the design team's mind. This approach also levels the playing field for all potential bidders and avoids a potential unfair advantage for contractors who knew the files would be available after bid letting.

Agencies that provide files to contractors prior to the bid letting should have a system in place to provide standardized deliverables for all projects. The agency should determine what files they will be providing to contractors and set standard naming conventions for all files. A good rule of thumb for standardized file naming is to include a one-word description of what each file contains. Examples of this are the following:

- Paving files should contain "_pave" somewhere in the file name.
- Grading files should contain "_grade" somewhere in the file name.

All deliverables that are 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.

Agencies may need to modify their existing specifications to accommodate 3D design files. The Iowa DOT still considers the paper plan set the "signed and sealed" data. The 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.

Any files that are provided prior to the bid letting should be provided on a web page or ftp site that can be easily accessed by contractors. Through experience, the Iowa DOT determined that files could be easily missed if they were hidden somewhere within a third-party bidding software package. By providing the files in an easy-to-access location, all contractors are able to utilize the same models, hopefully reducing the risk for contractors and potentially reducing bid prices.

During the early stages of 3D implementation, the Iowa DOT learned that contractors wanted a separate bid item for the development of 3D files for AMG. Contractors did not want to add the file development cost to their "mobilization" bid item. This bid item was always optional for contractors except for the very first AMG project that was let by the DOT. Not only did this provide a dedicated bid item for the development of AMG, but it also was used as a tracking method to see which bidders were planning to use AMG on each project. Now that AMG has become commonplace in a majority of DOT projects in this state, this bid item is no longer used.

Chapter 4: Application of 3D Engineered Models in Highway Construction

3D engineered models and the associated technology have many applications during the construction phase of the project and beyond. Construction equipment can be controlled through GPS or total station technology, eliminating the need for extensive staking and providing more accurate results. The reduction of workers adjacent to construction operations can enhance project safety. Contractors can reduce risk by utilizing DTMs for quick and highly accurate earthwork quantity calculations. Contractors can use schedule- and cost-loaded models to communicate progress or demonstrate the effects of changes. Technology also assists inspectors and facility managers in on-the-spot grade checks and by creating paperless as-built records.

AMG and Control Systems

Perhaps the most common application of 3D engineered models is the use of design files to facilitate AMG and automated machine control (AMC).

Automated Machine Guidance for Grading

Automated machine guidance for grading is a process in which grading equipment, such as a motor grader or dozer, utilizes onboard computers and positioning systems to provide horizontal and vertical guidance to the equipment operator.

Automated Machine Control

Automated machine control, although sometimes used synonymously with AMG, is a different system in which the guidance computer in the equipment is steering and guiding the equipment with minimal input from the operator. Automated machine control is often used in agricultural applications. The guidance system operates in the same way as AMG, utilizing GPSs, robotic total stations, or lasers to control its horizontal and vertical position on the site. There is still an operator on the equipment who can override the automated controls if necessary. The stringless paving systems on slip-form concrete pavers are an example of AMC.

Most new equipment can be purchased with AMG factory installed, but existing equipment can be retrofitted with this technology.

Equipment Applications

Automated machine guidance is often used on grading equipment, excavators, compaction equipment, and milling and paving equipment. This section covers how various pieces of construction equipment utilize AMG technology.

Grading Equipment

Grading equipment such as scrapers, motor graders, and dozers can be equipped with AMG that provides the operator with information on the position of the cutting edge with respect to the design surface without the use of grade stakes. A 3D engineered model, created by the contractor or designer, is loaded onto the AMG-equipped grading machinery. These machines reference the position of their cutting blades using GPSs, robotic total stations, or lasers. The machine's onboard monitoring equipment provides real-time grading information to the operator in the form of cut/fill distances based on the proposed grading surface contained in the 3D engineered model. Utilizing AMG for grading can reduce construction costs, optimize construction schedules, improve quality control, and, most importantly, improve the safety of workers. With AMG, the guidance system can make adjustments to the cutting edge of the machine but the operator is in control of steering the equipment. Figure 4-1 is a graphic that illustrates how grading equipment uses GPS satellites for AMG.

Automated machine guidance grading operators view a monitor inside the cab of their machinery that can provide information such as the current cut and fill distances in real time. Figure 4-2 shows a monitor inside the cab of a dozer equipped with AMG technology.

Figures 4-3, 4-4, and 4-5 show various pieces of grading equipment with AMG technology. Automated machine guidance equipment has the ability to adjust cutting blade elevations automatically if the cut/fill distance is small. If the

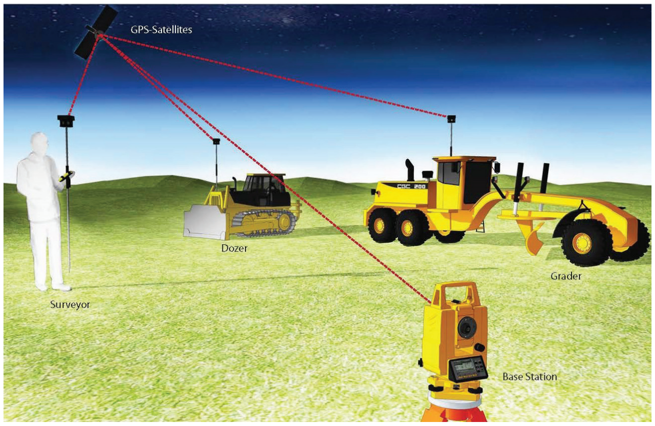


Figure 4-1. Automated machine guidance utilizes satellite positioning and onboard computers to guide the equipment.

Figure 4-2. Example of a monitor inside the cab of a dozer equipped with AMG technology.

Image obtained from Trimble Navigation Limited

Figure 4-3. A motor grader equipped with AMG technology.

Reprinted Courtesy of Caterpillar Inc.

Figure 4-4. A dozer equipped with AMG technology.

Image obtained from Trimble Navigation Limited

Figure 4-5. A scraper equipped with AMG technology.

Image obtained from McAninch Corp.

cut/fill distance is large, the machine operator adjusts the cutting blade elevations manually with the AMG equipment providing real-time grading data. In mass grading operations, this allows the equipment to perform grading operations without having to work around grade stakes. Although some staking is still provided as a quality control tool, the amount of construction staking is greatly reduced. Global positioning system-equipped dozers and scrapers are capable of cutting grade to an elevation of ±0.1 ft.

