3D Design Terrain Models for Construction Plans and GPS Control of Highway Construction Equipment

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16. Abstract

Research was conducted with the objectives of 1) identifying and characterizing benefits and technological, institutional, cultural, and legal impediments associated with adoption of 3D design and construction technologies, identifying strategies to overcome the impediments, and making recommendations to the target transportation organizations; 2) determining the relationship between surface-to-surface and average-end-area methods for earthwork calculations; and 3) describing, and providing examples of, methods for describing the functionality of 3D design software with the intent of suggesting techniques that could assist in evaluation of software products for those organizations considering adoption of them. The research was motivated by rapid development of 3D technologies for highway design and construction, but slow adoption of them by state highway agencies (SHAs).

A web-based survey, with 70 percent response rate, was conducted of all 50 SHAs and seven class one regional railroads. Analysis of the results yielded ranked benefits and impediments, and associated information, for 3D design methods and automated machine guidance. Based upon survey results, three exemplary SHAs were selected for in-depth case studies, yielding strategies that have been used to successfully overcome some of the impediments.

A comparison was made between average-end-area and surface-to-surface methods calculation of earthwork volumes at six roadway construction sites in North Carolina and Wisconsin. Data were provided by the respective SHAs and by two Wisconsin contractors. In general, differences between the results of the two methods increase as cross section intervals increase, although the relationship is not linear. Differences as great as 5% were observed. This results in significant cost differences for large projects.

Three methods for describing 3D design software functionality were described with examples. Such methods can be useful for SHAs doing comparisons of software alternatives. A total of 26 recommendations for SHAs are presented in five groups, depending upon the SHAs' objectives. The recommendations address buy-in and commitment from upper management, development of specifications for automated machine guidance, adoption of 3D highway design technology, development or improvement of 3D data flows from design to construction, and broader implementation of 3D technologies for design and construction, in general.

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Executive Summary

Advanced technologies, having significant benefits for highway design and construction, are being rapidly developed but slowly adopted. Many of these technologies, for example automated machine guidance (AMG) and 3D design software, are spatial in nature and address three dimensions, while traditional design products and construction contract documents are two dimensional. This, in itself, is an impediment to more rapid adoption of the technologies, but there are subtler and deeper obstacles that must be overcome before the full benefits of these technologies can be realized.

This research was undertaken to identify and articulate the benefits of, and impediments to, adoption of 3D design and AMG by the transportation industry. There are some notable success stories with a few State Highway Agencies (SHAs) having championed these technologies and taken the lead in their implementation. These early adopters developed strategies to overcome technological, institutional, cultural, and legal obstacles and are now enjoying benefits that flow from improved ways of doing business. These working strategies are employable by others who want and are committed to change for the better.

Automated machine guidance and 3D highway design software began to emerge a decade ago. Their slow adoption by SHAs has been recognized for some time, and others, including the National Cooperative Highway Research Program (NCHRP), were early investigators of the causes. Some benefits and some impediments have been identified, but not often ranked as to importance. Very few strategies to move forward have been articulated. The research team's own experience and deeper interest in these matters arose through recent work with the Wisconsin Department of Transportation (WisDOT) to develop and implement a specification for AMG construction of highway subgrade, followed by further collaboration with the agency and other stakeholders to prepare a much broader implementation plan for 3D technologies for design and construction, in general.

This one-year research project built upon previous findings and included a nationwide survey of all SHAs and seven class one regional railroads. The response rate to the web-based survey was 70 percent. Based upon survey results, three exemplary SHAs were selected for case studies. The project also included comparisons of earthwork calculations done with 2D data (average-end-area) and 3D data (surface-to-surface). The North Carolina and Wisconsin DOTs and two Wisconsin construction contractors (Hoffman Construction and Wondra Excavation) provided data for these comparisons. The final component of the research was articulation of descriptive methods for 3D design software functionality, intended as guidance for SHAs beginning to assess software alternatives.

Automated machine guidance has a number of clear benefits, with reported contractor productivity gains as high as 40 percent. These productivity gains and associated lower costs for construction, greater accuracy, less repeat work, and less staking are all perceived or proven benefits that a majority of survey respondents identified as very important. Eighty-two percent of responding SHAs use AMG, but only 32 percent of these have specifications. Procedures followed without specifications could easily vary among projects and there is potential for poor use or poor practices. Automated machine guidance requires 3D digital models of the design surfaces and 80 percent of responding SHAs give contractors primary responsibility for producing these models from 2D plans. It can be inferred that a primary underlying reason for this is that only 19 percent of all responding SHAs have fully adopted design methods that produce a 3D model. Furthermore, 60 percent of respondents assert that engineering consultants rarely or never provide 3D digital data to construction contractors to aid in 3D model development. Survey respondents recognize three-dimensional design model issues as the most important impediment to wider use of AMG.

Although the majority of SHAs have not fully implemented 3D design methods, many agencies are in the process of or planning for adoption of them. There are significant benefits associated with 3D design methods beyond support for AMG. The highest ranked additional benefit is detection and elimination of design errors prior to construction, followed by improved visualization, and having a more comprehensive representation of design intent. However, significant impediments must be overcome by agencies prior to adoption of 3D design methods. The majority of respondents recognize lack of resources, agency lack of knowledge, entrenched business practices, lack of functionality in currently installed software, and required staff training as major obstacles. Inevitable technological advances are addressing lack of functionality, but the other identified impediments beg for education, training, and shared perspectives of agency missions.

Legal factors also hinder the transfer of 3D digital data between designers and construction contractors. Only 11 percent of responding SHAs provide any legal standing for 3D digital data in contract documents. Primary issues include electronic signatures, transfer of liability as related to data exchange, data security, and auditability of plans. Professional licensure for those responsible for 3D model development is also an issue.

The case studies of Minnesota, North Carolina, and Wisconsin DOTs revealed some keys to overcoming impediments to adoption of 3D design methods and AMG:

1. Buy-in and support from upper-level management.
2. Cross-cutting, well-executed implementation planning, with short-term and long-term objectives.
3. Management-level oversight and coordination of large, interdependent initiatives.
4. Champions: individuals or small groups with vision and commitment who take leadership roles and are persistent at moving forward.
5. Timely, well-designed, and delivered education and training at multiple levels within the SHA.
6. Internal and external stakeholder participation in planning and implementation processes.

The majority of SHAs are still using average-end-area to compute earthwork quantities. The surface-to-surface method is possible when 3D models are available, and authoritative sources state that this method is more accurate than average-end-area. Moreover, if 3D models are available, the surface-to-surface method is easier than average-end-area because there is no need to generate cross sections.

A comparison between earthwork quantities calculated using the surface-to-surface and average-end-area methods was conducted for six different sites. Volumes were computed using the average-end-area method at cross section intervals ranging from 10 to 100 feet to determine effects of cross section interval on the difference between surface-to-surface and average-end-area results. In most cases, increasing the cross section interval used in average-end-area earthwork calculations led to larger percentage differences between average-end-area and surface-to-surface results. For large projects, the differences in earthwork quantity estimates are large enough to cause considerable cost discrepancies among methods, particularly when 100-foot cross section intervals are used. Cross section intervals of 50 or 100 feet are commonly used in practice when computing earthwork quantities using average-end-area.

These findings, and others described within, lead to the following recommendations:

For SHAs seeking buy-in and commitment from upper management:

1. Draw upon existing information sources for summaries of benefits and reasons for moving forward with adoption of integrated 3D technologies, including 3D design and automated machine guidance. Existing information sources include journals such as *Transportation Research Record* and *ENR*; proceedings of and presentations at conferences such as those of the Transportation Research Board (TRB) and the International Highway Engineering Exchange Program (IHEEP); documentation available from the AASHTO Technology Implementation Group on AMG; reports of

projects such as this one and those appearing below in the list of references, particularly (Hannon, 2007) and (Hannon & Sulbaran, 2008); and soon-to-be-forthcoming documents from the research project NCHRP 10-77: *Use of Automated Machine Guidance (AMG) within the Transportation Industry*.

2. Document statewide use of AMG by contractors and their desires for 3D design data. In many cases, the construction industry is ahead of the SHAs in realizing benefits of 3D technologies.
3. Prepare and present executive summaries of the materials recommended in (1) and (2) and tailor them to the particular needs and circumstances of your SHA.
4. Encourage upper management to attend sessions on 3D technologies at TRB and IHEEP conferences, especially sessions that are designed for upper-management-level audiences.

For SHAs seeking specification development for AMG:

Recognizing that SHAs formulate and present their specifications in many different ways:

1. Draw upon the experiences and results of those SHAs that have gone through the process (e.g., Iowa, New York, Minnesota, Missouri, North Carolina, Wisconsin, etc.).
2. Involve both internal and external stakeholders in the specification development process to obtain their insight and their sense of ownership.
3. Include pilot projects, selected for their diversity in extent, duration, management characteristics, and terrain types in the specification testing and refinement process.
4. Begin with rough grading and move on to fine grading, base course placement, and paving.
5. Include aspects of quality assurance and inspection. These should be given careful consideration during development and thorough testing on the pilot projects.
6. Look to soon-to-be-forthcoming documents from research project NCHRP 10-77: *Use of Automated Machine Guidance (AMG) within the Transportation Industry* for more detailed guidance.
7. Include education and training for office and field personnel as the specification is being implemented.

For those SHAs moving towards adoption of 3D highway design technology:

1. View and describe the process as “adoption of 3D design methods”, not “adoption of 3D design technology”. The technology is necessary, but not sufficient. Effective 3D design requires change (for the better) in the way of doing business.
2. Before embarking upon assessment of software alternatives, establish and agree upon business objectives and a structure for, if not details of, improved design processes.
3. Plan for phased implementation of the new methods and technology, beginning with simple steps and leading to more complex tasks and broader adoption.
4. Anticipate needs for training and retraining as new versions of software become available. Draw upon vendor training materials supplemented with examples specific to your SHA.

For those SHAs seeking to develop or improve 3D data flows from design to construction:

1. Document and understand existing data flows. Include internal (agency) and external (consultant and contractor) stakeholders.
2. Use the results from (1) to identify specific obstacles and bottlenecks (technological, institutional, and legal) that must be overcome.
3. Develop content, quality, and data exchange standards for 3D models. Include QC/QA procedures. Test and refine the standards. Involve key internal and external stakeholders in these processes.

4. Agree upon responsibilities for development and management of the data and changes to them. Include contractual priorities between 2D plans and 3D models. Consider adopting these aspects within specifications.
5. Consider revising policy documents and procedures that require the average-end-area method for earthwork calculations (both estimates and final quantities).
6. Establish a timeline for phased implementation (e.g., from selected projects to statewide; from pre-construction to pre-bid).

For those SHAs seeking broader integration of multiple 3D technologies:

1. Recognize that 3D is a way of thinking and doing business, not merely a collection of technologies.
2. Recognize that there are potential uses for 3D data beyond design and construction, into operations, maintenance, and planning.
3. Establish a vision statement describing the ultimate long-term goal of the undertaking.
4. Develop a high-level implementation plan for achieving the vision. The plan should identify business areas, technologies, and initiatives and the relationships and dependencies among them; include short-term and long-term goals; assign priorities and responsibilities; and include timelines and milestones. From the outset, involve internal and external stakeholders in the planning process.
5. Establish implementation teams at the operational level and a management team to oversee and coordinate the operational-level teams' efforts. Such teams should be identified in the implementation plan (3).
6. Develop a strategy for presentation and dissemination of the plan (3).

1. Introduction

1.1. Problem Statement

In recent years, three-dimensional (3D) design has become a part of the highway construction industry. A major reason for the use of 3D design is the emergence of automated machine guidance (AMG) for construction. In AMG, Global Navigation Satellite System (GNSS) and other spatial sensor technologies are used to aid earthmoving operations, which increases accuracy, reduces time, and reduces costs. Automated machine guidance requires a digital terrain model (DTM) that includes a 3D representation of surface topography. Such a representation of the design surface is required to guide the earthmoving equipment to appropriate elevations and grades. Three-dimensional design software is becoming more prevalent in the transportation industry, which allows for production of the appropriate models for AMG. However, many transportation agencies are currently providing contractors with two-dimensional (2D) plans. Thus, contractors are required to develop 3D models from the 2D plans, which increases time and cost. Figure 1.1 illustrates current and desired data and process flows from design to construction.

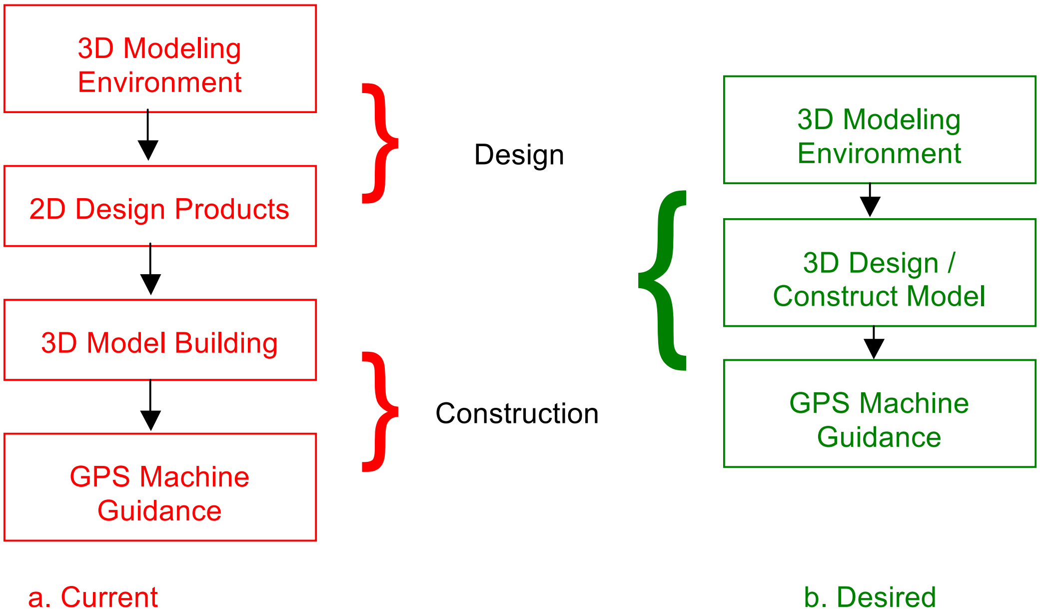


Figure 1.1: Data and Process Flows

Existing and final ground DTMs are typically developed for transportation construction projects. The existing ground surface is generated from survey data prior to design and construction. To determine earthwork volumes for a project after completion, an as-built survey to collect breakline and spot elevation data is typically conducted. These data are then used to produce an as-built DTM. Typically, an as-built DTM is overlaid with the original ground DTM and cross sections are cut through the two surfaces. These cross sections are typically used to compute earthwork volumes via the average-end-area method. However, it is possible to directly compute volumes from the two surfaces without generating cross sections. Computing volumes by differencing surfaces directly rather than using the average-end-area method is more efficient and some sources state it is also more accurate (U.S. Army Corps of Engineers, 2002).

There are numerous cultural, legal, and work process issues that must be addressed before agencies adopt 3D models as contract documents, fully adopt 3D design software, eliminate use of traditional cross sections, use DTMs to determine final quantities, and allow contractors to construct facilities directly from 3D models. These are not minor issues and must be identified and addressed carefully prior to implementing 3D design completely.

1.2. Scope and Objectives

The scope of this research is highway design and construction at state-level highway agencies and selected railroads in the United States. The objectives are to:

1. Identify and characterize benefits and technological, institutional, cultural, and legal impediments associated with adoption of three-dimensional design and construction technologies, identify strategies to overcome the impediments, and make recommendations to the target transportation organizations.
2. Determine the relationship between surface-to-surface and average-end-area methods for earthwork calculations. Models available from 3D design enable direct calculation of volumes between surfaces and it is important to understand numerical differences in results from this method versus those from the traditional average-end-area method.
3. Describe, and provide examples of, methods for describing the functionality of 3D design software with the intent of suggesting techniques that could assist in evaluation of software products for those organizations considering adoption of them.

1.3. Approach

This study had five primary components:

1. A literature review of previous research conducted in the area of 3D transportation design, AMG, and DTMs.
2. A survey of all fifty state highway agencies and seven class one regional railroads to determine the state-of-the-practice in 3D design, AMG, and computation of earthwork quantities and to identify benefits and impediments associated with adoption of 3D design.
3. Case studies of three progressive state highway agencies identified from the survey results to determine successful strategies and identify pitfalls when moving forward with 3D design and AMG.
4. Comparisons between results of surface-to-surface and average-end-area earthwork calculations for six different sites. The ability to use surface-to-surface calculations might serve as an incentive to adoption of 3D design.
5. Description, with examples, of three different methods for characterizing the functionality of 3D design software.

2. Literature Review

2.1. Automated Machine Guidance

In traditional earthmoving operations, grade stakes are used to provide machine operators with a visual guide to move materials to desired locations and grades. These grade stakes are marked to indicate the level of cut or fill required at the stake location, and machine operators use their best judgments to accomplish the desired grades between stakes (Hickerson, 1967; Baertlein, Carlson et al., 2000). The process of staking is iterative and requires close communication between surveyors and earthmoving machine operators. Surveyors must constantly place and replace stakes (as they are easily knocked out) and also measure grades and elevations as earth is moved to check for deviations from the design (Baertlein, Carlson et al., 2000).

An alternative to staking for aid in earthmoving operations is automated machine guidance, which uses GNSS and other spatial sensor technologies. Operators of earthmoving equipment receive information via GNSS to guide them in moving appropriate amounts of material to reach desired grades. In some instances, the earthmoving equipment automatically sets blade edges to appropriate elevations as the operator steers. AMG requires communication between satellites, base station receivers, and receivers on earthmoving equipment. The differences between existing and design elevations must also be known (Hannon, 2007). To obtain the difference between existing and design elevations, a 3D model of the design surface is required. Also, laser guidance is starting to be used in conjunction with GNSS for machine guidance. GNSS has limitations in vertical accuracy, which can be improved by augmentation with laser technology (Hampton, 2005). Figure 2.1 is a picture of a motor grader with GNSS technology attached for use in AMG.

Figure 2.1: Picture of a Motor Grader with GNSS Antennae Attached for Use in AMG

There are many benefits associated with AMG. One advantage is that it enables more accurate grading than traditional methods, yielding a smoother ride. Contractors benefit from work being accomplished more quickly and safely. AMG also allows contractors to use less experienced machine operators. Survey and stakeout time and effort requirements can be reduced. Three-dimensional models generated by transportation agencies can lead to reductions in re-engineering from the design to construction process. Reductions in time and resources can lead to significant cost reductions. Customers also benefit from reduced traffic interruptions and a better ride (Barrett, 2008).