Global positioning systems include a complex system of sensors that knows the three-dimensional position of the cutting edge in space, adjusting for the angle of the blade, the slope of the ground, and even articulation of the wheels.

Excavators

Excavators can be equipped with a GPS or laser-controlled sensors that accurately measure slope, reach, and, ultimately, elevation. The operator is able to see both the design elevation and the elevation of the tip of the excavator bucket. See Figure 4-6. Typical systems include light bars in the cab, which give the operator an easy visual reference to check the progress of excavation. Most sensors are waterproof, allowing the operator to submerge the bucket under water without damage to the equipment. This technology is also coupled with excavators for operations other than utility trenching, such as grading slopes or drainage ditches. Excavators are equipped with a GPS to safely grade slopes or hazardous soils without the need for stakes, providing a safer working environment for construction crews.

Reprinted Courtesy of Caterpillar Inc.

Image obtained from Trimble Navigation Limited

Figure 4-6. The photo on the top shows an excavator equipped with AMG technology. The photo on the bottom shows a typical monitor found inside the cab of an AMG equipped excavator.

Compaction Equipment

Intelligent compaction (Figure 4-7) is a process that provides real-time data to roller operators regarding the compaction of material directly under the roller as it is operating. A roller outfitted with intelligent compaction equipment also has the ability to adjust the frequency and amplitude of the vibrating drum to ensure consistent and uniform material compaction across the entire project area. Rollers equipped with intelligent compaction technology can use accelerometers or other technology mounted on the machine to calculate compaction values in real time. The data collected with the accelerometers are coupled with location data relative to the project datum allowing the inspection staff and contractor to see where passes have met target values. By utilizing intelligent compaction, the roller has the ability to efficiently compact material to meet density specifications with fewer passes, reducing labor and fuel costs. The added information that intelligent compaction provides to field personnel can also improve the quality control operations of highway reconstruction projects.

Milling and Paving Machinery

Milling and paving machinery can use "stringless" control to guide the machine vertically and horizontally, creating very smooth, finished surfaces. Both portland cement concrete (PCC) and hot mix asphalt (HMA) paving machines (Figure 4-8) can be equipped with AMG technology.

Each State requires certain tolerances that need to be met when it comes to milling and pavement specifications. A typical stringless paving or milling machine that is controlled via robotic total stations can achieve tolerances as noted in Table 4-1. These tolerances are only approximate and various factors could affect the accuracy of each of these machines.

The accuracy of stringless milling machines (Figure 4-9) depend on the condition of the existing pavement that is being milled and the condition of the milling "teeth" on the machine.

Stringless operations eliminate the time of setting and removing the stringline and the hassle of diverting traffic around the stringline; they are also generally safer than conventional operations.

Stringless Technology

Stringless paving helps contractors deliver a more precisely controlled and constructed product—and pave more consistently, with improved ride quality. Figure 4-10 shows how stringless paving uses robotic total stations for machine control.

In order to understand how replacing stringline with stringless control improves paving accuracy in terms of machine control, one must first understand how a paving


Image obtained from Dr. David White, Iowa State University

Figure 4-7. Intelligent compaction can utilize GPS for location on a project site.


Image obtained from Trimble Navigation Limited

Figure 4-8. Stringless paving can be used for asphalt applications in addition to concrete.


Image obtained from Trimble Navigation Limited

Figure 4-9. Stringless technology mounted on a milling machine.

Table 4-1. Typical Tolerances Achieved with AMG.

AMG Machine Type	Verticle Tolerance	Steering Tolerance
PCC Paver	0.010 ft	0.036 ft
HMA Paver	0.016 ft	0.036 ft
Milling Machine	0.017 ft	0.036 ft

machine references a stringline in a string-controlled operation. Stringline operations use a steering control sensor and an elevation sensor on the paving machine (Figure 4-11). The steering control sensor touches the inside of the string, and the elevation sensor touches the top or bottom of the string. This is the guidance control mechanism for

Stringlines represent the three-dimensional pavement edges using a series of chords, or line segments. The chords are easy to see in Figure 4-12. Even with the stringline support stakes at very close intervals around this intersection radius, true curves cannot be built. The pavement smoothness can only be as good as the segmented stringline

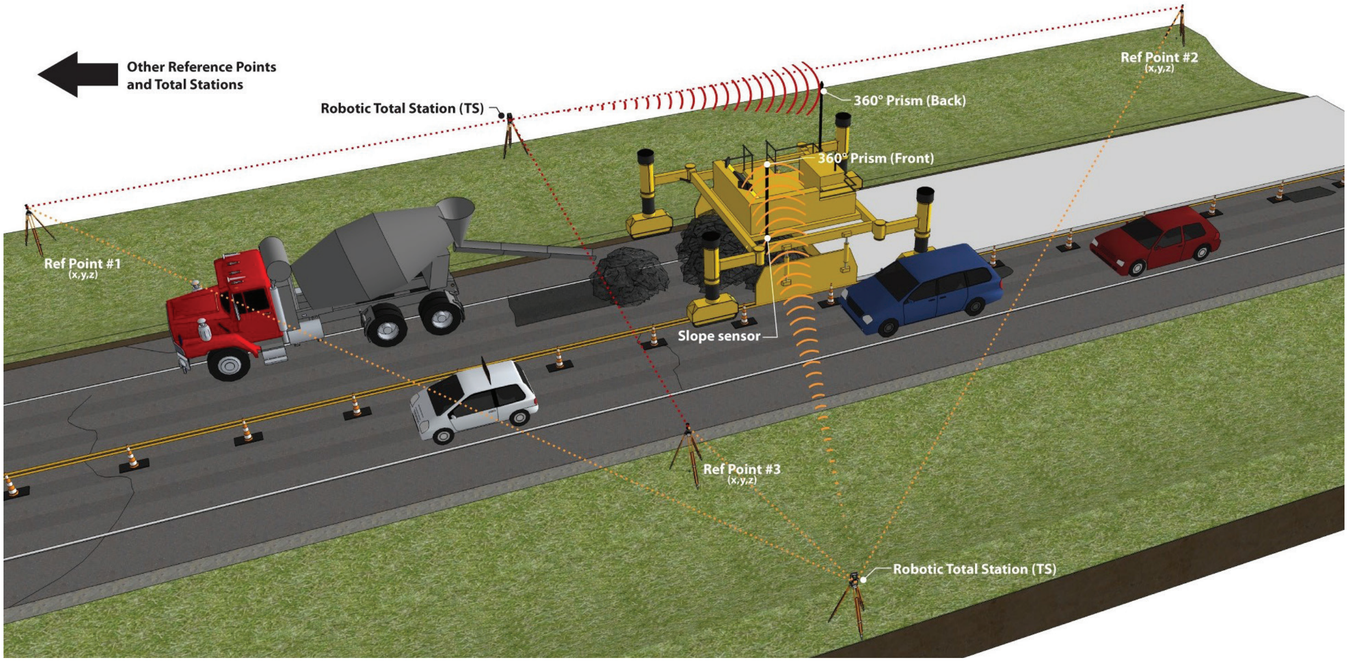


Figure 4-10. How stringless paving machines use robotic total stations for horizontal and vertical machine control.