Although there are benefits associated with AMG, obstacles to implementation exist. Problems include lack of agency specifications, lack of equipment, lack of knowledge concerning benefits, and budget (Hannon, 2007). Another dilemma arises when transportation agencies do not provide contractors with 3D models. While some transportation agencies provide contractors with complete

3D models, many only provide paper plans from which the contractors must construct their own 3D models (Barrett, 2008). Although labor-intensive staking is reduced, contractors assert that 3D conversion work is also very labor intensive. Software vendors have to work to keep up with advances in technology because modeling for machine guidance is very complex and there is a need to make conversion of 2D plans into 3D files compatible with AMG easier (Hampton, 2005; Hampton, 2009). McAninch, Inc. claims file preparation to achieve the appropriate model is frustrating. Figure 2.2 provides a schema prepared by McAninch of workflow enabling use of machine guidance (Hampton, 2005).

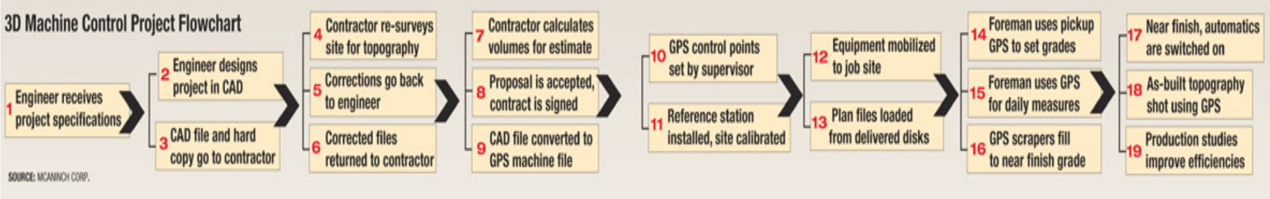


Figure 2.2: Schema of Workflow Enabling Use of AMG by McAninch, Inc.

2.2. Three-Dimensional Transportation Infrastructure Design

In traditional 2D designs for roadways, horizontal and vertical elements are generated and viewed separately. However, when using 2D design, critical information pertaining to geometry might be missing from the planar projections of a roadway (Kari, 2007). With increasingly complex transportation systems, generation of 3D designs is needed (Easa, Strauss et al., 2002).

Three-dimensional design has many advantages. Cross sections and profiles, if needed, can be easily extracted from 3D models. An analytical model of 3D geometric design revealed that 2D designs can overestimate and underestimate required radii of horizontal curves and lengths of vertical curves (Easa, Strauss et al., 2002). Using a 3D approach was also found to aid in design of pavement drainage and highway aesthetics through coordination of horizontal and vertical alignments. Structural design of pavement can also be enhanced with 3D because actual properties and behavior can be modeled (Easa, Strauss et al., 2002). It has been asserted that 3D design allows faster completion and more efficient designs, taking on tasks in house that would otherwise need to be outsourced, and improving precision of route selection (Hatake, 2006).

In recent years, four-dimensional (4D) computer-aided design (CAD) technology has also been developed. Four-dimensional CAD includes three spatial dimensions and the additional dimension of time. Time is typically represented in the form of a Gantt chart, critical chain, or critical path network. Use of 4D CAD requires a 3D CAD application combined with a scheduling application. The major benefit of 4D CAD is the ability to sequentially visualize construction design plans through time. This facilitates identification of constructability issues that could not have been detected using 2D plans. Such issues include conflicts between equipment placement, material fabrication and staging, and site organization. When used in transportation applications, traffic counts can be included as a part of the 4D model to analyze different scenarios for projects constructed during traffic use (Hannon, 2007). Currently, 4D CAD is not used extensively in the transportation industry. Reasons include cost; software interoperability, contract specification, and agency procedural issues; lack of technical skills and training; and lack of standards and references (Hannon, 2007).

2.3. Digital Terrain Model Definition

The 3D surface models used in AMG are often referred to as *digital terrain models* (DTMs). A DTM represents a topographic surface in 3D space. Typical DTMs used in transportation projects consist of triangulated irregular networks (TINs). A TIN model represents a surface as a set of contiguous, non-overlapping triangles. Each triangle within a TIN represents a planar facet of the surface with a data point (measured or known X, Y, Z) at each vertex. TINs can be constructed in many different ways, yielding different results for a given data set (Vonderohe, 2003). One common method for generating TINs is *Delaunay triangulation*, a proximal method such that a circle drawn through the vertices of any triangle will contain no other data points in the set (Vonderohe, 2003). Figure 2.3 is a depiction of Delaunay triangulation. The primary advantage of Delaunay triangulation is that the triangles are as equi-angular as possible, thereby minimizing the number of long, narrow triangles (U.S. Army Corps of Engineers, 2002).

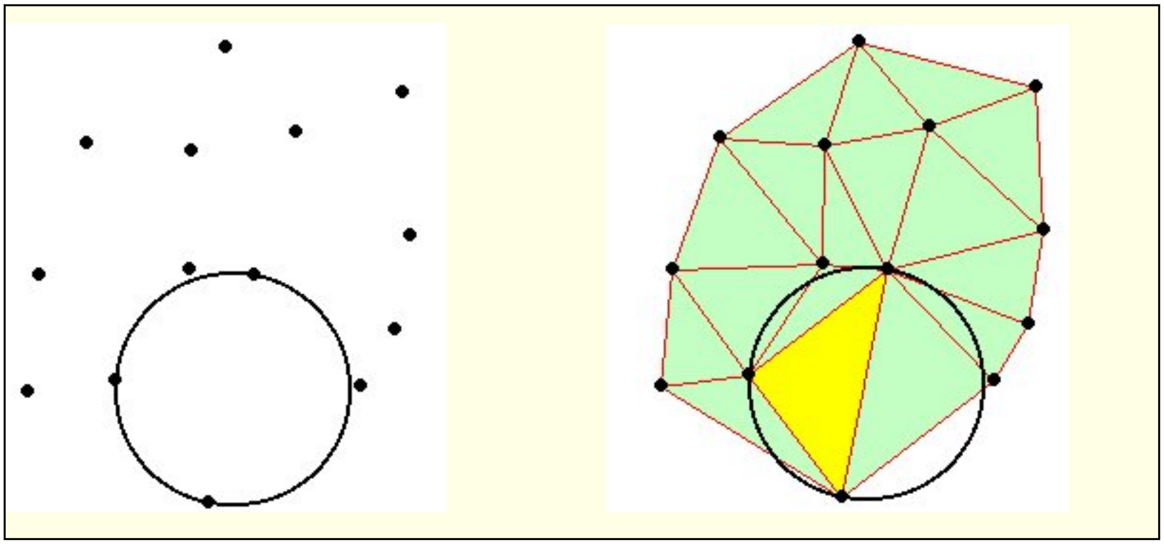


Figure 2.3: Delaunay Triangulation (source: http://www.ian-ko.com/resources/triangulated_irregular_network.htm)

Data used to generate DTMs generally consist of a combination of spot elevations and breaklines. Spot elevations are points in 3D space and are often chosen at peaks, pits, and other locations of significance. Spot elevations can also be collected on a regular grid in which case they are termed *mass points*. Breaklines are a set of line segments connecting points in 3D space and are used to represent significant changes in slope (Vonderohe, 2003). Boundaries to define the perimeter of the surface are often included as well.

There are multiple data collection techniques for DTMs and the optimal method depends on the project. Conventional surveying techniques (total station) can be used to gather DTM data and are appropriate for small projects with obstructions to satellite signals, such as forested or urban areas. GNSS is optimal for small projects where signals from satellites can be received. Photogrammetry is preferred for large projects. LiDAR (Light Detection and Ranging) is also emerging as a practical method for DTM data collection. LiDAR uses laser scanning to produce clouds of X, Y, Z data points from reflective surfaces and allows for collection of data thousands of times faster than other techniques (Archarya, 2000). These data collection techniques can be used individually or in combination on a project, depending on the site circumstances.

2.4. Earthwork

Earthwork is defined as excavation, hauling, and placing of soil, rock, gravel, and other earthen materials. Earthwork includes measurements of such materials in the field, to determine the total volume of material transported to and from a site (Hickerson, 1967). At the beginning of a project, a survey is conducted to collect data necessary for generation of an original ground DTM. After project completion, an as-built survey containing breakline and spot elevation data is typically conducted and the data are used to produce an as-built DTM. Comparisons between the original ground DTM and the as-built DTM are used to determine earthwork volumes. The amount of excess dirt, requiring removal to reach the desired elevation and grade, is the *cut volume*.

Similarly, the amount of material that must be added to reach the desired elevation and grade is the *fill volume*. Cut material can be used as fill. If there is more cut than fill, the excess that has to be removed from the site is *waste.* If there is more fill than cut, then the material that has to be brought onto the site is *borrow*. Figure 2.4 depicts cut and fill volumes.

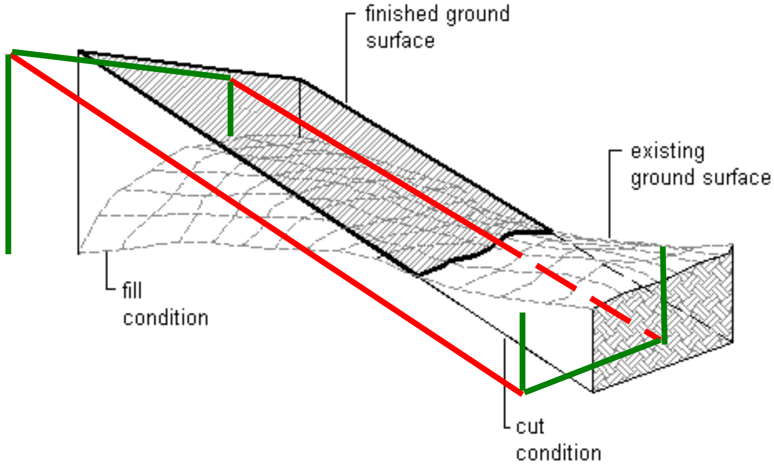


Figure 2.4: Cut and Fill Volumes (Source: Autodesk's Civil 3D 2009 Help Menu)

Traditionally, earthwork volumes were computed using average-end-area. Volumes are calculated by averaging the areas of two consecutive cross sections and multiplying by the distance between them. The general equation for the average-end-area method is given by Hickerson (1967):

$$V = \frac{L}{2(A_1 + A_2)}.$$

Total cut and fill for a project are computed by summing the volumes between all consecutive pairs of cross sections.

Prior to the use of DTMs, cross-sectional survey data along an alignment were collected for use with the average-end-area method. However, cross sections can easily be extracted from DTMs by passing sectional-spaced planes through the DTMs and interpolating depths at intersecting section planes. The average-end-area method is nearest to exact only when the actual volume object between each successive pair of cross sections is a prismatoid, which is not usually the case. Higher accuracy can be achieved by decreasing the interval between cross sections (U.S. Army Corps of Engineers, 2002).

Another method for calculating earthwork is the surface-to-surface (DTM-to-DTM) method, based on the overlaying and differencing of two TIN surfaces. The two surfaces are overlaid by vertical projection onto a horizontal plane, creating a set of composite triangles. Each composite triangle is then re-projected onto each of the two surfaces, creating a set of truncated triangular prisms. The volume of a truncated triangular prism is given by

$$V = \frac{(h_1 + h_2 + h_3)}{3} * A$$

where h1, h2, and h3 are heights from one surface to the other at each triangle vertex, and A is the area of the composite triangle common to both surfaces (U.S. Army Corps of Engineers, 2002). The overall volume is found by summing the volumes of all the prismoidal elements. Figure 2.5 depicts the surface-to-surface method for computing volumes.

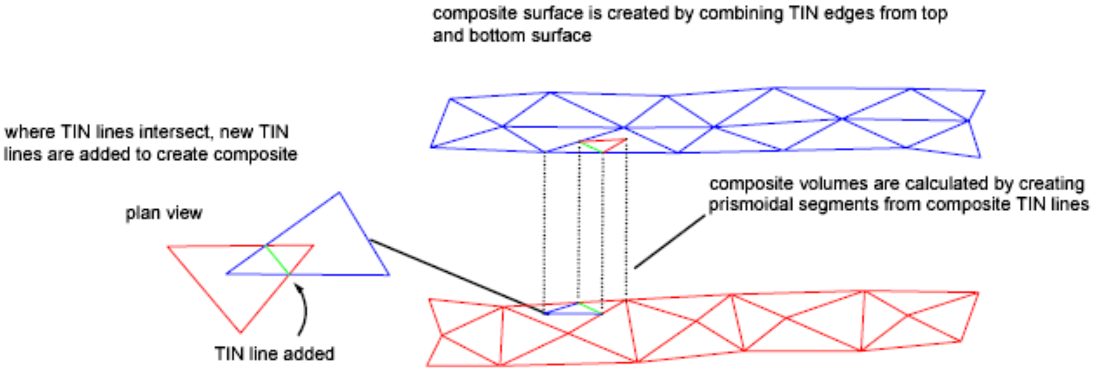


Figure 2.5: Depiction of Surface-to-Surface Volume Calculation (Source: Autodesks Civil 3D 2009 Help Menu)

As stated previously, it has been asserted that the surface-to-surface method is more accurate than average-end-area (U.S. Army Corps of Engineers, 2002; Cheng, 2005). Earthwork computations are also affected by the manner in which surfaces are represented. Kellie et al. (2007) studied the effects of surface representation methods on computed volumes. Three representation methods were used: 1) TIN, 2) kriging, and 3) minimum curvature. TINs were described previously, as they are the most common representation method for transportation applications. Kriging estimates elevations from a given set of 3D data points using weighted interpolation. Weights are dependent on a variogram function. The minimum curvature method develops a surface by mathematical emulation of a linear elastic plate passing through the data points. The result is an iteratively smoothed grid of elevations. In the study, the different surface representation techniques resulted in significant differences in calculated volumes.

Surface-to-surface and average-end-area methods are most commonly used for computing earthwork quantities in transportation applications. However, the grid method is sometimes used for borrow pit volumes. In this method, the site being analyzed is broken into small unit areas. The depth of cut or fill is recorded at the corners of each unit area. The cut/fill depths of a given unit area are averaged and multiplied by the area of the unit to determine the volume of cut or fill. Summation of the cut and fill of the individual unit areas provides total cut and fill for a site. In this method, the actual ground is assumed to be a plane representing a linear ground surface (Dewberry, Rauenzahn et al., 2008).

2.5. Digital Terrain Model Assessment

One of the major challenges associated with use of DTMs is evaluating their accuracy. The quality of a DTM can be defined as the degree to which the representative surface resembles the actual surface (Meneses, Chasco et al., 2005). A study by Meneses et al. (2005) described the accuracy of volumetric characteristics of a DTM by analyzing the relationship with data point density. The research was based on topographic surveys where structural features in the area were considered breaklines and a closed contour line surrounded the study area to define the surface boundary. The DTMs used in this study had point densities between 5 percent and 100 percent of the original survey and volumetric characteristics were compared. Point densities above 60 percent of the sampled points achieved minimal increases in volume accuracies. A comparison of surveyed heights and interpolated heights was used to evaluate the accuracy of computed terrain heights. As in the volumetric analysis, DTMs were generated using 5 percent to 100 percent of the surveyed points. Results revealed high stability in height errors relative to sampling density and thus, height errors are less sensitive than volumetric errors when evaluating the quality of a DTM. Menes et al. (2005) concluded that using both volumetric and height assessment is an acceptable method for determining DTM quality.

Archarya et al. (2000) also assessed the quality of DTM data. Three stereo models were analyzed in this study. A stereo model consists of object points that appear in the overlap of two adjacent aerial photographs (DeWitt & Wolf, 2000). For each model, 21 extra well-defined points, measured by a surveyor in the field, were used to check the accuracy of photogrammetric DTM points. Thus, there were a total of 63 extra well-defined points. For each model, a separate bundle adjustment was performed on the 21 extra well-defined points for that model to generate coordinates. Bundle adjustment is a technique used to process photogrammetric measurements to optimize object space coordinates (DeWitt & Wolf, 2000). Checkpoint files were generated with the coordinates (x, y, z) including the extra control. This checkpoint file was used to assess the DTM data collected on each model and for the merged DTM file containing the extra well defined point data. It was found the method used in this study is valid for quality control testing of DTM data.

Gaps can arise in DTMs for various reasons. Most gaps in photogrammetric data arise from trees and shadows. Gaps in DTMs can also occur between consecutive photogrammetric models (Katzil & Doytsher, 2000). Thus, it is often necessary to fill in gaps when photogrammetry is used for data acquisition.

Katzil and Doytsher (2000) conducted an evaluation of methods for filling in gaps in gridded DTMs. In the study, several polynomial estimation techniques as well as others were evaluated. One polynomial technique was linear estimation, which estimates the height of a point by calculating the average of the height of the two or four points closest to it. Another polynomial method used was 1D polynomial of third order, which consists of a polynomial passing though the point whose height is to be estimated in one primary direction (North-South or East-West) and through four neighboring points in that primary direction. The four points are used to generate the four coefficients of a third-order polynomial. A third polynomial technique was an improved cubic spline method, which uses a 1D polynomial of third order based on four adjoining points in a grid of elevations. Slopes at the end points are used to maintain the continuity of the function. The final polynomial technique was a 2D third-order polynomial method that requires at least 10 points surrounding the point whose height is to be computed. The points are used to generate the ten coefficients of the polynomial based on a least squares adjustment. The two methods that did not utilize polynomials were pyramid structure and kriging. Pyramid structure uses points with measured elevations close to the point whose height is to be interpolated to generate a 3D structure with the center being the point whose height is unknown. The perimeter of the base of the pyramid is defined by connecting all points contributing to height determination of the unknown point. The height is estimated from minimization of the area of the structure. As mentioned previously, kriging uses a statistical method to estimate elevations of unknown points. It was found that, as terrain becomes increasingly hilly, the accuracy of filling in gaps decreases. However, there was no significant difference in accuracy based on the method used to fill in gaps. The effect of grid density was also analyzed using linear estimation, improved cubic spline, and kriging. Lower point densities resulted in smoother contours than high point densities and there was not a significant difference in accuracy based on the method used to fill in gaps. However, using improved cubic splines on the sparse point density DTM resulted in faster processing time than did the other methods. A DTM covering a broad area with a point density of 50 meters was evaluated and the accuracies for filling in gaps produced similar results but processing time varied between methods. Linear was found to be the fastest. Filling in gaps between coverage area of photogrammetric models and strips was also analyzed using linear estimation and improved cubic splines only. Comparisons between the two methods revealed no significant difference between methods with respect to accuracy.