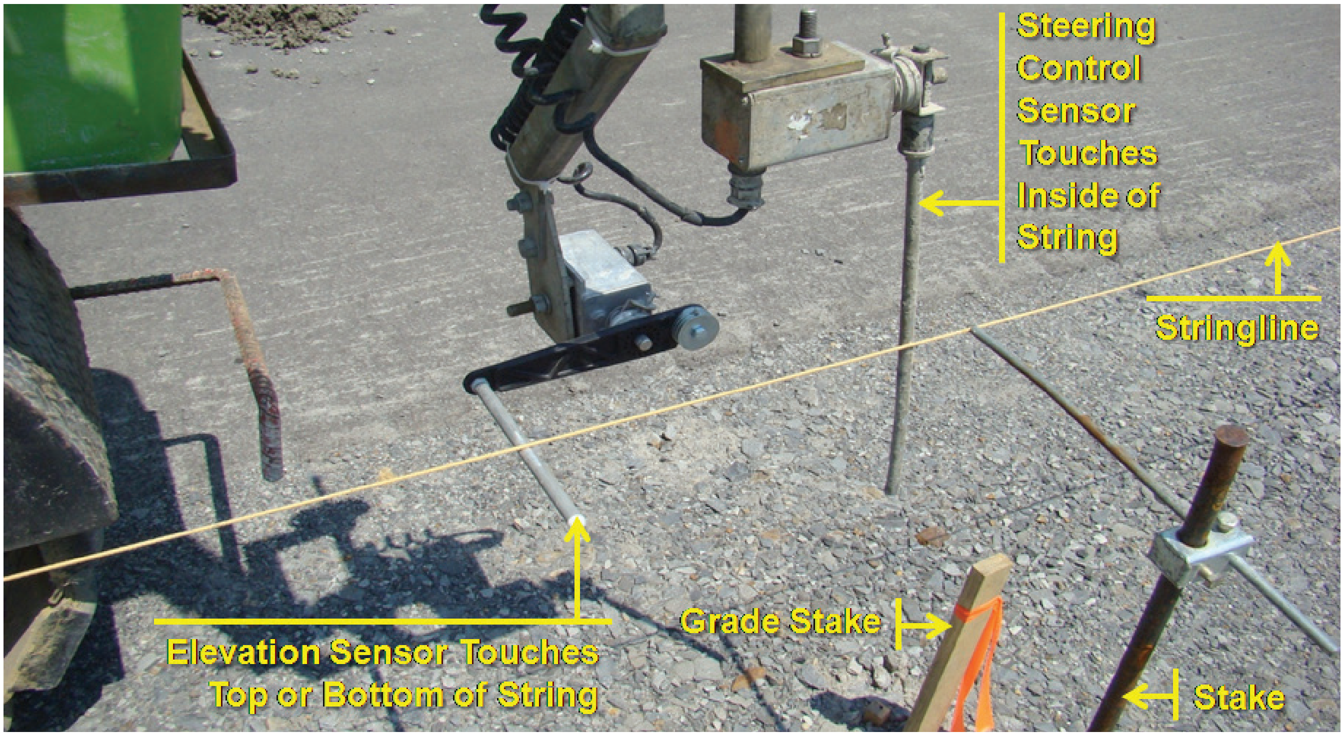


Image obtained from the American Concrete Pavement Association

Figure 4-11. Traditional stringline paving relied on sensors to detect changes in elevation and direction, which introduced the opportunity for human error.

input. This is true for horizontal curves and vertical curves as well.

Stringless technology represents the pavement using mathematical equations representing tangents and curves, creating a “true” profile. The 3D model will represent the pavement edge as a smooth arc, which is how the paving machine will subsequently pave the edge. Figure 4-13 shows a smooth curve using stringless paving technologies. The result is a higher-quality pavement surface.

Stringless paving also eliminates potential problems with string-controlled technology, such as the following:

- 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.

Image obtained from the American Concrete Pavement Association

Figure 4-12. Traditional stringline near a curve.

Image obtained from the American Concrete Pavement Association

Figure 4-13. A horizontal curve that was paved using stringless technology.

Figure 4-14 shows potential problems that can be caused by using traditional stringline.

Because of the improvements in how a paving machine is controlled by a stringless system, there are many overall quality and process control advantages with stringless paving technology.

Stringless milling machines use a process similar to stringless paving. Stringless milling operations enable truly variable-depth milling versus traditional milling operations. With traditional milling techniques, a consistent mill depth would be set on the machine and it would maintain the existing profile of the roadway. With the existing profile of the roadway being maintained after milling, overlay projects run the risk of quantity overruns to balance “bumps” and “dips” in the existing pavement to achieve the proposed pavement profile. Stringless milling operations are superior in these cases because the machine automatically adjusts the track height of the machine to meet the milled surface profile called for in the 3D engineered model.

Computer Inputs

Contractors should use the same 3D engineered model for all aspects of construction. This ensures consistency between the grading, trimming, and paving surfaces. For example, if the contractor were to use a grading file that has been manipulated, the unmodified paving surface may not match the ground elevations after grading. By using the same 3D model for all AMG activities, there will be a reduced risk of surface elevations that do not match.