Based on these results, Katzil and Doytsher (2000) concluded that automatic completion of a DTM to fill in gaps adds to the integrity and continuity of the model without decreasing accuracy. Linear estimation is the simplest technique and works well with dense grids. Improved cubic spline is the fastest technique when dealing with sparse grids.

3. Survey

3.1. Description of Survey

A survey was constructed with the objectives of identifying and characterizing both benefits and technological, institutional, cultural, and legal impediments to the adoption of 3D design and construction technologies, data flows, and workflows. The survey was web-based and was designed, programmed, and administered with assistance from the University of Wisconsin–Madison Survey Lab. The survey was provided to all 50 state highway agencies and seven class 1 railroads. The survey instrument appears in Appendix A.

To access the survey, responders chose their agency from a pick list and entered a secure password that had been provided in an initial email message. A trial run of the survey was conducted with the SHAs represented on the American Association of State Highway and Transportation Officials (AASHTO) Technology Implementation Group for AMG. After a few refinements, an initial email message was sent to all remaining SHAs using the contact information provided by the AASHTO Subcommittee on Design. Assistance in receiving responses was provided by the Transportation Research Board (TRB) AFB80 Committee on Geospatial Data Acquisition Technologies in Design and Construction. The SHA representatives on TRB AFB80 were notified when the initial email messages were distributed and they then encouraged their colleagues to respond to the survey. The initial email message was followed by two reminders (over a two-month period) to those organizations that had not yet responded.

The survey had three sections (i.e., design, contracting, and construction) and was designed to allow multiple responders from a single agency. Responders were asked to answer only questions for which they had knowledge and then pass the survey access information along to others, if necessary, to obtain correctly-completed surveys. Each of the three sections had a screen for identification, background, and contact information for the responder for that section. In some cases, a single individual completed all sections. In others, there were two or three responders for a given agency. In many cases, the initial contact person (on the AASHTO Subcommittee on Design) did not actually fill out any of the survey, but passed it along to others for completion. There was a mix of background-types in our responders. Some were design engineers, some surveyors, some contract specialists, some construction managers/administrators, and some CAD specialists, depending on the questions and the level of knowledge of the individuals. Most responders held managerial or supervisory positions. Overall response to the survey was good. The number of SHA responses on a given question varied between 33 and 37. Email and telephone follow up was conducted with some responders on some of the questions.

3.2. Analysis Methods

In analysis of the survey data, all states' responses were weighted equally. Percentages of respondents selecting each answer option for all questions were calculated. This allowed for identification of the relative prevalence of individual answer options to a given question. For each question that allowed respondents to select one answer, percentages for each answer were calculated based on the total number of respondents. Similarly, for questions allowing selection of multiple answers, percentages were calculated based on the total number of respondents, not the total number of answers selected. The survey included questions in which respondents were asked to evaluate the importance of listed items such as benefits or impediments. For these questions, respondents were given answer options of "not at all important," "not very important," "somewhat important," "very important," and "extremely important." Results of questions requiring evaluations of importance were reported in two ways. Firstly, the overall distribution of percentages of respondents selecting each answer option was calculated. Secondly, an average rating for a given benefit or impediment was computed. This was accomplished by transforming the qualitative answer options into numerical values. Table 3.1 provides the numerical values assigned to qualitative ratings of importance. Thus, if a given item has an average rating of importance of 2.5, its average rating is between “somewhat important” and “very important.”

Table 3.1: Numerical Values Assigned to Qualitative Ratings of Importance

Qualitative Value	Numerical Value
"Not at all important"	0
"Not very important"	1
"Somewhat important"	2
"Very important"	3
"Extremely Important"	4

Analysis for geographic trends was conducted on selected questions. For geographic analyses, the United States was divided into the four regions defined according to AASHTO’s Regional Associations of State Highway and Transportation Officials. The official titles of the regions are Northeastern Association of State Highway and Transportation Officials (NASHTO), Southeastern Association of State Highway and Transportation Officials (SASHTO), Mississippi Valley Conference of State Highway and Transportation Departments, and Western Association of State Highway and Transportation Officials (WASHTO). Abbreviations used in the proceeding discussion for these regions are given in Table 3.2. The four regions are shown in Figure 3.1. In the survey, respondents were assured that their responses would remain confidential. Thus, grouping states into region rather than providing individual responses by state was used to maintain the confidentiality of respondents. The percentages of responding SHAs by region are indicated in Figure 3.1.

Table 3.2: Abbreviations Used for AASHTO Regional Associations of State Highway and Transportation Officials

AASHTO Regional Associations of State Highway and Transportation Officials Titles	Abbreviation
Northeastern Association of State Highway and Transportation Officials	Northeast
Southeastern Association of State Highway and Transportation Officials	Southeast
Mississippi Valley Conference of State Highway and Transportation Departments	Mississippi Valley
Western Association of State Highway and Transportation Officials	West

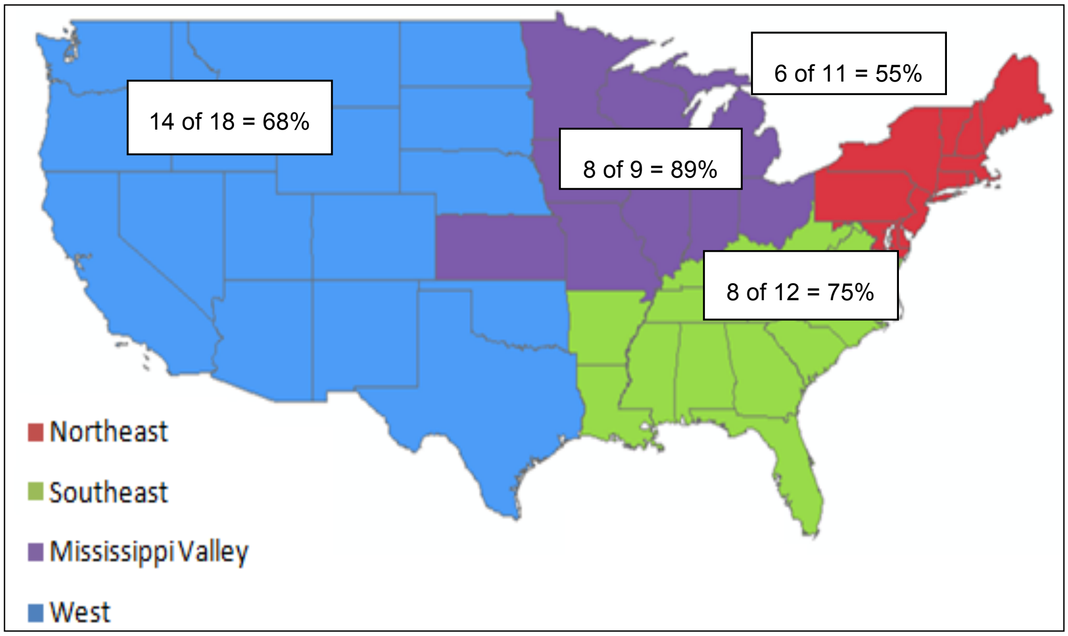


Figure 3.1: Regional Associations of State Highway and Transportation Officials with Survey Response Rates

3.3. State Highway Agencies

3.3.1. Design

One section of the survey was devoted to questions concerning design. One purpose of the design section of the survey was to determine the extent of use of design methods that produce 3D models. Additionally, the design section aimed to identify the importance of impediments and benefits associated with 3D design methods.

Respondents were questioned on the approximate percentage of design work performed in-house as opposed to being contracted to engineering consultants. Figure 3.2 shows the overall widespread distribution of percentages of highway design work performed in-house. The most frequent response was 20 to 39 percent of design work is completed in house (26 percent of respondents).

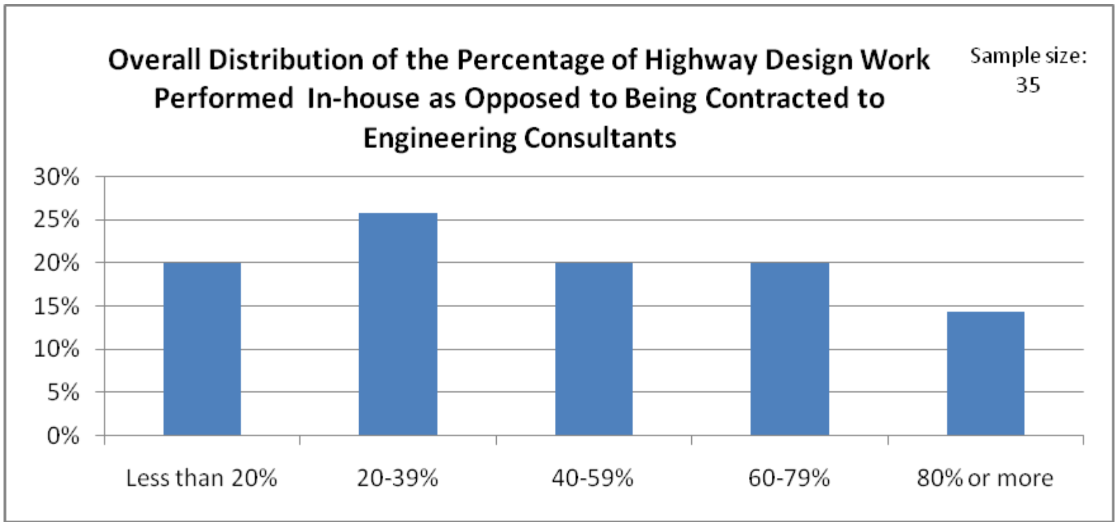


Figure 3.2

The regional distribution of responses for the percentage of design work completed in-house is presented in Figure 3.3. The West Region has a significantly higher number of responding agencies that fall into the categories of conducting between 60-79 percent and 80 percent or more of design work in-house than other regions. Response rates within the 20-39 percent categories were very high for the Mississippi Valley and Northeast Regions in comparison to other regions. The most frequent response from Southeast Region SHAs was 20 percent or less.

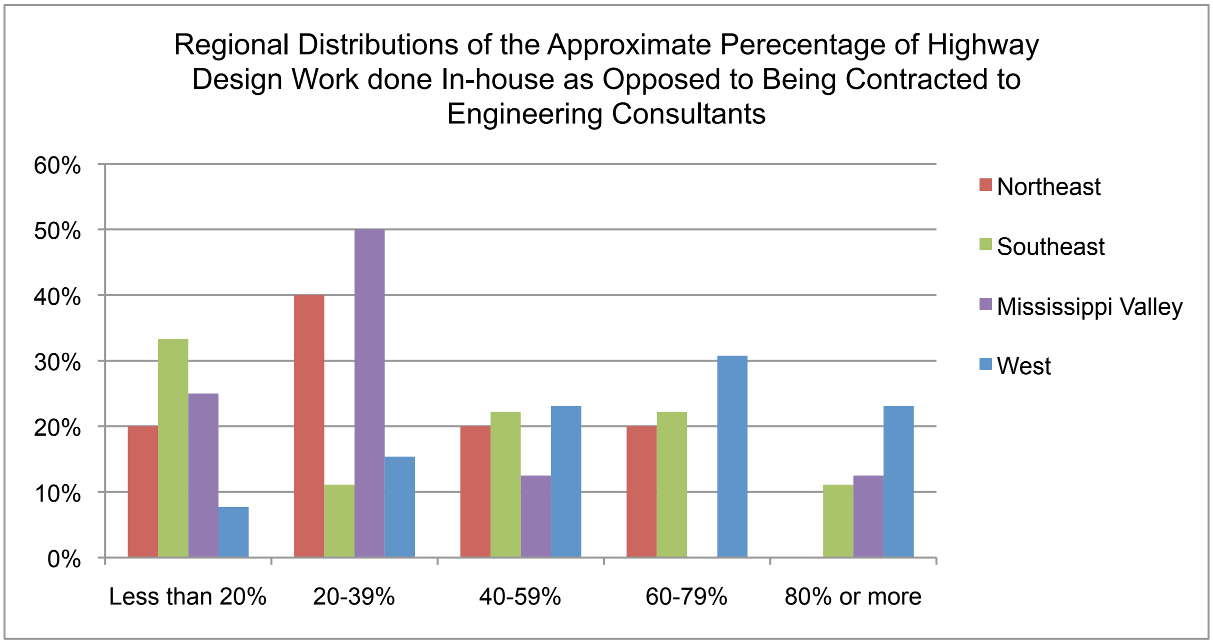


Figure 3.3

Of the responding SHAs, approximately 95 percent have content standards such as features, layers, colors, and line types for digital design files. All agencies that have content standards for design files require that engineering consultants conform to these standards. Additionally, 73 percent of agencies have format standards for transferring digital design data.

Figure 3.4 depicts the overall distribution of the status of adopting 3D design models as part of the design process in SHAs and Figure 3.5 shows the regional distributions. Approximately 19 percent of all SHAs have fully incorporated development of a 3D design model as part of the design process. Regional results indicate the Southeast and West Regions have the highest percentage of agencies that have fully adopted 3D design methodology. However, there are not large differences among regions in these percentages.

Approximately 22 percent of all responding agencies are in the process of adopting 3D design and 24 percent of agencies are planning to adopt 3D design methods. Thus, a total of 65 percent of responding SHAs are planning for, in the process of, or have fully implemented design methods that produce a 3D model. The Northeast Region has the highest percentage (50 percent) of respondents that are in the process of adopting design methods that produce a 3D model. The Mississippi Valley Region has the highest percentage (50 percent) of respondents that are planning for the adoption of 3D design methods. Additionally, 24 percent of responding SHAs are considering adopting 3D design methods. There are also 8 percent of respondents not considering adopting design methods that produce a 3D model. Based on survey results, 3 percent of agencies (i.e., one respondent) have considered adopting 3D design methods, but rejected them. No respondents from within the Mississippi Valley Region indicate they are not considering or have rejected adopting 3D design methods.

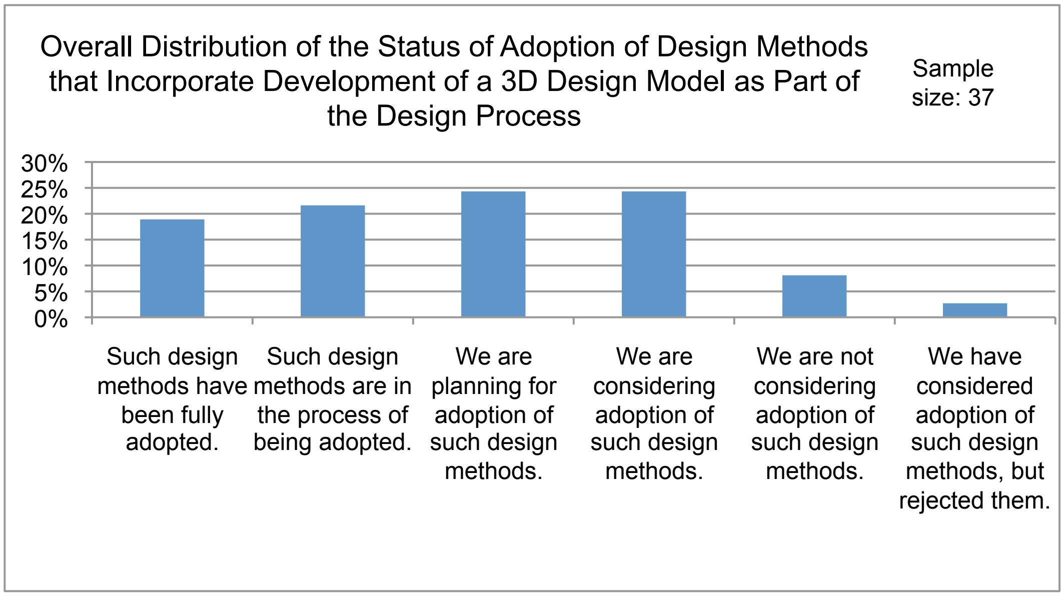


Figure 3.4

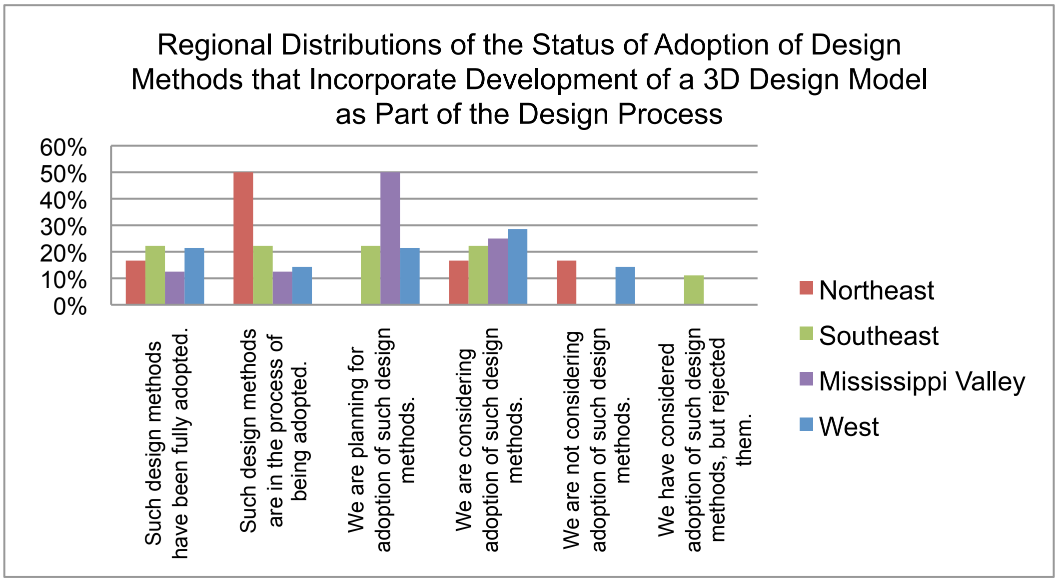


Figure 3.5

Respondents were asked to rate the importance of individual benefits of design methods that produce a 3D design model. Figure 3.6 provides the overall average ratings. In Figure 3.7, one can see the distributions for evaluations of the importance of the benefits of 3D design. Figure 3.8 provides the average ratings of importance by region and shows there is not significant variability among regions. Detection and elimination of design errors prior to construction has the highest average ratings. It also was rated as extremely important by more respondents than any other benefit. However, having a more comprehensive representation of design intent has an average rating of very important, signifying it is also a major benefit. Improved visualization and improved support for construction had average ratings of between somewhat and very important. These results indicate all of the benefits provided to respondents for rating are important incentives for SHAs to move towards design processes that produce a 3D model.

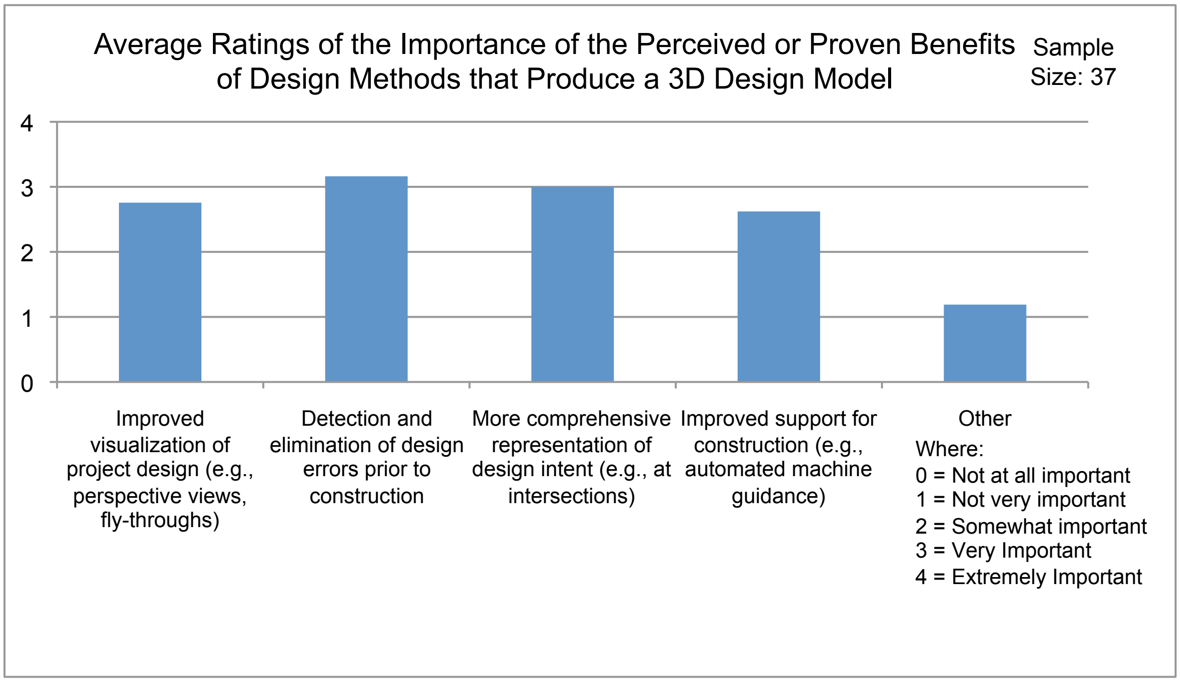


Figure 3.6

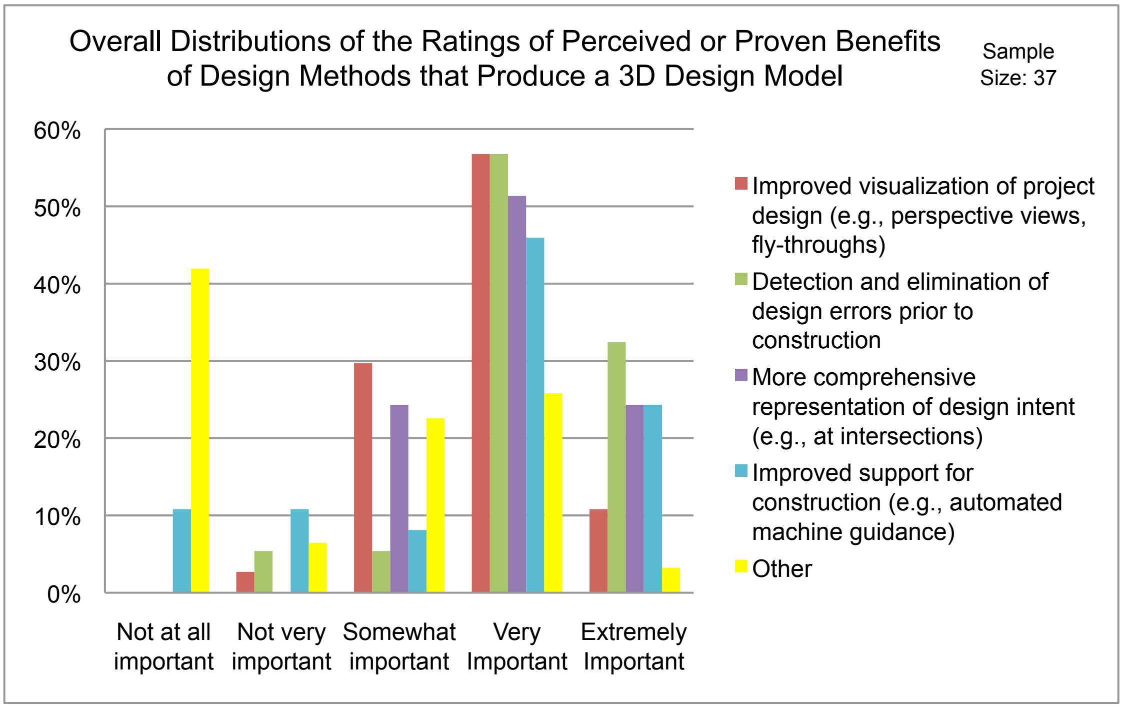


Figure 3.7

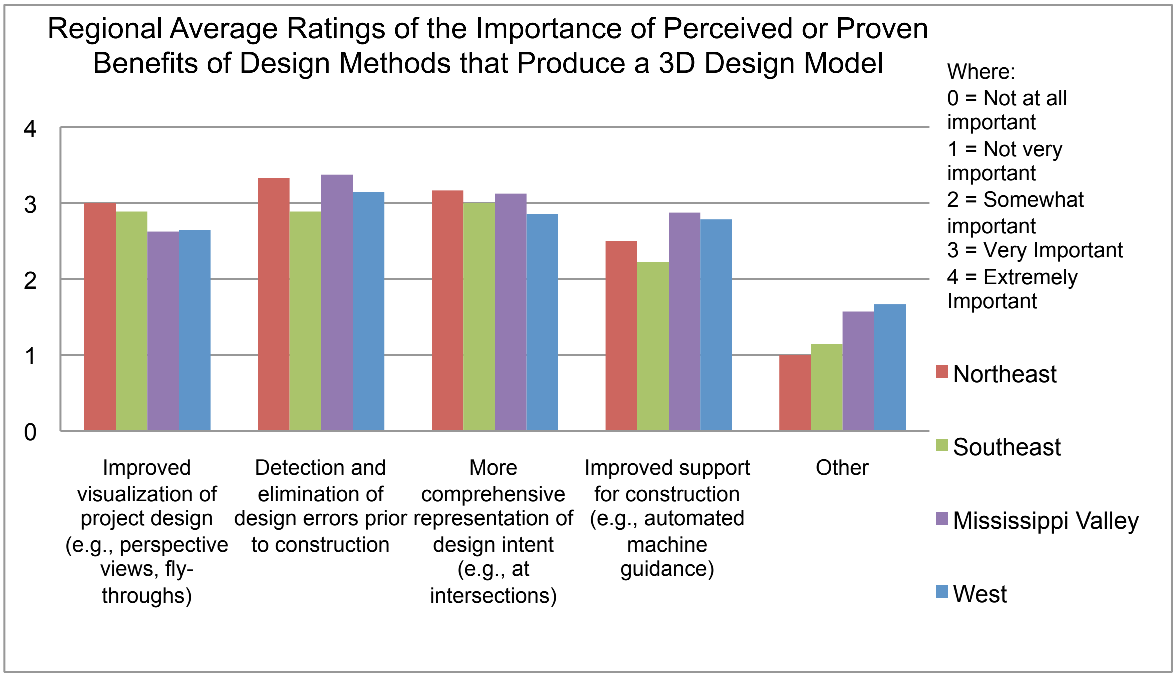


Figure 3.8

Other benefits, not provided for rating, were ranked as being very important by approximately 26 percent of respondents. Respondents were asked to identify these other benefits. Multiple respondents expressed that 3D design methods allow those working on design, construction, and contracting to work with the same data set. One respondent stated 3D design methodology allows production of models for subsequent phases of the project without actual survey information. Another respondent stated that elimination of construction staking and better quantity management are important benefits. Allowance for better hydraulic drainage design and better identification of hydraulic and utility conflicts were also identified as benefits. Safety checks including horizontal/vertical clearances and stopping sight distances can also be enhanced through production of a 3D model according to one respondent. Several respondents also feel 3D design models allow for better representations of project information at public involvement events. Based on these responses, it appears there are numerous benefits to using 3D design methods. Many of these benefits might still be undiscovered by the majority of agencies.

To determine if the perceived importance of the benefits is a significant factor in whether agencies choose to adopt 3D design methods, the percentage of agencies adopting 3D methods that feel individual benefits are either very or extremely important were compared to those not adopting 3D design methods. Agencies that have fully adopted, are in the process of adopting, or are planning for the adoption of design methods that produce a 3D model are considered to be currently adopting 3D design methods. Agencies that are considering, not considering, or have rejected adopting 3D design methods are considered to not be adopting 3D design methods. The percentage of SHAs currently adopting 3D design methods that feel benefits of 3D design are either very or extremely important versus those not currently adopting 3D design methods is presented in Figure 3.9. Percentages for those adopting 3D design methods that feel benefits are very or extremely important are based on the total number of respondents adopting 3D design methods. Similarly, percentages for those not adopting 3D design methods are based on the total number of respondents not adopting 3D design methods.

Ninety-two percent of respondents adopting 3D design methods feel having a more comprehensive representation of design intent is either extremely or very important while only 42 percent of those not adopting 3D design methods feel it is very or extremely important. A significantly higher percentage of respondents from SHAs adopting 3D design methods feel support for construction is either very important or extremely important than those from agencies not adopting 3D design methods. It is also interesting to note that while 92 percent of responding state highway agencies not adopting 3D design methods feel detection and elimination of design errors prior to construction is very or extremely important, only 60 percent of those who are adopting 3D design feel it is of great importance. Similar percentages of respondents that are and are not adopting 3D design methods feel improved visualization and other benefits are either very or extremely important.

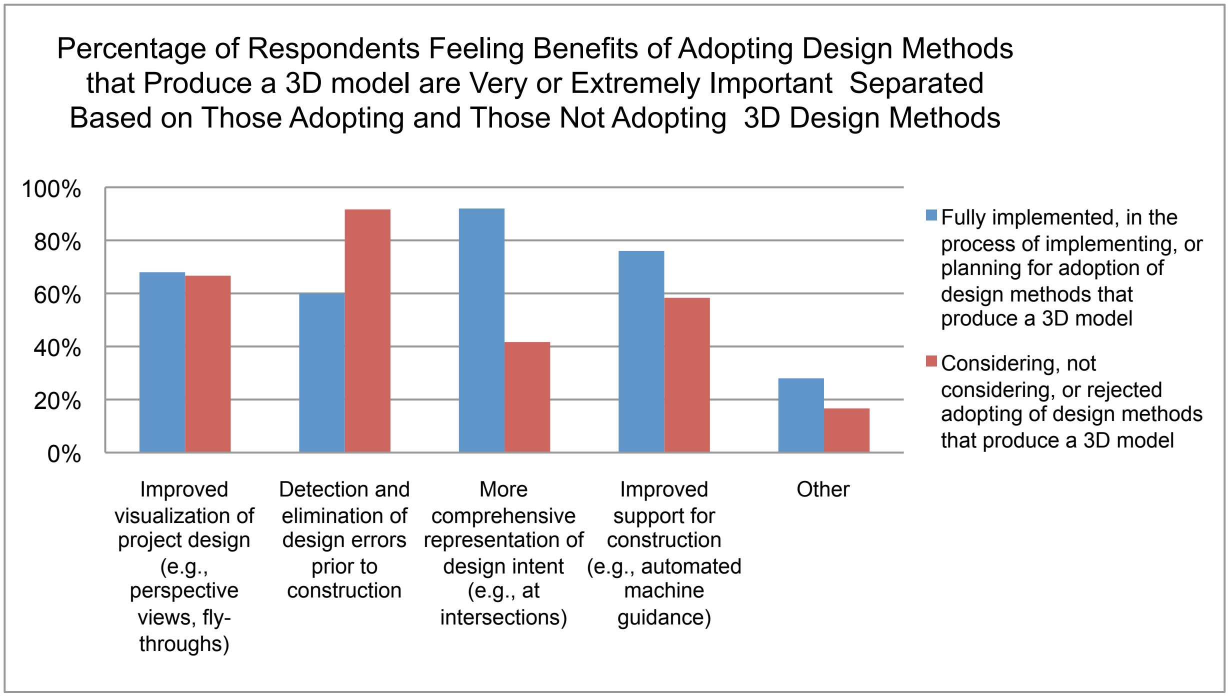


Figure 3.9

Respondents were asked to provide their opinions on the importance of typical prerequisites for adoption of design methods that produce a 3D model. Figure 3.10 provides the overall average ratings of importance for individual prerequisites, Figure 3.11 gives the overall distribution of the ratings, and Figure 3.12 provides regional average ratings. The prerequisite with the highest average response is proven (documented) benefits. Approximately 22 percent of respondents feel proven benefits are extremely important, and an additional 46 percent consider proven benefits to be very important. Proven benefits have the highest average rating of importance of all prerequisites in the Northeast, Southeast, and West Regions.

Implementation planning is also considered to be an important prerequisite to adopting 3D design methods. Twenty-five percent of respondents consider implementation planning to be extremely important. Implementation planning has the highest average rating of importance of all prerequisites within the Mississippi Valley Region. Many respondents also feel undocumented benefits, feasibility studies, and cost/benefit studies are very important, indicating these prerequisites are also significant.