As with all AMG-equipped machinery, the contractor will need to upload the 3D engineered model into the AMG system. Automated machine guidance systems are only capable of accepting specific file types. When the Iowa DOT began providing 3D files to contractors, they initially tried to provide files in formats that were compatible with individual pieces of equipment. This was very time consuming, however, and the additional effort did not seem to meet the needs of contractors and their equipment. The DOT arrived at the generic formats shown in Table 4-2. Contractors need to convert the generic file formats into a compatible file type prior to uploading it to their system. A fully designed 3D engineered model contains the proposed grading surface and proposed features, and it is able to guide grading machines and excavators when they are referenced to control points set up on or near the project site.

The 3D model file is parsed, or trimmed, by the contractor's CAD technician to eliminate unnecessary data and manage file size. Excess data are excluded in the transformation process. Much of the technique and specifics pertain

Table 4-2. Iowa DOT Recommended File Formats for Data Sharing.

Information Contained Within File	Recommended File Format
Alignment	Land XML
Surfaces	Land XML
3D Line Strings	DXF

Automated machine guidance excavation equipment requires similar inputs to AMG grading. The surface or surfaces (existing or proposed, or both, depending on the type of excavation), as well as the bottom of the trench, must be loaded into the equipment. Depending on the type of excavation, it can also be useful to include 3D lines of existing and proposed utilities. This ensures the operator will know the location of the excavator's bucket in relation to the proposed and existing features. Figure 4-16 shows how an AMG-equipped excavator uses the 3D model for trench excavation.

Paving and Milling Machines

Stringless paving uses different inputs compared to AMG grading and milling. Design data for stringless paving must be derived from the 3D engineered model, including the

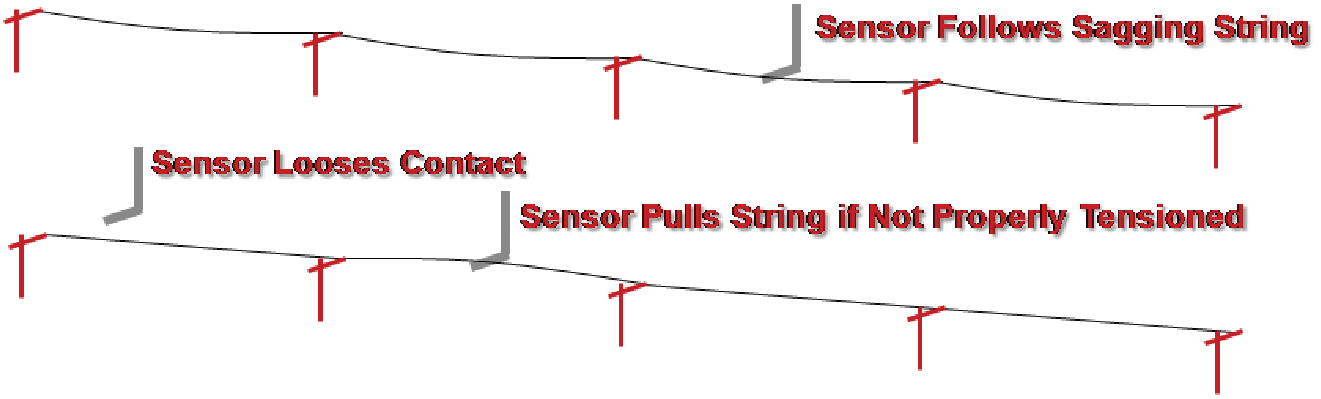


Image obtained from the American Concrete Pavement Association

Figure 4-14. Illustration of the errors that can be introduced using traditional stringline for paving operations.

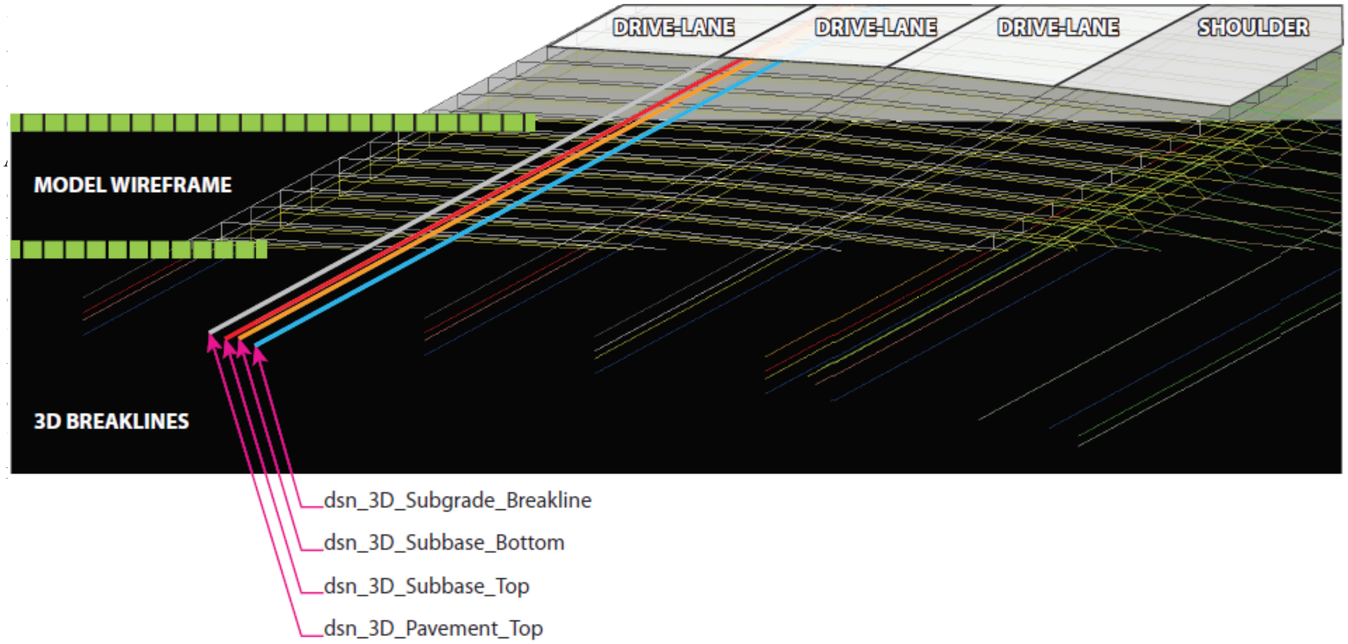


Figure 4-15. 3D breaklines contained within the 3D engineered model are used by AMG equipment for horizontal and vertical control.

plan, profile, and geometrics. The contractor must manipulate and reduce the 3D engineered model to create the machine input data that control the paving machine.