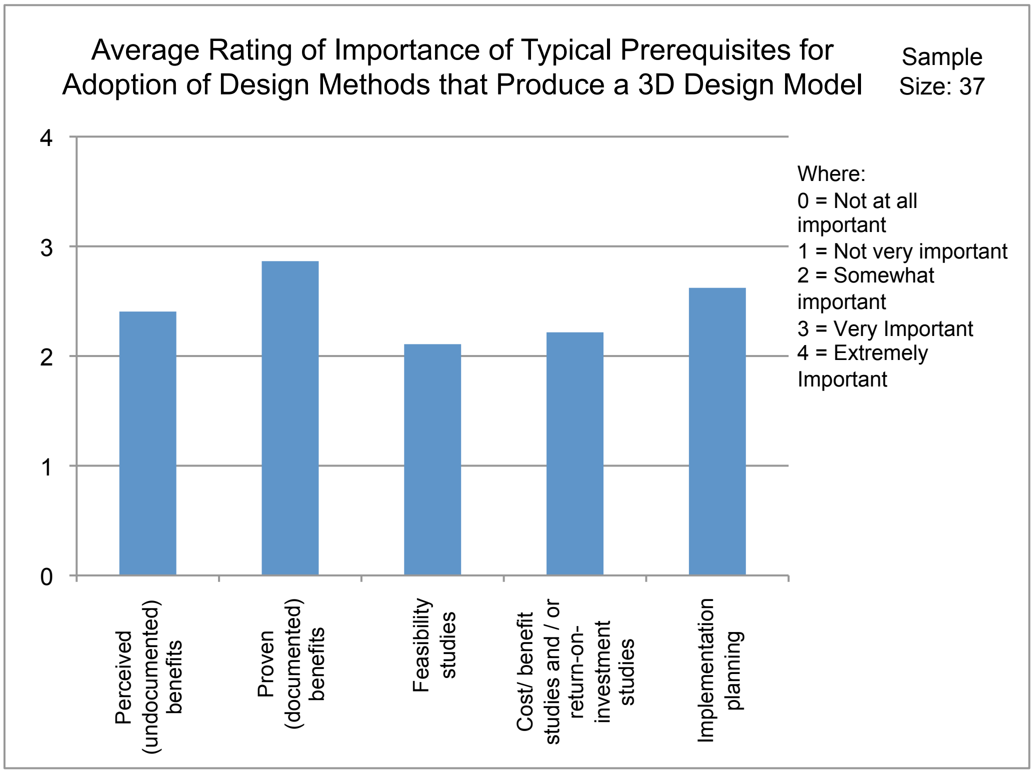


Figure 3.10

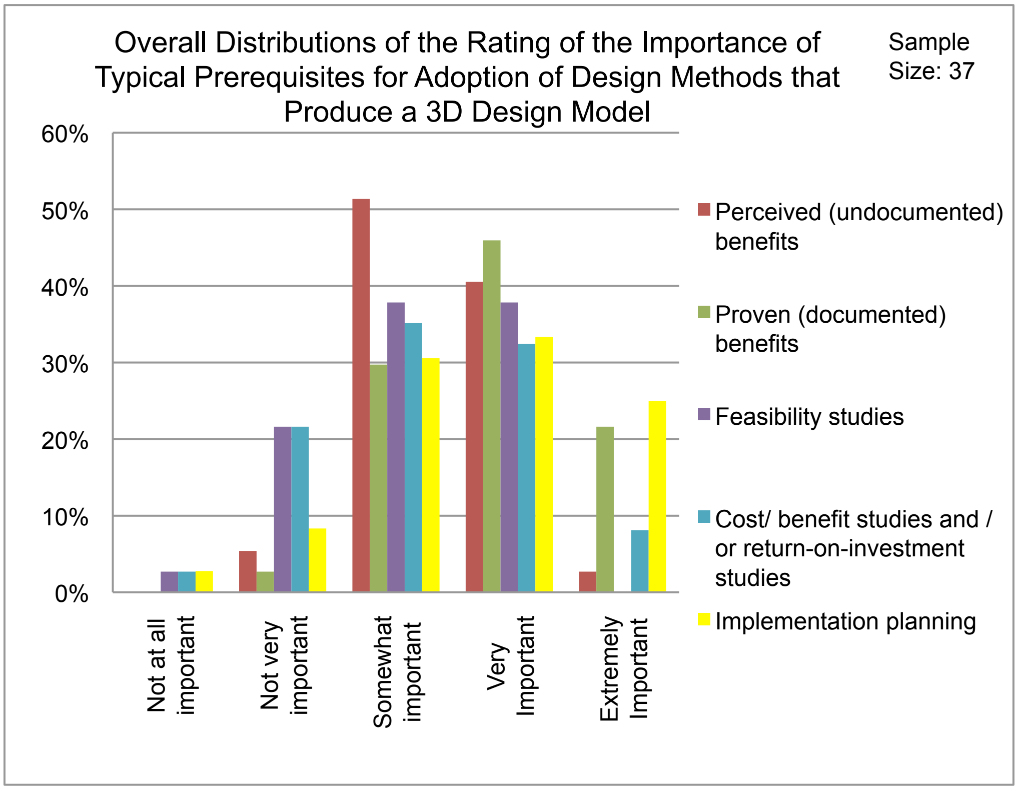


Figure 3.11

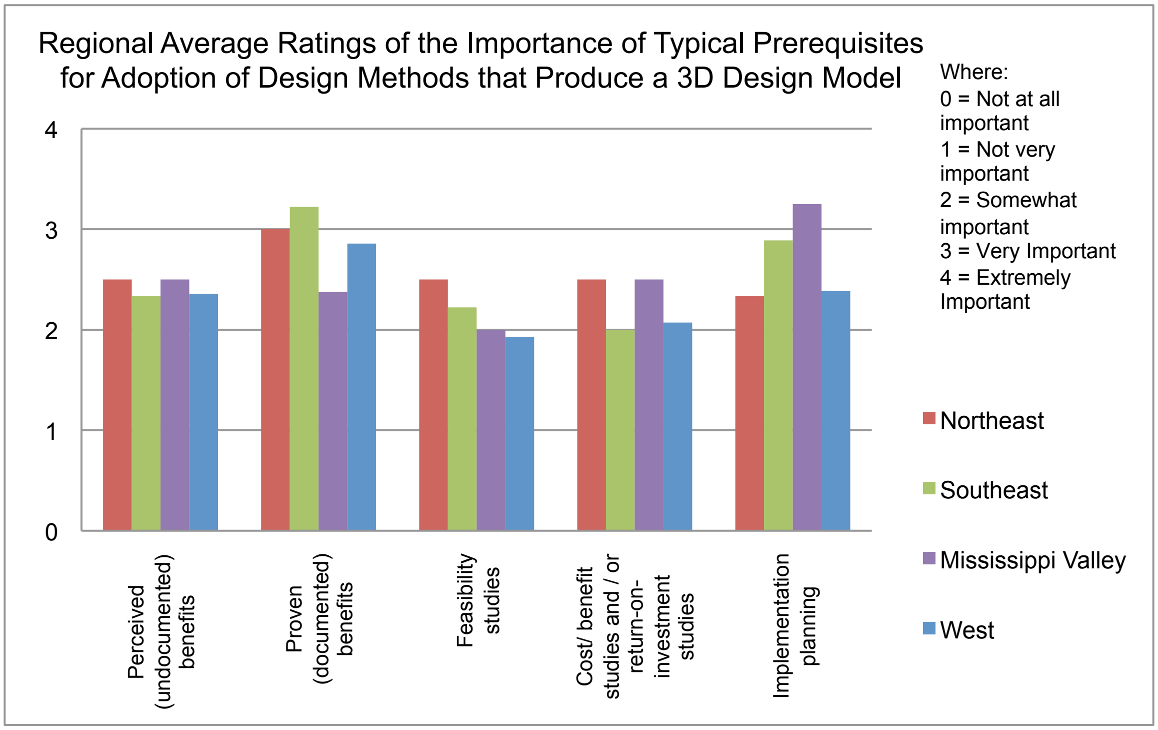


Figure 3.12

In addition to evaluating the importance of the benefits of adopting design methods that produce a 3D model, respondents were asked to evaluate the importance of various impediments to adopting such methods. Figure 3.13 provides overall average ratings for individual impediments, Figure 3.14 provides the overall distribution of the importance of each impediment, and Figure 3.15 offers average ratings of importance by region.

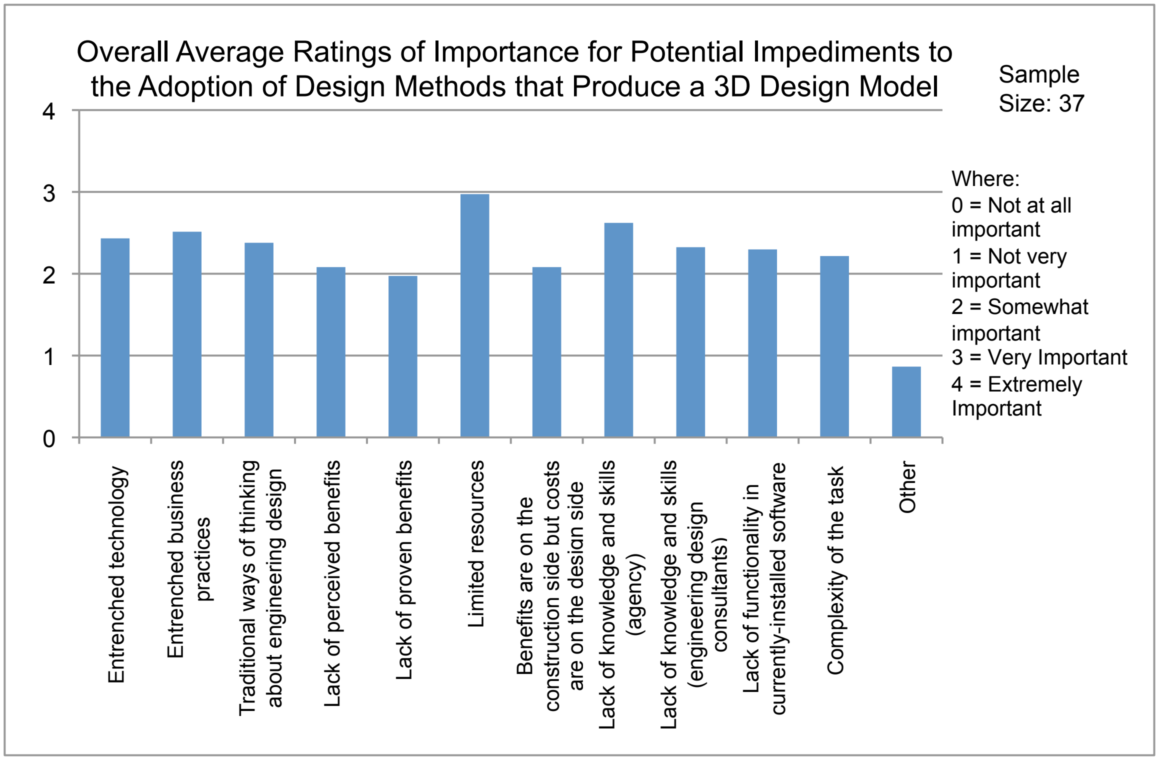


Figure 3.13

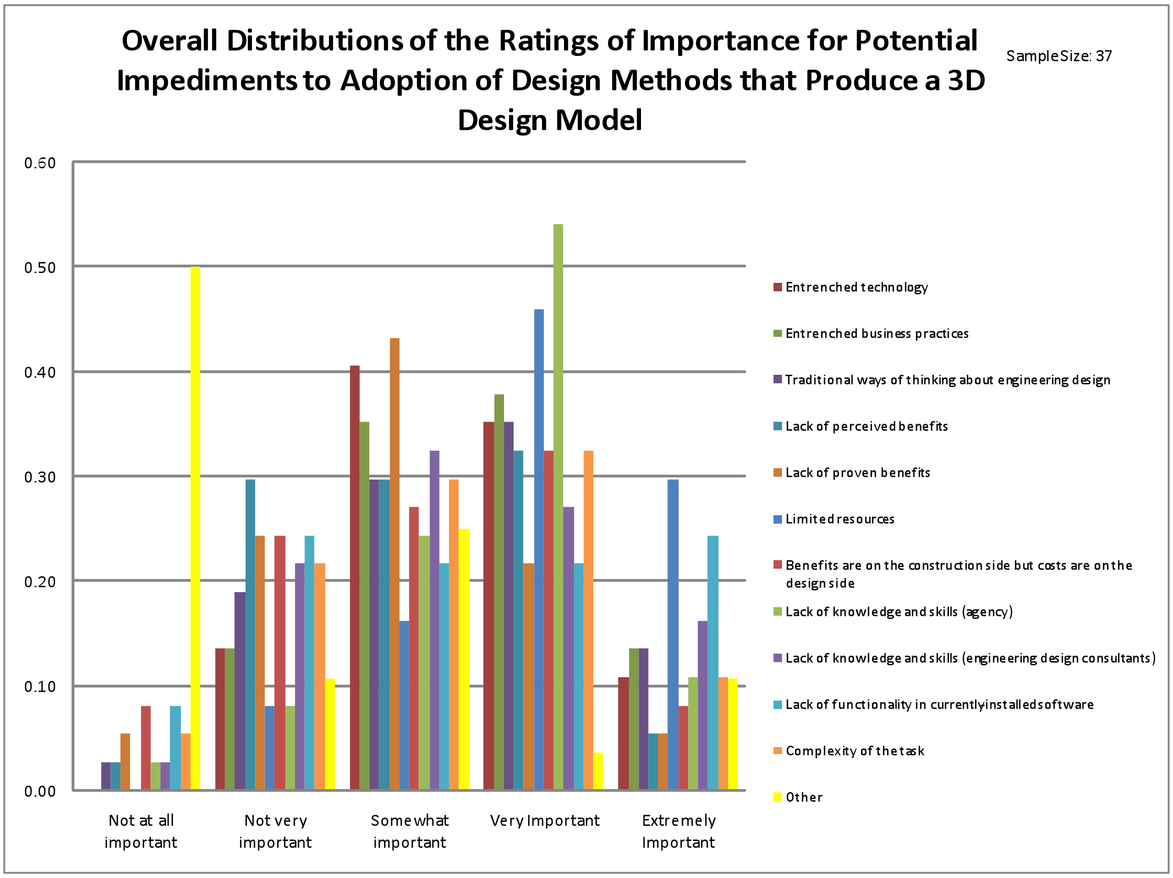


Figure 3.14

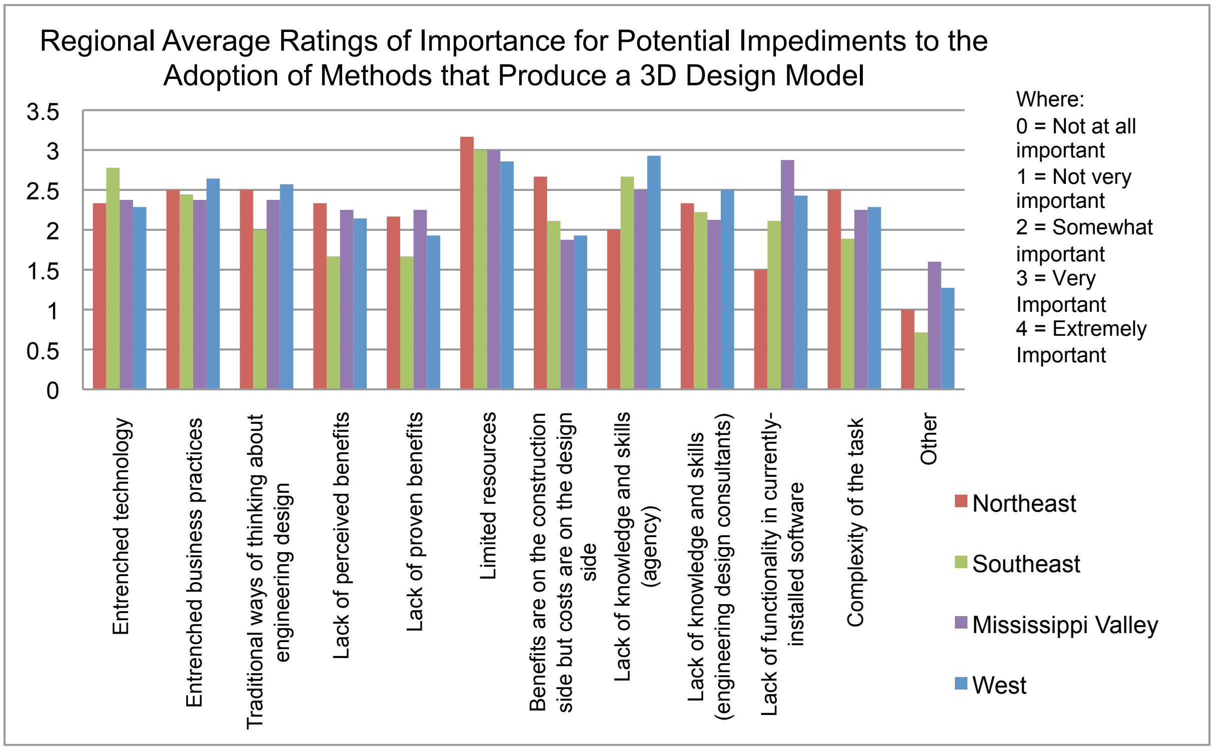


Figure 3.15

Limited resources have the highest average rating of importance of all impediments. Thirty percent of respondents consider limited resources to be an extremely important impediment to the adoption of design methods that produce a 3D model. Additionally, limited resources are considered to be very important by 46 percent of respondents. Among regions, there is a general consensus that limited resources are a major impediment to adopting 3D design methods.

Lack of knowledge within SHAs is another crucial impediment to implementing 3D design as 65 percent of agencies consider it to be either very or extremely important. There is considerable variability in the average ratings of importance of agency lack of knowledge among regions. While the average rating in the West Region is 2.9, it is only 2.0 in the Northeast Region. Entrenched business practices also appear to be a critical impediment because 51 percent of all respondents feel it is either very or extremely important. There is little variability in the average rating of importance of entrenched business practices among regions.

Forty-six percent of all respondents believe lack of functionality in currently installed software is a very or extremely important impediment to the adoption of 3D design methods. However, there are inconsistencies in the average ratings for this impediment among regions. The Northeast Region responses led to an average rating halfway between not very important and somewhat important. Thus, lack of functionality in currently installed software is a major concern for most Northeast agencies. On the contrary, the average rating in the Mississippi Valley Region indicates the majority of respondents feel lack of software functionality is very important.

It is also noteworthy that the Northeast Region seems to feel that having benefits on the construction side but costs on the design side is of greater importance than other regions. Entrenched technology, traditional ways of thinking about engineering design, engineering consultants' lack of knowledge and skill, and the task complexity are not trivial issues for many SHAs. These impediments all have average rankings above somewhat important.

Approximately 11 percent of respondents feel there are other impediments to adopting 3D design methods not identified as answer options that are extremely important. Respondents were asked to identify these other impediments. Staff training and time required to implement methods that produce a 3D model was the most common response, indicating it is a critical barrier. A lack of data translation software that is able to convert 3D designs produced by the agency to software used by contractors was identified as being an issue because LandXML is not a 100 percent effective translation tool. Lack of a construction inspection process to use 3D data was also recognized as a problem as was not having a method to perform quality assurance and control for 3D models. Unawareness of available 3D design tools and a lack of user proficiency to use the tools were identified as issues.

The need for a policy to identify what projects require use of design methods that produce a 3D model and what projects do not was also brought up as an impediment. The question of whether there is reciprocation for the cost of designers' efforts to produce a 3D model was also recognized as being an issue. Data accountability, with respect to the liability for errors and omissions, was identified as a possible problem. Another impediment to using 3D design methods is the potential for 3D models to conflict with contract documents. A need for a means to perpetuate the data once the contractor receives it was also identified as an issue. Additionally, the need to address professional practice issues, such as whether or not a licensed land surveyor should be required to oversee grading operations prior to full implementation of 3D design methods, is a recognized impediment. Thus, while there are clearly important benefits of 3D design methods, there are numerous potential impediments to adopting such methods.

As an aid in determining why agencies are making the decision to adopt or not adopt 3D design methods, the percentages of agencies that perceive impediments to be very or extremely important were calculated separately for those adopting and those not adopting 3D design methods. The percentage of respondents adopting 3D design methods that feel impediments are very or extremely important and the percentage of respondents that are not adopting 3D design methods that feel impediments are very or extremely important are provided in Figure 3.16. The definition of those adopting versus not adopting 3D design methods and the manner in which percentages were calculated are similar to those used in evaluating benefits of design methods that produce a 3D model (above).

Lack of proven benefits was rated as a very or extremely important impediment to adopting 3D design methods by 50 percent of agencies that are not currently doing so. However, only 16 percent of respondents adopting 3D design methods feel lack of proven benefits are very or extremely important. A significantly higher percentage of respondents from SHAs that are not currently adopting 3D design methods also rate lack of perceived benefits as being very or extremely important in comparison to those adopting 3D design methods. A higher percentage of respondents from SHAs that are not adopting 3D design methods feel that it is very or extremely important that benefits of 3D design are primarily on the construction side but costs are on the design side than agencies adopting 3D design methods. A lack of knowledge and skills within the agency is rated as being very or extremely important by a higher percentage of SHAs that are not currently adopting 3D design methods than those that are.

However, lack of knowledge and skills among engineering consultants is rated as being very or extremely important by a higher percentage of agencies adopting 3D design methods. Also, a considerably higher percentage of agencies that have chosen to adopt 3D design methods feel lack of resources is an extremely or very important impediment. These differences could reflect a shift in thinking about impediments once the decision as been made to adopt 3D design and experience has been gained in doing so.

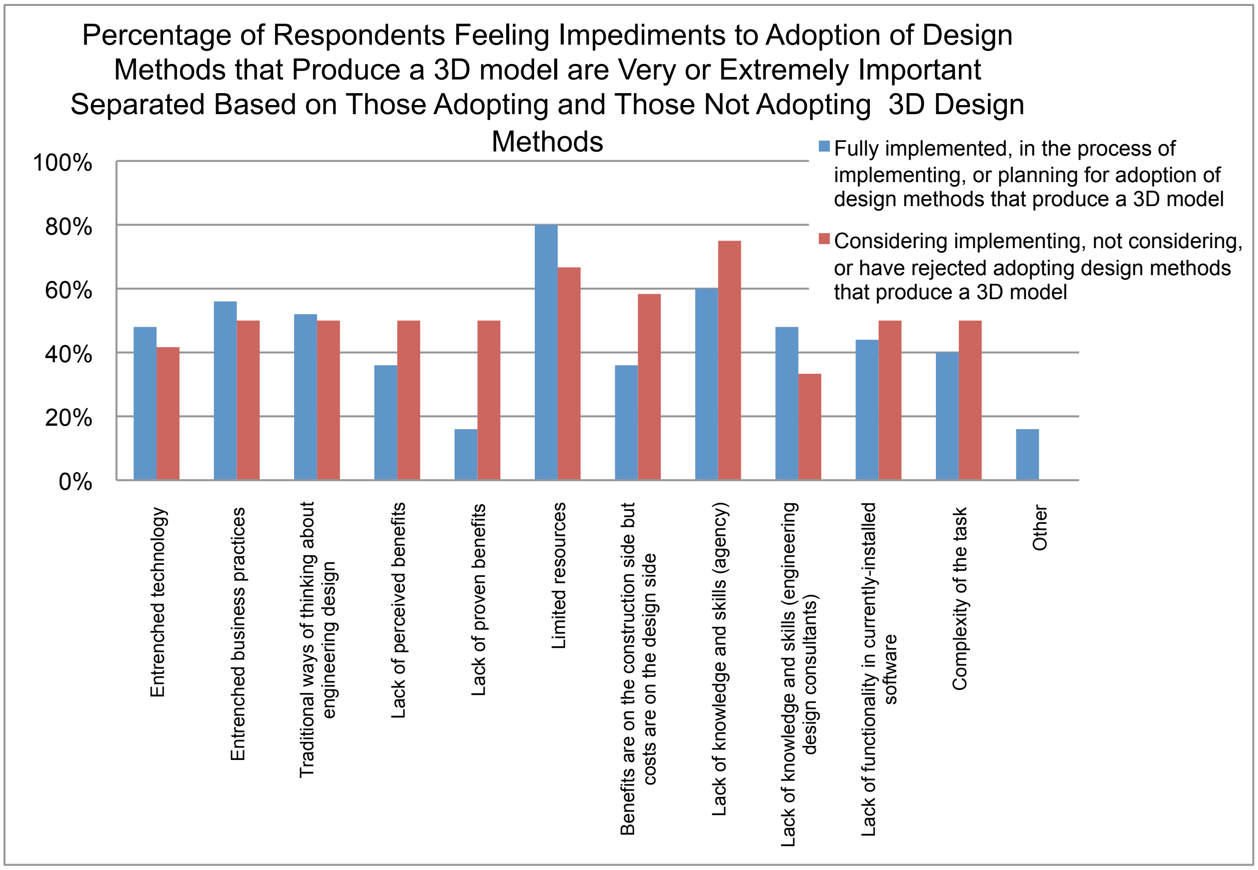


Figure 3.16

Some additional questions on CAD software and data transfer with design consultants were included in the survey. Analysis of responses to these questions appears in Appendix B.

3.3.2. Contracting

One section of the survey focused on contracting. One intention of this portion of the survey was to determine the standing of 3D digital data and 3D models in contract documents and to identify legal issues associated with them. Additional objectives included determination of responsibility for 3D model development and what forms of digital data are provided to contractors.

One hundred percent of responding SHAs include 2D plans in construction contract documents. However, only 11.4 percent of state highway agencies give 3D digital data any legal standing. The regional distribution of the percentage of responding state highway agencies that give 3D digital data legal standing in contract documents is shown in Figure 3.17. Approximately 17 percent of responding agencies from both the Northeast and West Regions, and 11 percent from the Southeast Region grant 3D digital data some legal standing. No respondents from the Mississippi Valley Region indicate 3D digital data has legal standing.

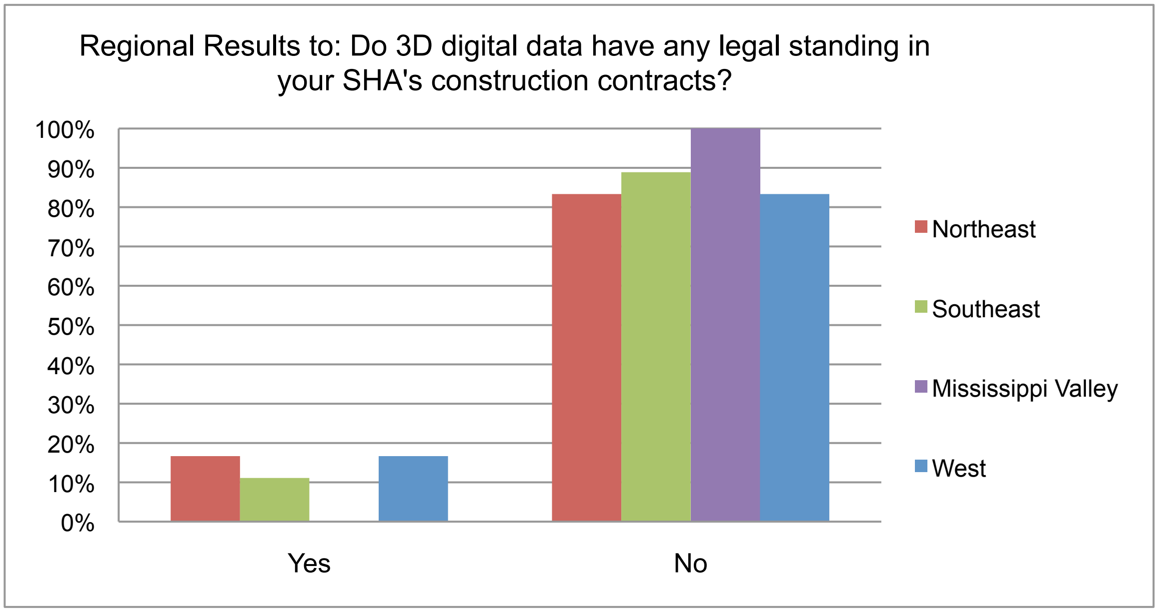


Figure 3.17

Twenty-nine percent of all respondents have identified legal issues associated with adopting 3D models as contract documents. Figure 3.18 provides the distribution. Seventy percent of them identified issues with electronic signatures, transfer of liability (as related to electronic data exchange), and data security (e.g., protection against unauthorized changes, integrity of revision history). Fifty percent have also found auditability of plans is of concern and 30 percent feel unintended use of electronic data is an issue. Thirty percent of these respondents also identified other legal issues such as discrepancies between paper documents and electronic data and lack of a known method to electronically sign and seal a 3D model or coordinate geometry information.

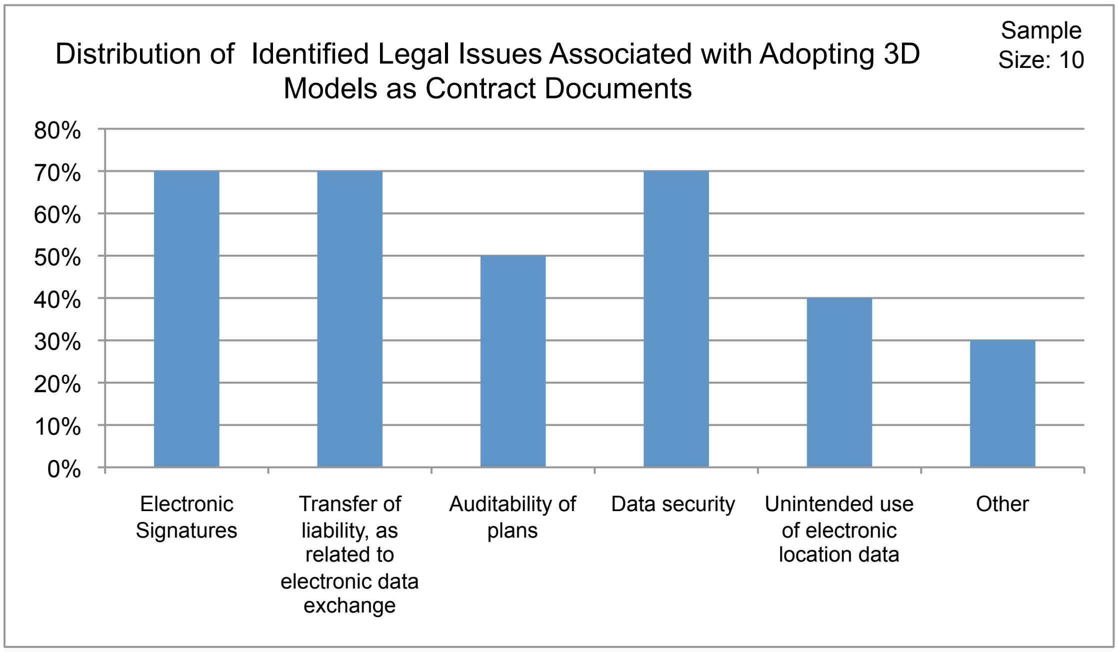


Figure 3.18

Eighty-two percent of responding SHAs are using automated machine guidance for highway construction. Figure 3.19 indicates the percentage of agencies using AMG in individual regions. One hundred percent of responding SHAs within the Mississippi Valley Region, between 70 and 80 percent within the Southeast and West Regions, and approximately one third within the Northeast Region use AMG for highway construction. Thus, there is considerable variability in use of AMG among regions.

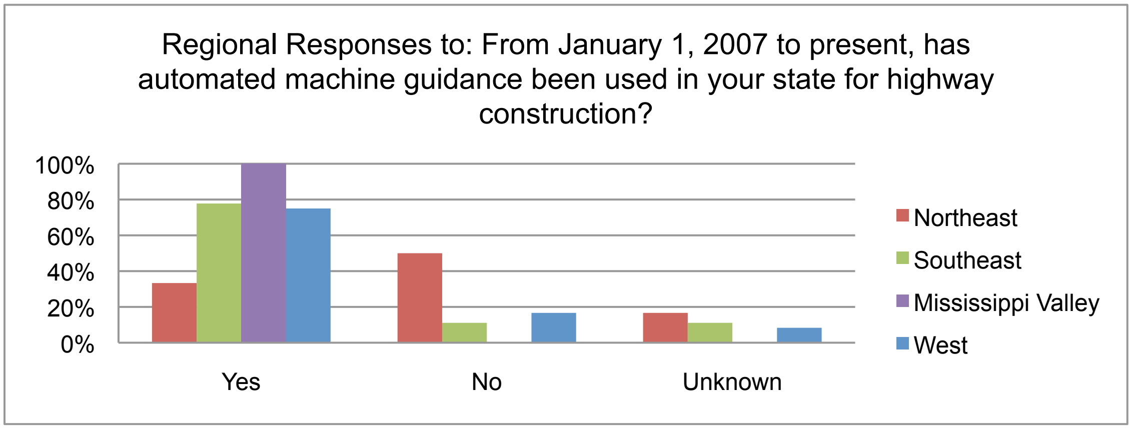


Figure 3.19

Respondents who stated that AMG is used in their state were questioned on primary responsibilities concerning 3D models. Figure 3.20 displays the distribution of delegation of primary responsibilities for 3D model development and assurance of compliance with contract documents. Eighty percent of SHAs give contractors primary responsibility for developing 3D models. Also, 92 percent of respondents give contractors responsibility for ensuring that 3D models conform to contract documents. The majority of other SHAs indicate the agency has responsibility for developing 3D models used in AMG.

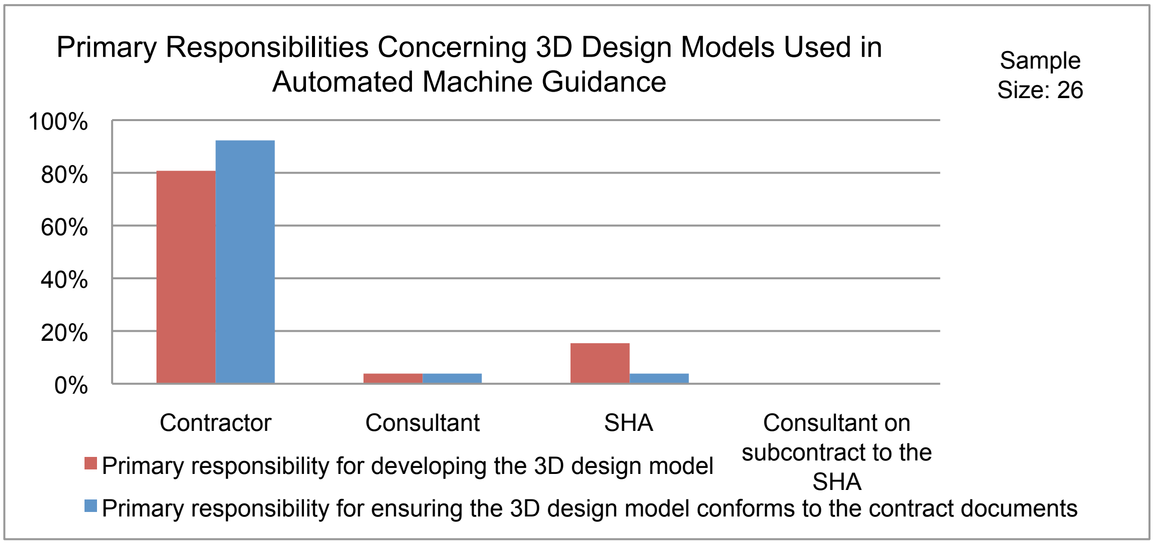


Figure 3.20

All respondents were asked which forms of digital data that might assist in 3D design model development are provided to construction contractors. Figure 3.21 provides the overall distribution of responses and Figure 3.22 provides the regional distribution. A full 3D design model is provided to construction contractors by 23.5 percent of responding SHAs. The Mississippi Valley Region, in which 100 percent of respondents stated AMG is used in their state, has the lowest percentage of responding agencies that provide a full 3D design model to construction contractors. Fifteen percent of responding SHAs provide no digital data for aid in 3D model development to construction contractors. All respondents from the Mississippi Valley and West Regions provide some form of digital data. However, one third of responding agencies from the Northeast and Southeast Regions provide no such digital data to construction contractors.

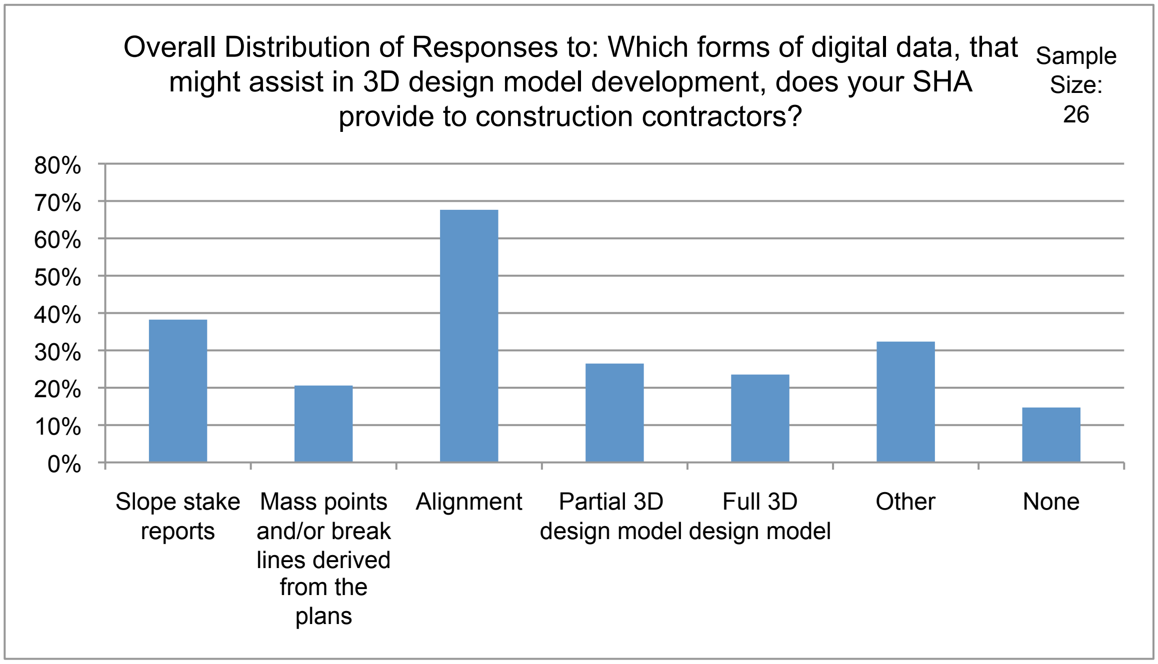


Figure 3.21

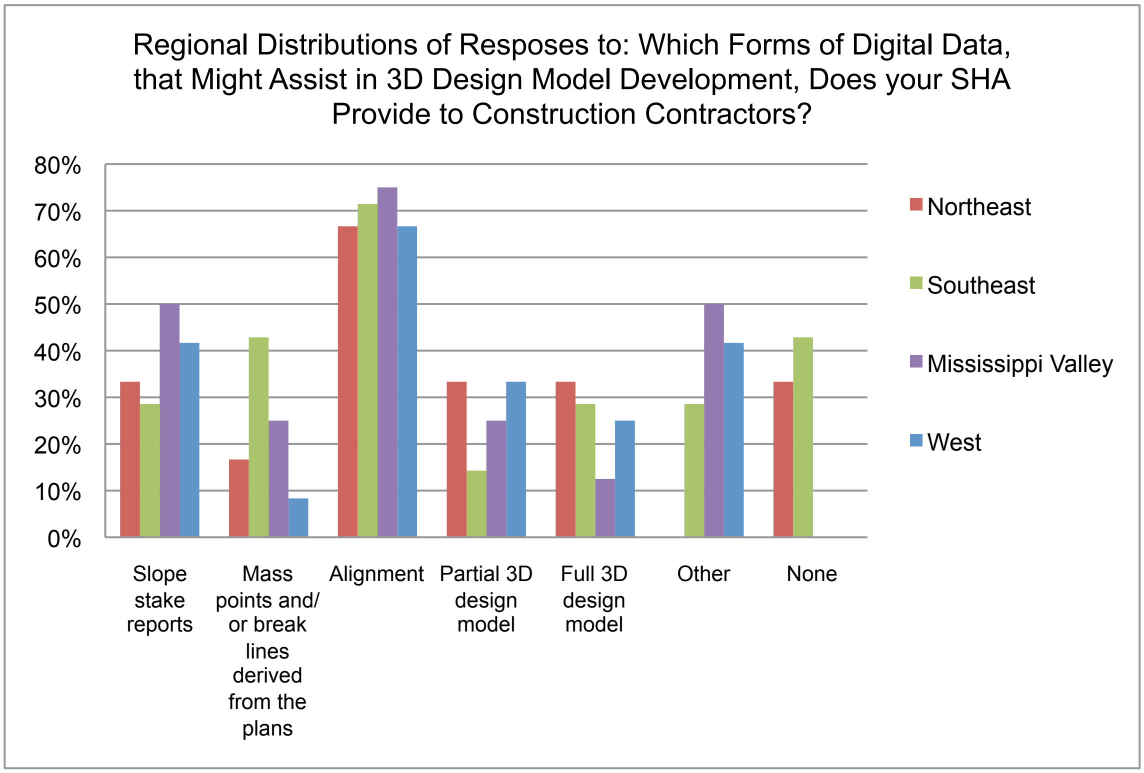


Figure 3.22

A partial 3D model is provided to contractors by 26.5 percent of responding SHAs. A significantly lower percentage of responding agencies from the Southeast Region provide a partial 3D model. Contractors are given alignment data by nearly 70 percent of SHAs. Also, slope stake reports are given to contractors by 38 percent of all respondents. Approximately 20 percent of all SHAs provide contractors with mass point and/or breakline data, with considerable variability among regions. While approximately one third of respondents from the Southeast Region do this, only 8 percent of West Region respondents do.

Thirty-two percent of respondents give other forms of digital data to contractors. The other types of data provided to contractors include cross sectional data, existing ground DTMs, superelevation data, coordinate geometry, and survey files.