3D Breaklines

3D breaklines are lines in a file that reflect a distinct change in surface type or slope. 3D breaklines contain X, Y, and Z coordinate information that can be referenced by AMG equipment.

Data conversion transforms the CAD coordinate data contained within the 3D engineered model into 3D line strings and curve equations representing the pavement edges and interior breaklines (Figure 4-17). A typical CAD file contains a significant amount of information that is not actually necessary for paver guidance.

Figure 4-18 shows a portion of the I-35 and IA92 interchange with the 3D line strings visualized. Part of the transformation process is to extract the 3D line strings that represent the pavement edge lines, significantly reducing the amount of information the onboard stringless computer must interpret. Conversion takes a series of 3D points within the model or coordinates and turns them into lines and curve equations.

Stringless milling machines operate similarly to AMG grading technologies. Stringless milling machines must have the 3D engineered model converted into a format that is compatible with the AMG system prior to uploading it to the machine. The milling machine reads the 3D engineered model's proposed pavement elevations and adjusts the mill heads to remove existing pavement to the appropriate depth.

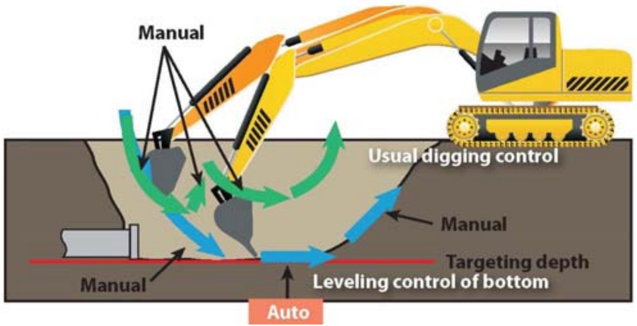


Image obtained from Hitachi Construction Machinery Co, Ltd.

Figure 4-16. AMG excavators use the 3D engineered model for trench depths and alignment.

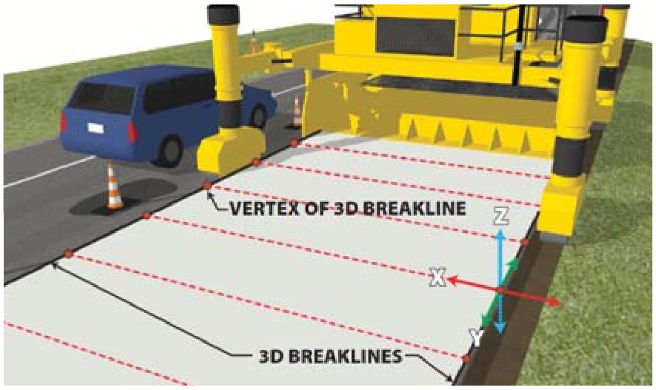
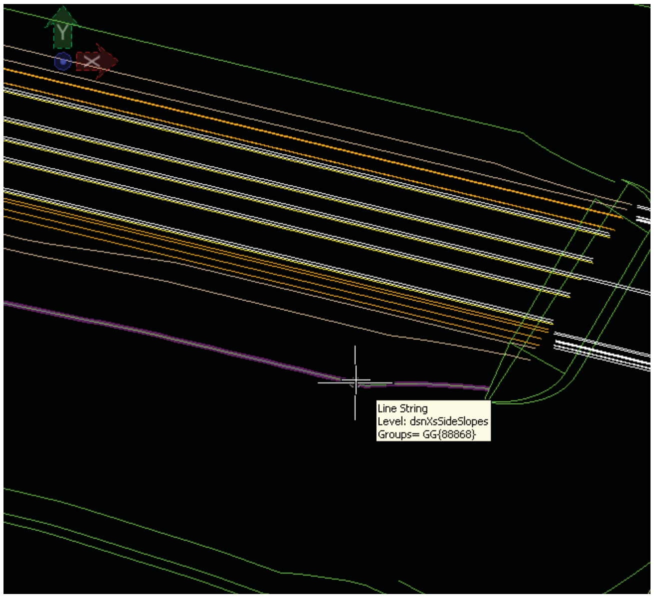


Figure 4-17. Pavement edge lines and breaklines are necessary for stringless paving control.



Line String
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Groups= GG{88868}

Figure 4-18. 3D line strings on the mainline alignment on the I-35 and IA92 interchange.

AMG User Guidelines

This section provides guidelines for training, error checking, file management, and other specific topics related to the use of AMG.

Training

With so many types of advanced AMG systems in use today, it is important for contractors to seek out training opportunities for their equipment operators. Global positioning system usage has become so commonplace in the construction industry, it is generally assumed that operators are familiar with GPS technologies. Many operators are union members and receive formal training as a part of their apprenticeship. When new equipment is purchased, some amount of training is typically provided by the equipment vendors. Many vendors offer additional training classes free of charge when equipment is purchased. Often, there are yearly courses or renewal opportunities that contractors can attend. These range in cost and complexity, from free seminars to in-depth training costing several hundred dollars per person to attend.

Agencies are encouraged to work closely with contractors and AMG equipment manufacturers when developing specifications and methods for implementing AMG construction. Contractors and suppliers will provide useful input when it comes to files that are useful and those that are not necessary.

Error Checking

Error checking the data from the CADD files is one of the most important steps in data transformation and should be performed prior to parsing, or trimming, the 3D engineered model. Error checking also is critical to finding misalignments and other issues that are not reflected in the CADD files. This should be considered similar to a contractor "eyeballing" a stringline or checking stakes prior to commencing operations.

Traditional methods of construction relied on surveyors as another layer of quality assurance. Surveyors typically filled in "holes" in the construction documents by interpreting plan information. With the reduced amount of grade stakes provided with AMG construction methods, 3D engineered models need to be checked on the computer screen with a higher degree of scrutiny. The 3D engineered model cannot contain any gaps or "holes" in the design surface. It is also likely that pavement tie-in elevations will be slightly different than the original design and should be checked prior to paving. For example, a 3D engineered design model would be designed to tie into the end of a constructed bridge approach at the precise design elevation. It is likely the actual constructed approach varies slightly from designed elevations because of construction tolerances. These variations will have to be corrected in the model before paving. If the variations are significant, it is good practice to involve the designers to be able to make corrections to the model to reflect the actual field conditions.