When asked if engineering design consultants are required to provide 3D design model data to construction contractors upon request, 74 percent of responding SHAs replied “no.” Respondents were asked how often engineering consultants provide 3D design model data to construction contractors upon request. The overall and regional distributions of responses are provided in Figures 3.23 and 3.24, respectively. Ironically, only 3 percent (or one) respondent said engineering consultants always provide contractors with 3D design data upon request, even though 26 percent of respondents said engineering design consultants are required to provide data to construction contractors upon request in response to the previous survey question.

Approximately 12 percent of all responding SHAs indicate engineering consultants usually provide contractors with 3D digital data upon request, all of these being in the Northeast and Southeast Regions. No respondents from the Mississippi Valley Region indicate 3D digital data is provided to contractors more often than “sometimes.”

Thirty percent of responding SHAs indicate engineering consultants never give contractors 3D design model data upon request. An additional 30 percent of respondents say 3D data is rarely provided to contractors upon request. Fifty percent of the respondents from the Southeast Region state that 3D digital data is never provided to contractors upon request, which is a significantly higher percentage than other regions. The Northeast and Mississippi Valley Regions have high percentages (60 percent and 43 percent, respectively) of respondents indicating that engineering consultants rarely provide 3D digital to construction contractors upon request.

Approximately 12 percent of all responding agencies indicate engineering consultants sometimes or usually provide contractors with 3D data upon request. The Mississippi Valley Region has the highest percentage (29 percent) indicating that 3D digital data is sometimes provided to contractors upon request. It is also noteworthy that 36 percent of respondents from the West Region do not know how often engineering consultants give 3D digital data to construction contractors upon request.

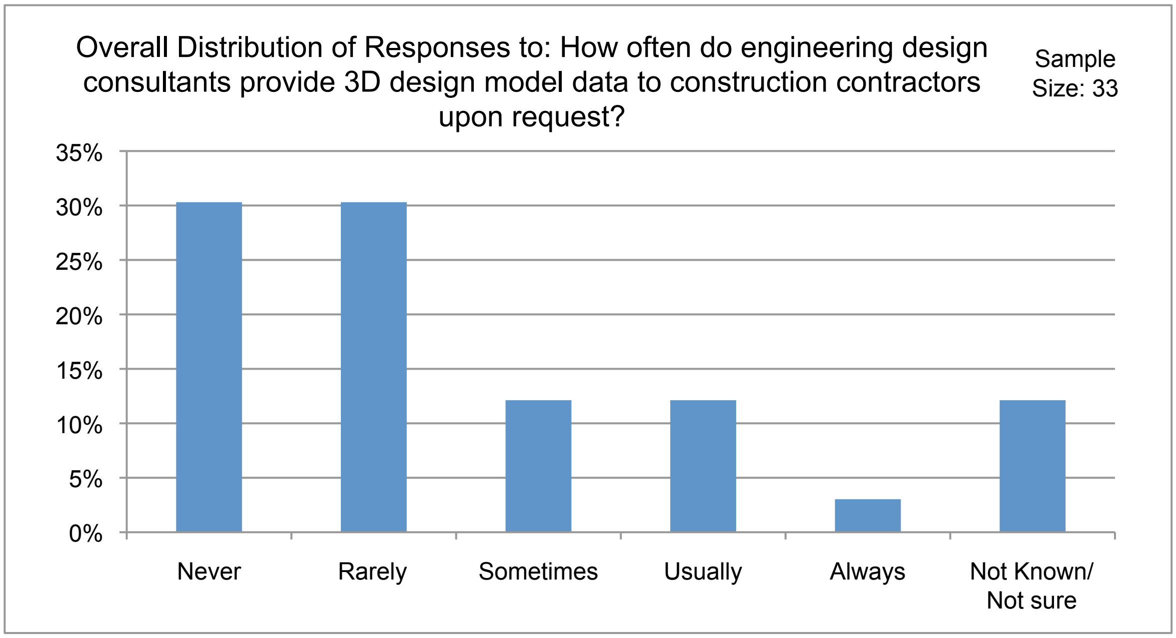


Figure 3.23

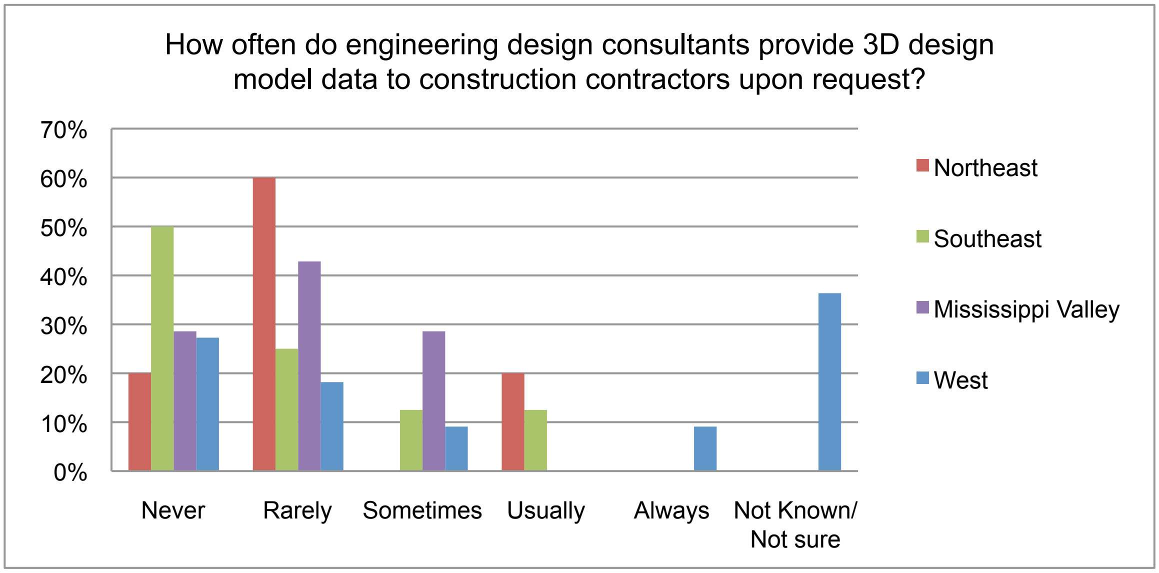


Figure 3.24

3.3.3. Construction

The construction section of the survey focused on automated machine guidance with one objective being determination of the extent of use of automated machine guidance on different construction types and another being discovery of how many SHAs have AMG specifications. Additionally, the importance of both benefits AMG and impediments to its wider use were investigated.

Respondents were asked to provide the approximate annual number of construction projects delivered by their SHAs. The overall and regional distributions are provided in Figures 3.25 and 3.26, respectively. State sizes and populations should have an impact on the annual number of construction projects and it was, therefore, anticipated that high variability exists among states. Approximately 47 percent of all responding SHAs deliver 200 or fewer construction projects per year. Twenty-eight percent deliver between 401 and 600 construction projects annually and 19 percent deliver between 401 and 600. There are very few responding agencies that perform more than 600 construction projects per year.

The majority of respondents in the Northeast and West Regions deliver 200 or fewer construction projects per year. The two regions also have the lowest percentage of responding states using AMG. It was expected that most agencies within the Northeast Region deliver fewer construction projects annually as many Northeast states are small in size. Most of the states in the West Region (except California and Texas) have sparse populations. The majority of SHAs in the Mississippi Valley and Southeast Regions deliver between 200 and 600 construction projects annually and exhibit higher use of AMG than the other regions. This suggests that states delivering higher numbers of construction projects are more likely to utilize AMG.

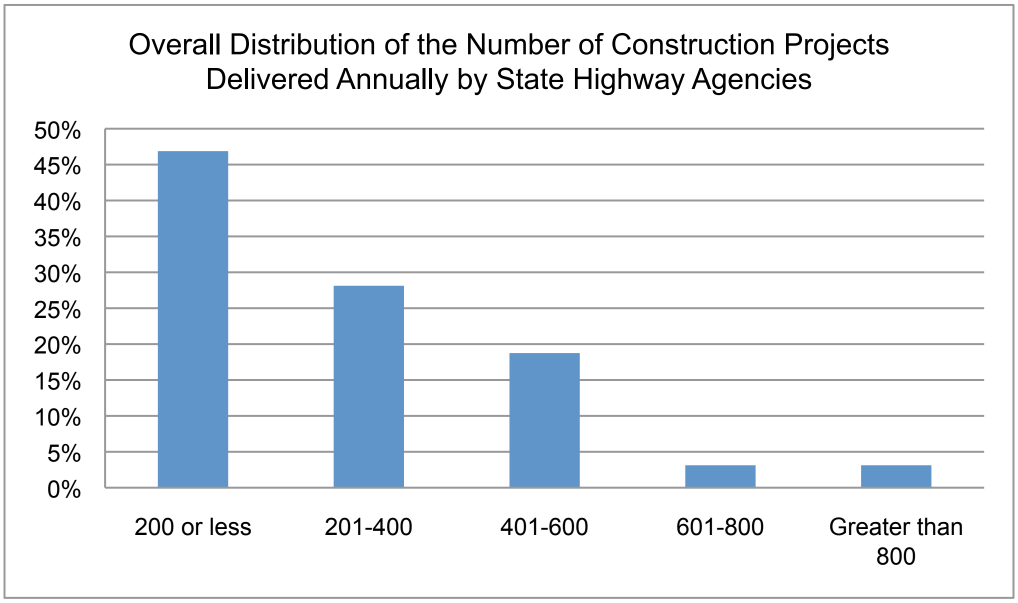


Figure 3.25

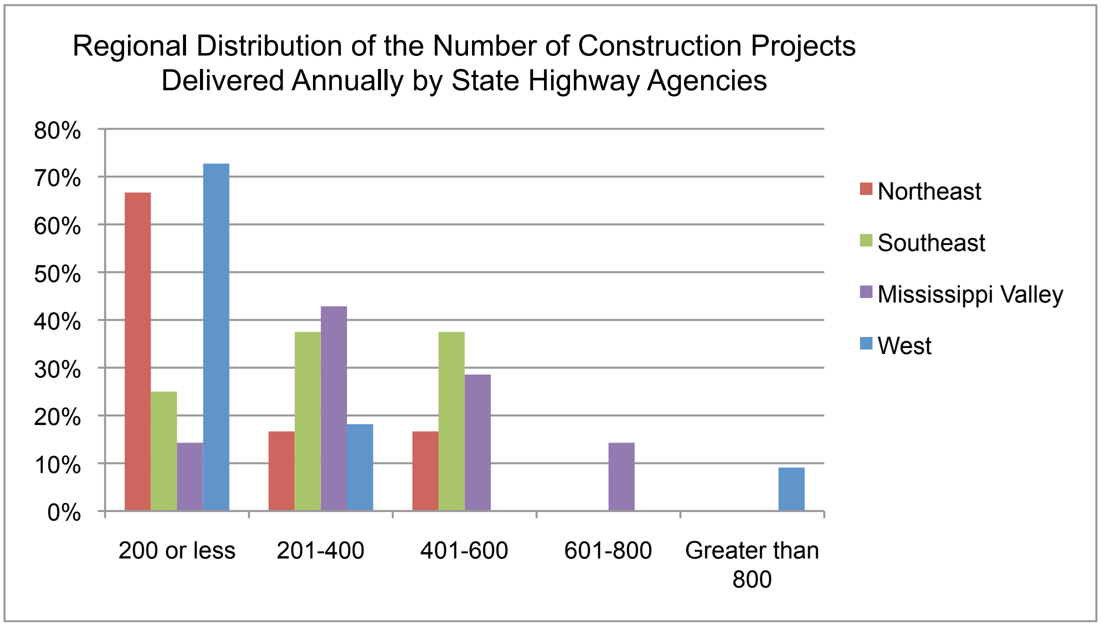


Figure 3.26

SHAs using AMG were asked to provide the approximate percentage of highway construction projects in their state that do so. The distribution of responses is presented in Figure 3.27. None of the respondents use AMG on more than 40 percent of construction projects. Of the agencies that use AMG, 93 percent use it on less than 20 percent of projects. The remaining 7 percent use it on 20 to 39 percent of projects. These low percentages might be due to the fact that AMG is primarily used as an aid in subgrade construction and many rehabilitative highway construction projects do not require subgrade reconstruction.

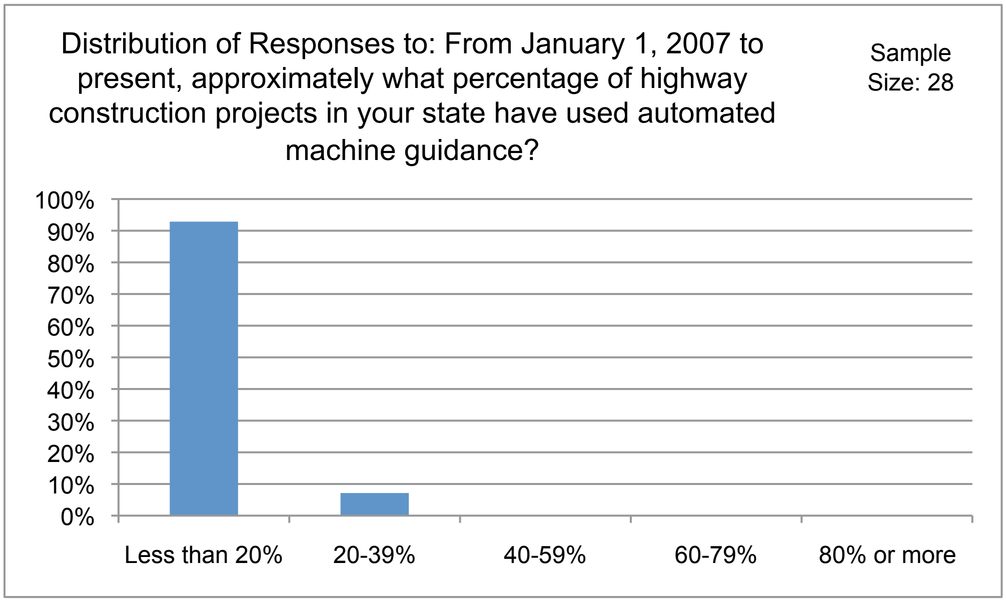


Figure 3.27

While AMG is used by 82 percent of responding SHAs, only 32 percent of those agencies have AMG specifications. Figure 3.28 provides the percentage of agencies in each region that have such specifications. The Mississippi Valley Region has the highest percentage of responding SHAs with an AMG specification. This is also the region with the highest percentage of responding agencies using AMG. The Northeast Region has the second highest percentage of agencies with an AMG specification. However, the Northeast Region has the lowest percentage of states that utilize AMG. The Southeast and West Regions have significantly lower percentages of agencies with AMG specifications than the Northeast and Mississippi Valley Regions. Eighty-two percent of SHAs that have AMG specifications address preparation and/or responsibility for 3D design models in their specification.

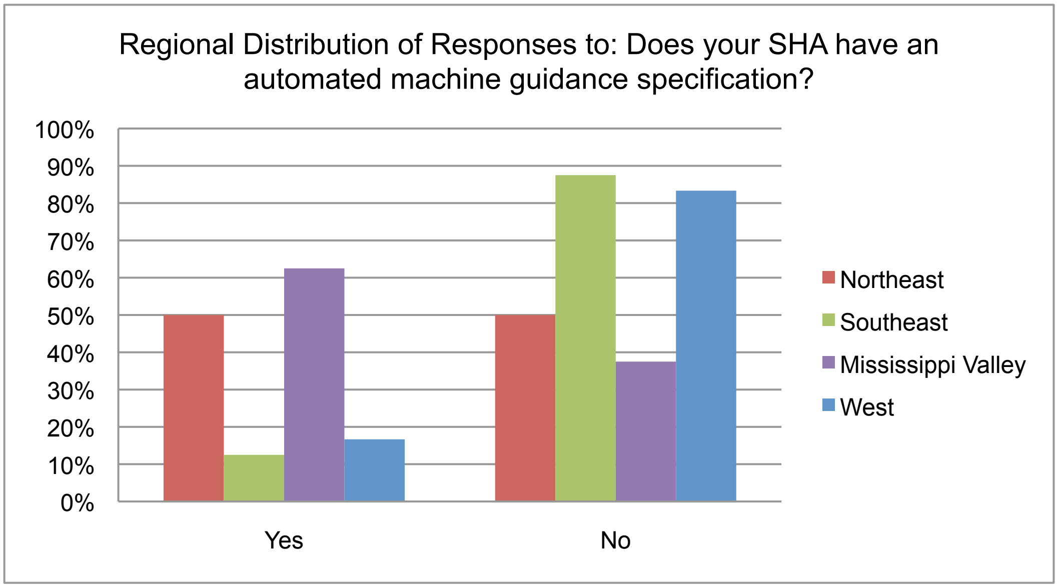


Figure 3.28

Respondents were questioned about types of AMG construction in their state. They were also asked which types of construction activities have AMG specifications. Respondents were instructed to select all applicable answers to both questions. The distributions of responses for both are presented in Figure 3.29. Figure 3.30 provides the percentage of agencies in each region using AMG for different construction types. (Note: Percentages for analysis of AMG use and specifications were calculated based on the total number of respondents for that section of the survey, including those that do not use AMG).