File Management

File management is an important task. Data files should 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. Stationing-based naming is recommended for paving segment files. Overlap or "run-in and run-out" sections from the 3D model should be provided for each paving segment. Run-ins and -outs should be several machine-lengths to make the job easier for the machine operator to get "online" and aligned by the beginning of the actual segment.

Contractor Creation of 3D Engineered Model

In some cases, the 3D engineered model is not made available to contractors, leaving the contractor to create a proposed surface on their own. Some larger contractors have in-house staff to perform this task, and others hire a subconsultant to build it for them. Using AMG for grading operations saves a substantial amount of time and money, so often a contractor will still be "money ahead" by paying to have this file built.

Recreating the proposed grading or paving surface from the construction plans is sometimes a difficult proposition, and contractors are happy to take any files that are provided to them instead of having to build the model from scratch. Sometimes the contractor's technicians are able to uncover errors in the original design during this process. Uncovering errors at this stage in the project before construction is under way can save everyone involved significant time and money. If an error is significant, the designer can often make plan revisions to account for it prior to construction. In other cases, new errors can be introduced by the creator of the AMG files. For this reason, surveyors are needed to accurately stake out specific project details and finished surfaces at reduced intervals. The AMG grading file is typically sufficient to "rough in" the site grading, and surveyors provide stakes for utilities, paving, and other elevation-sensitive items.

Uploading the 3D Engineered Model

In addition to the initial AMG setup and training, the contractor needs to have the ability to upload the 3D engineered model into the AMG equipment. As mentioned previously, the 3D engineered model provided by the designer may need to be converted into a compatible file format that can be loaded onto the appropriate machinery.

The contractor needs to be able to receive these types of files, condense or convert them as needed, and transfer them onto their equipment. This can be done through traditional methods, such as memory cards or USB devices, or via wireless methods in more high-tech applications. Some new equipment has Wi-Fi technology built in, and files can be sent wirelessly to users in the field.

Equipment Check

When the AMG equipment arrives on the site, the contractor must perform an equipment check prior to use. Automated machine guidance equipment should be checked for any parts that could have become loose or damaged in transit. If the AMG equipment requires adjustment or repair, the contractor needs to ensure it is remounted and checked for proper elevations prior to beginning construction. If not installed properly, AMG equipment is not able to achieve the required tolerances needed for accurate machine control. Concrete slip-form pavers equipped with stringless AMC must be calibrated each time the paver is modified in any way (width is changed, prism masts are removed and replaced, etc.). This allows the system to know the exact position of the pan of the paver in relation to the prisms on the paver. Failure to properly calibrate the stringless paving system may result in a poor concrete surface finish or the paver not paving at the correct elevation and position.

Construction Staking Requirements

Traditional construction staking requirements can be reduced for machine guidance in an effort to increase cost savings. Reducing the requirements for construction staking also improves safety for surveyors traversing the construction site while in close proximity to large equipment. Construction staking, although limited, is still required at reduced intervals to assure the 3D engineered model and construction equipment is giving the correct layout and elevations. This provides another layer of quality control for a more accurate finished product.

It is important to note that construction surveyors are still a necessary component in project construction utilizing AMG. The construction surveyor will play a larger role in the quality-control process than with traditional methods.

Survey Base Station

A survey base station or control network needs to be set up near the site prior to any machine control use. Machine control grading activities including dozers, excavators, and motor graders typically use GPSs for AMG. The AMG system needs to be able to reference a known X, Y, Z coordinate location through a GPS base station, such as a portable GPS unit on site, or a CORS. The GPS base station transmits corrections to the GPS receiver on the associated AMG equipment.

For proper use of AMG technology, accurate survey control is a necessity. The survey control should contain at least one “monument” survey point that is set by a licensed surveyor and remains undisturbed throughout construction. Some states that have successfully implemented AMG technology rely on a monumented survey point that has specific X, Y, Z coordinate data that are used by the surveyor, contractor, and inspection personnel. The benefit of all parties using the same control point is an added layer of quality assurance that construction is meeting the designed elevations.

Survey Control and Machine Control for Stringless Operations

Survey control and machine control for stringless operations is different than the GPS base stations used for grading operations. Stringless paving and milling machines typically use total stations for machine control purposes because paving and milling operations require tighter tolerances than what is necessary for grading purposes. As with machine control grading, stringless guidance systems need to know their location in space (X, Y, Z coordinate). For total stations, survey control points are set by a surveyor. Typically, control points are set along the project corridor at approximately 250-ft intervals. Control points for stringless paving should be established from accurate field surveying and tied to known benchmark(s). These control points should be positioned out of the way of any operations, where they are not disturbed by the public, and to allow instruments for machine control to see at least three control points at all times. Figure 4-19 shows a typical layout for control points on stringless paving applications.

Challenges and Limitations

Contractors are often faced with difficult or challenging conditions on sites in which to deploy their equipment. Contractors should be aware that not all sites can easily use some of the technologies discussed. Challenging conditions can include everything from hilly terrain, obstructed satellite windows, or even small sites with lots of equipment in a congested space. When satellite views are obstructed on the project site, contractors may have to incorporate the use of total stations because of the lack of satellite signal strength. Heavily wooded sites or urban environments with tall buildings are common areas where obstructed satellite views may be present. Contractors need to ensure adequate satellite signal strength to use GPS-controlled AMG construction.

Scheduling, Cost Estimating, and Project Management Applications

3D engineered models can assist contractors with scheduling, cost estimating, and project management applications.

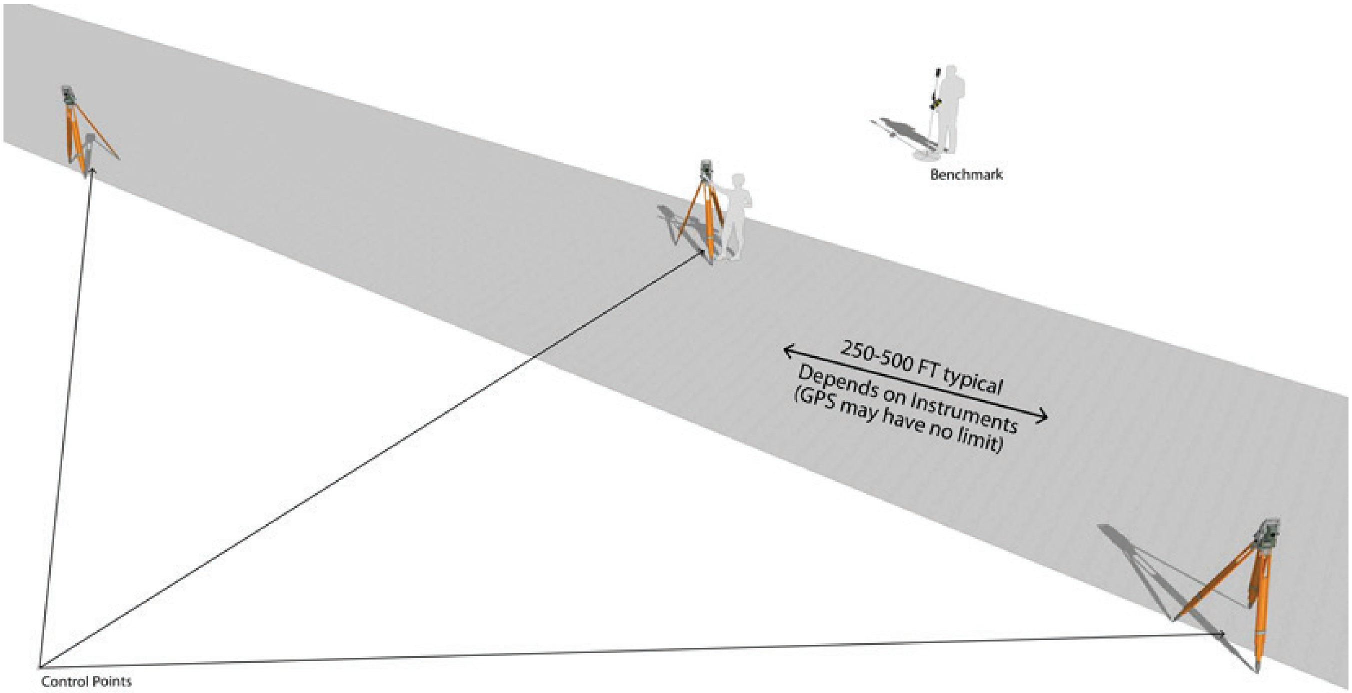

Figure 4-19. Survey control points on a typical stringless paving project.

These applications not only benefit the contractor, but they also provide increased value to the project owner.

DTMs and Earthwork Quantity Estimation

With a DTM and the detailed site survey collected by expanding survey technologies, contractors are able to precisely and accurately calculate the project quantities using the 3D engineered model. The methods of earthwork calculation between proposed and existing 3D surfaces have a significant advantage over the end-area method still used by many DOTs. The computer effectively calculates the cut/fill quantity at very small intervals throughout the model limits. The DTM may also be used to balance earthwork and plan haul routes with optimal efficiency. Last-minute changes to the construction plans may be referenced in the model but not make their way into the details of the construction plans. Accounting for these intricate details can also be the difference between making money and losing money on a project.

Figure 4-20 shows a cross section earthwork shape using the traditional end-area method.

4D and 5D Modeling and Beyond: Contractor Applications

While currently only used on very complex projects in which modeling efforts produce a return on investment, advanced models can be constructed using the 3D engineered model as a base. This is beyond the scope of this manual, but the use of 3D engineered models can bring about the use of civil integrated management (CIM) and 4D and 5D models.

While a 3D model is a digital graphic representation of the project in three dimensions, a 4D model incorporates temporal sequences (e.g., construction activities schedule) and/or temporal dynamic objects (e.g., moving vehicles or pedestrians) progressing over time. A 5D model carries the concept even further, taking the schedule-loaded project

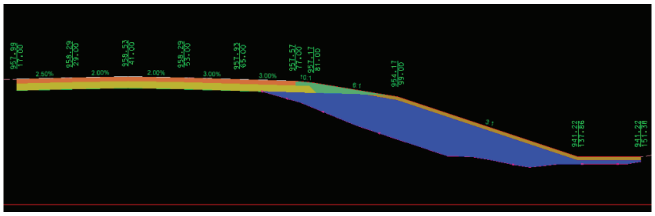

Figure 4-20. Traditional earthwork calculations were performed using the average end-area method at evenly spaced cross sections, similar to this graphic.

model and incorporating budget and cost expenditures.

Creating 4D models from 3D engineered models can facilitate communication between multiple stakeholders and allow contractors to streamline construction schedules. By having a 4D engineered model that incorporates scheduling information, contractors are able to see how each individual task can impact the schedule of the next phase of the project. The 4D model can graphically show progress and work areas through time. For instances in which crew productivities are incorporated into the model, durations of activities can be automatically adjusted if quantities are changed in the design model.

4D modeling is also very useful in projects with complicated staging. Whereas a model of a finished project may not appear to have any conflicts between proposed and existing features, a more detailed look at how the model evolves throughout the construction project may indicate problems with constructability such as deep utilities next to an existing lane that must be kept open for traffic or existing utilities within a trench for proposed utilities that must remain in service. 4D modeling is a powerful tool to identify and rectify these problems before construction, allowing the contractor to optimize the construction schedule.

When project cost information is incorporated into the model, it is referred to as a 5D engineered model. The Federal Highway Administration defines a 5D engineered model as “a 4D model intelligently linked with cost information for a project.” 5D modeling uses the scheduling component associated with 4D modeling and links that information to cost data associated with each aspect of the project. The major benefit of 5D engineered modeling is that all stakeholders in the project can see how changes/revisions in the project can affect the overall cost and schedule and provide cash flow models. It also allows contractors and designers to create more accurate cost estimates prior to construction.

The concept of linking other project data to the 3D engineered model is not limited to cost and schedule. Linking other data to the model would create the xD model. Like GIS, as the use of the technology becomes more widespread and interacts with other disciplines, new ways of using the technology and information will evolve.

Facilities Management

Civil integrated management is the collection, organization, and managed accessibility of accurate data and information related to a highway facility including planning, environmental, surveying, design, construction, maintenance, asset management, and risk assessment. It is similar to building information modeling (BIM), which has been successfully implemented by the architectural industry. Building information modeling is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle—defined as existing from earliest conception to demolition. One could easily replace the building with a roadway or bridge and this cycle would also apply to CIM.

Civil integrated management links the 3D engineered model created by the designer with schedule (4D) and cost (5D) information to create a model that can be viewed by all stakeholders of a project. Further as-built information is incorporated into the model. The techniques used in BIM can transfer to modern highway construction projects.

The CIM philosophy is not widely used today, and the benefits of CIM along with 4D and 5D modeling are only recognized if users have been properly trained in successful operation of the associated software. Implementation of 4D and 5D modeling software can be difficult, and contractors that would like to implement CIM on their projects should recognize that training is required for employees to utilize the software efficiently. The extent of training required can vary widely depending on which software program is used. Also, wise decisions about the appropriate level of detail for the model are necessary to optimize management efficiency.

Quality Assurance and Post-construction Applications

In addition to increased schedule efficiency and cost savings, another benefit of 3D engineered modeling during the construction phase is the ability for inspectors to use handheld GPS equipment to spot-check elevations and horizontal offsets. With traditional 2D methods of construction, inspectors had to rely upon grade stakes and 2D paper plan sheets to ensure that grading operations were being constructed as the design intended.

With the proposed grading surface within the 3D engineered model, inspectors should traverse the site and take random spot checks with GPS rovers similar to the one shown in Figure 4-21 to make sure the site is being graded properly. The handheld GPS equipment is able to compare the currently graded elevations to the proposed design surface at all locations within the 3D engineered model’s limits.

Similarly, the inspector should spot-check elevations behind the paver to ensure the paving equipment is set up and working properly. If problems exist, they can be quickly resolved, thus reducing the amount of rework needed. By having the ability to spot-check elevations quickly and easily, inspectors can improve the QA/QC process during construction.

Inspectors can also benefit from the use of electronic tablets and laptop computers while on the job site similar to the one shown in Figure 4-22. These devices can be uploaded with the most current 3D engineered model, and they will have access to any design changes or other modifications that have been updated in the model through an Internet connection. Inspectors will also have the ability to quickly calculate quantities and document testing information on the tablet, reducing paperwork and streamlining the project documentation process. Inspectors would be able to store information and type notes on the tablet, sending the information wirelessly to the engineer and/or contractor. It should be noted that unless a tablet is coupled with measuring sensors, current technology does not provide the capabilities for it to be used as a measuring device.

To successfully provide quality control during construction, on-site inspectors should be working from the same up-to-date files the contractor is using. Any irregularities or discrepancies between surfaces can create coordination problems and the potential for costly rework.

Through the experience gained by working with 3D engineered models during construction, the Iowa DOT requires the contractor to provide their own equipment for quality control on-site. The contractor provides the GPS equipment for use by inspection personnel with some training. There are a few different reasons for this. First of all, the cost of the equipment is incorporated into the project cost so the agency does not have to budget for the expense of buying and maintaining the rovers. Secondly, any potential discrepancy caused by different equipment suppliers is eliminated. If the contractor provides the rover, all parties are working from the same files and equipment.

New technologies have also provided the ability to accurately gather utility location information during and after construction, improving the as-built documentation process. Handheld GPS devices enable the inspector to record the horizontal locations of utilities such as fire hydrants, structures, valves, and pipelines. This location information can then be transferred into an agency's GIS database, allowing the data to be shared among a variety of users. This new technology also allows for quick and accurate documentation of any utility relocations and design modifications as they are happening during construction. Handheld GPS devices similar to the ones shown in Figure 4-23 and Figure 4-24 do not provide reliable elevation data collection. Rather, GPS rovers need to be utilized to accurately record the elevation value of utilities.

Image obtained from Trimble Navigation Limited

Figure 4-21. Construction inspectors can use survey-grade GPS rovers to traverse the site and spot check elevations.

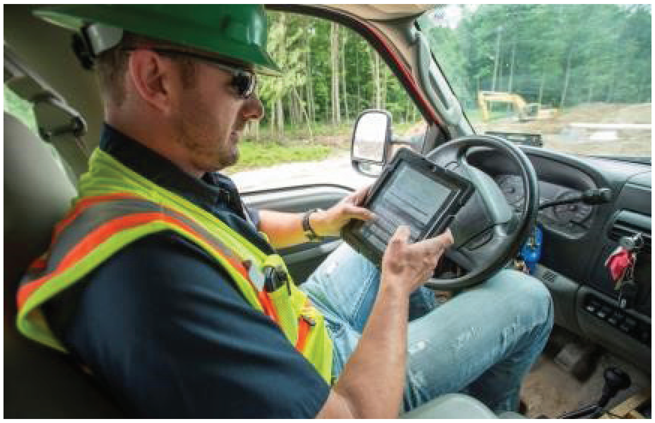

Image obtained from the Michigan DOT

Figure 4-22. Tablets can be used by inspection personnel to record notes, calculate quantities, and document field modifications.

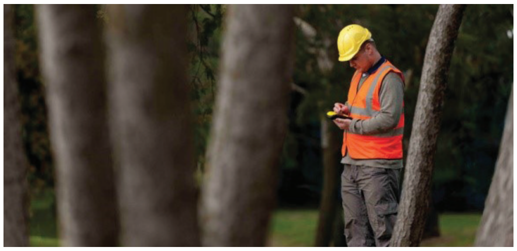

Image obtained from Trimble Navigation Limited

Figure 4-23. Handheld GPS devices can record horizontal locations of utilities and other pertinent information on the project site.

Image obtained from Trimble Navigation Limited

Figure 4-24. Handheld GPS device.

Record Drawings

Construction completion is not the end of the usefulness of the 3D engineered model. With traditional 2D methods, record drawings were developed based on memory and hand-written documentation of the contractor, construction observer, and engineer. If the record drawings are not updated throughout construction, there is a risk of forgetting important information that should be included. Traditional methods of developing record drawings also included obtaining as-built survey information—often requiring the owner to incur additional costs to perform this survey.

The 3D engineered model can be updated throughout construction using a mobile computer system. Special construction information and field modifications can quickly and easily be updated in the model. After construction is complete, the 3D model becomes the record drawing without the need to obtain an additional as-built survey.

Thorough record drawings are also a very important aspect when maintenance needs develop along the corridor. All construction projects have a useful life, including projects that originally utilized 3D engineered models. The 3D model, as updated through construction, will have useful benefits after construction as a base map for future maintenance or reconstruction projects, as accurate data in a GIS database, or to update asset management systems.

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