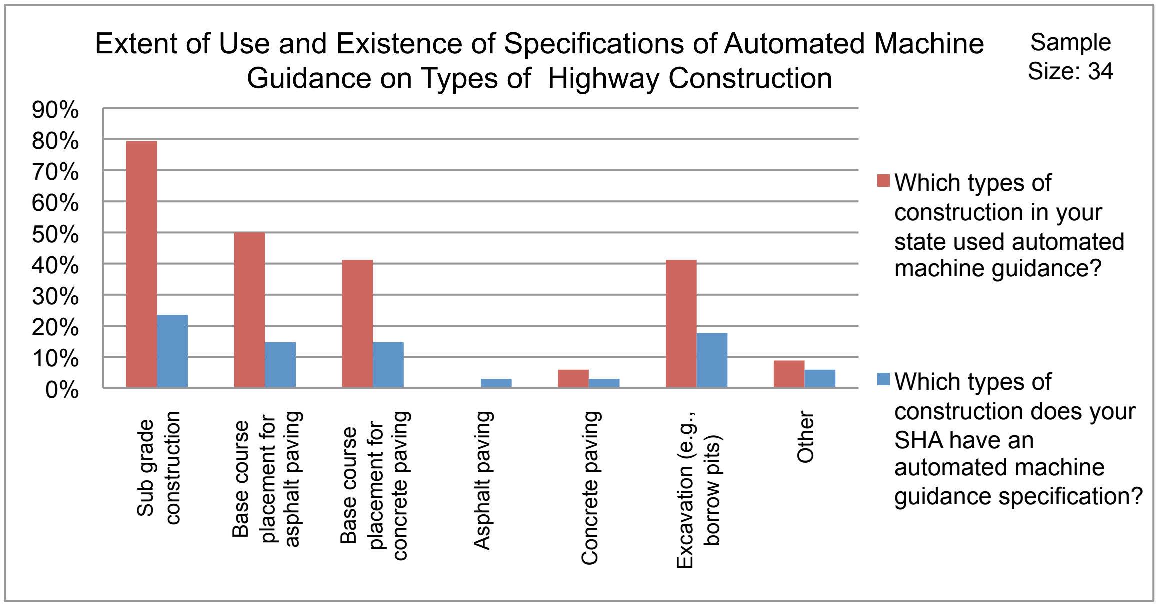


Figure 3.29

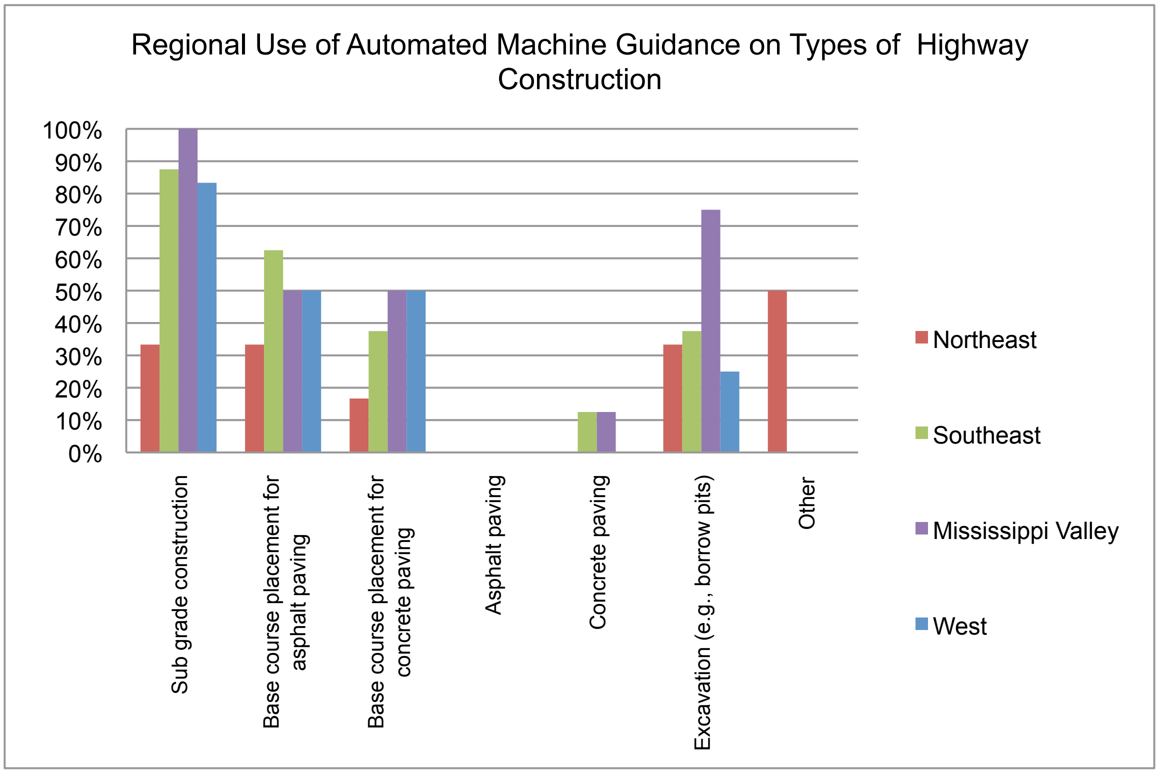


Figure 3.30

By far, the most prevalent application of AMG is subgrade construction. Eighty percent of all responding SHAs use AMG for subgrade construction. However, only 23.5 percent of them have an AMG subgrade specification. One hundred percent of respondents from the Mississippi Valley Region use AMG for subgrade construction.

Other common applications of AMG include base course placement for asphalt and concrete paving with use by 50 percent and 41 percent of respondents, respectively. Fifteen percent of agencies have specifications for base course placement in both concrete and asphalt paving activities. The Northeast Region has a significantly lower percentage of states using AMG for subgrade and base course construction, which is reasonable because the Northeast is also the region with the lowest percentage of states using AMG overall.

AMG is also used for excavation by 41 percent of responding SHAs but only 18 percent them have a corresponding specification. The Mississippi Valley Region has a significantly higher percentage of respondents that use AMG for excavation. Approximately 6 percent of responding SHAs use AMG for concrete paving but no responding agency uses AMG for asphalt paving. All respondents using AMG for concrete paving were from the Southeast and Mississippi Valley Regions. Three percent of responding agencies have specifications for both asphalt and concrete paving.

Eight percent of all respondents also use AMG for other types of construction (i.e., storm water pond excavation, wetland restoration, and trenching for utilities). They are all from the Northeast Region. Six percent of responding agencies have AMG specifications for types of construction other than those previously discussed. One respondent stated they have an AMG specification that is applicable to any operation.

Respondents were asked to rate the importance of specific individual benefits of AMG. Figure 3.31 provides average ratings, Figure 3.32 provides the distribution of responses for individual benefits, and Figure 3.33 provides regional average ratings.

Lower construction costs has the highest average rating (i.e., very important) of all benefits. However, less repeat work, contractor productivity gains, and greater accuracy are also considered to be very important or extremely important by the majority of respondents. Respondents from all regions produced similar ratings of importance for lower construction cost, greater accuracy, and contractor productivity gains. Less repeat work has average ratings exceeding very important in the Southeast and Mississippi Valley Regions, but the average rating of this benefit in the Northeast Region is considerably lower.

More uniform surfaces in the final product are quite important, as 70 percent of respondents feel it is either very or extremely important. The average rating (i.e., exceeding very important) for this benefit is considerably higher in the Southeast than in other region. Less staking is also considered to be very or extremely important by approximately 62 percent of responding agencies. The only benefit that respondents generally do not feel is especially important is support for night work.

Approximately 20 percent of respondents indicated that other benefits, not included for rating, are either very or extremely important. Several respondents listed increased safety as an important benefit of AMG. Higher production and reduced construction time were both identified as benefits not included for rating. Fewer disputes between contractor and owner were also recognized as a benefit. It was stated that contractors are able to refine their bids based on precision of equipment when using AMG.

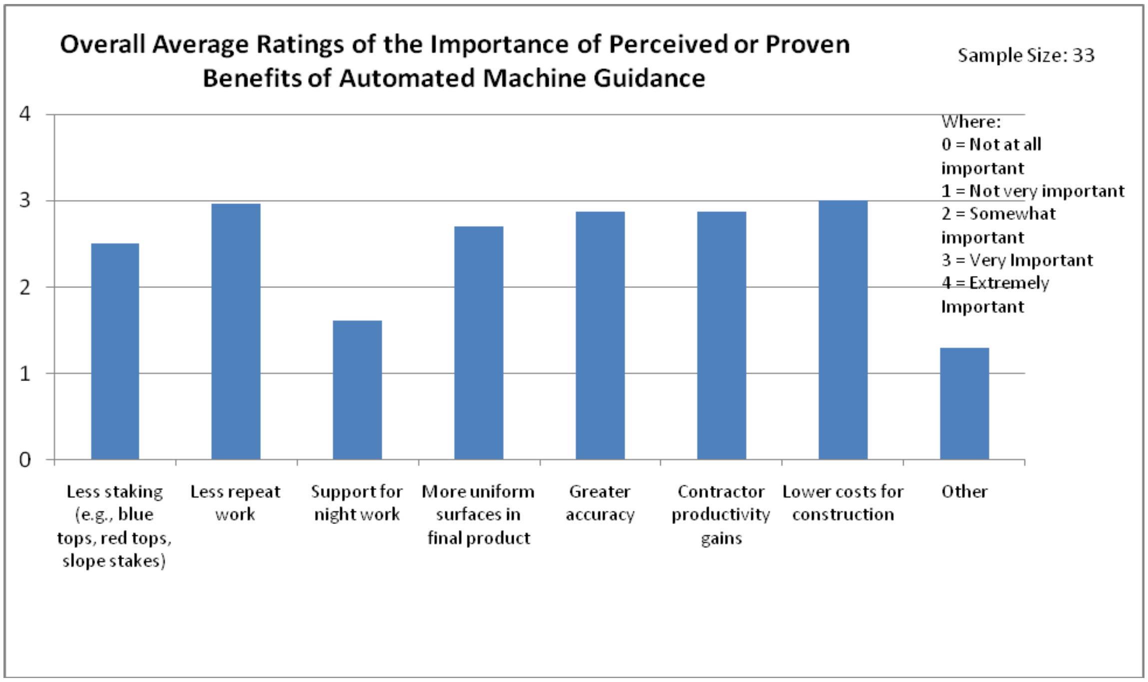


Figure 3.31

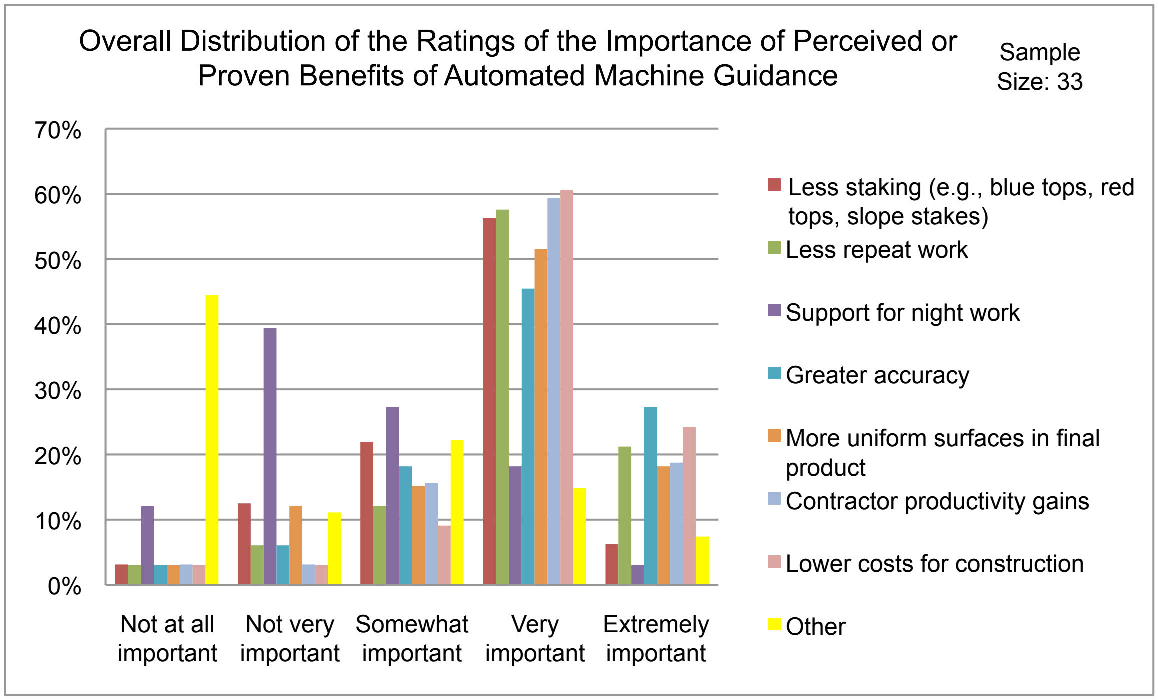


Figure 3.32

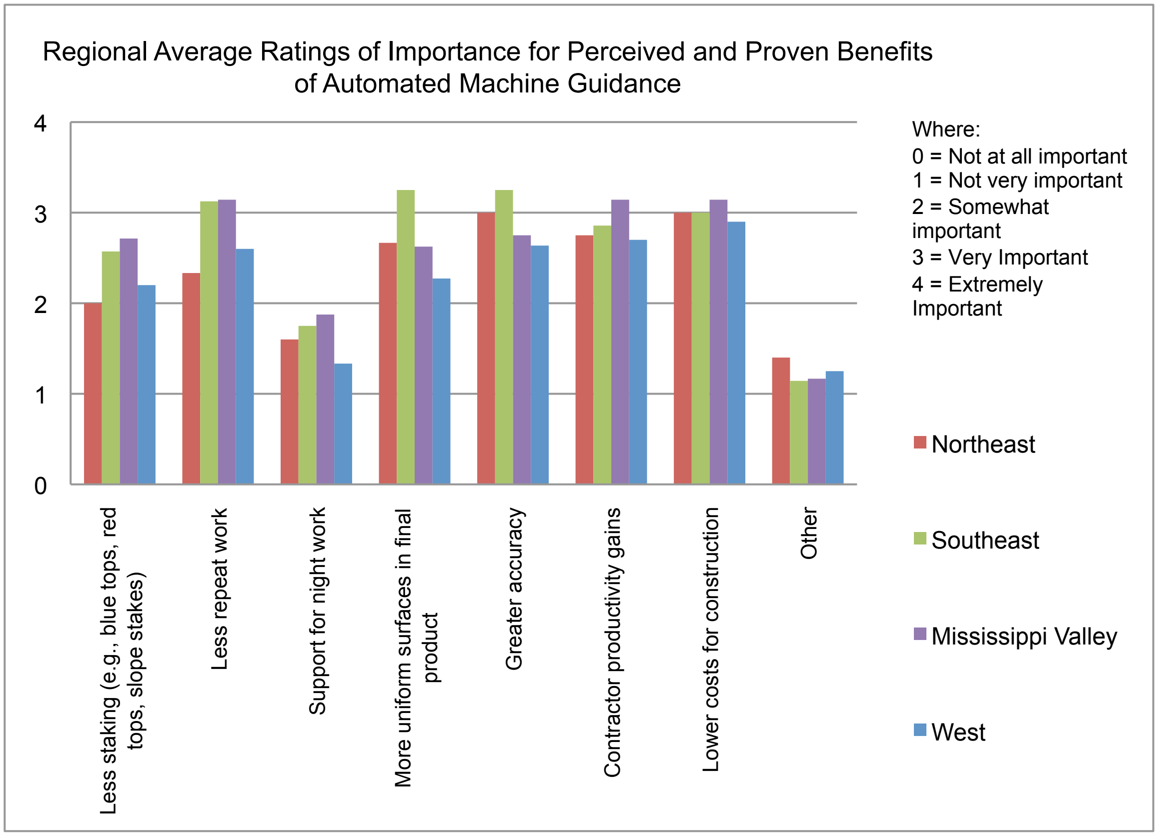


Figure 3.33

Comparisons were made between the percentage of agencies using AMG that state a given benefit is very or extremely important and the percentage of agencies not using AMG that state the same benefit is very or extremely important. The differences in perception of importance are presented in Figure 3.34. There is a considerably higher percentage of agencies using AMG who state that contractor productivity gains are either very or extremely important than those not using it. Thus, the perceived importance of contractor productivity gains might be a deciding factor in whether SHAs implement AMG technologies. There are also 11 percent more respondents using AMG that state greater accuracy is very or extremely important than respondents not using it. On the other hand, there is a substantially higher percentage of agencies that do not use AMG, stating a more uniform surface in the final product is a very or extremely important benefit. Other benefits were given similar evaluations of importance by those that use and do not use AMG.

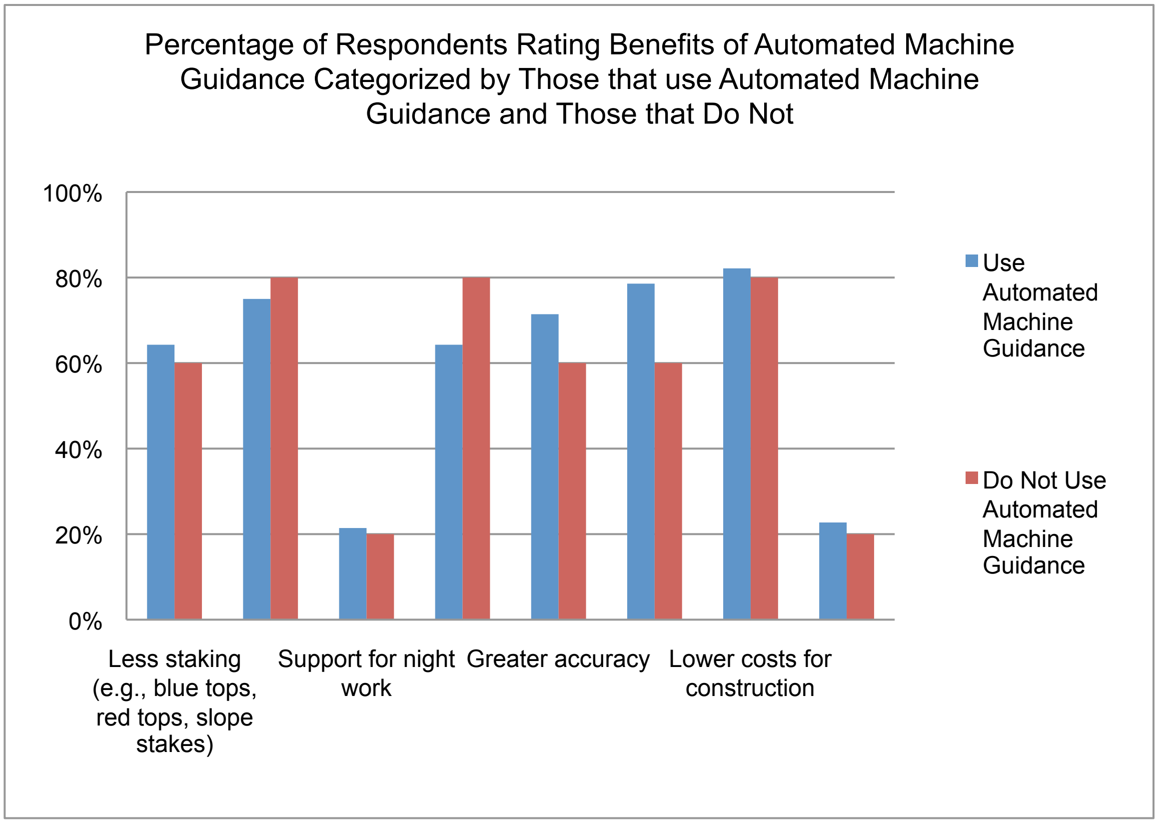


Figure 3.34

Respondents were asked to rate the importance of individual impediments to wider use of AMG. Figure 3.35 provides overall average ratings, Figure 3.36 provides the distribution of responses, and Figure 3.37 provides the regional average.

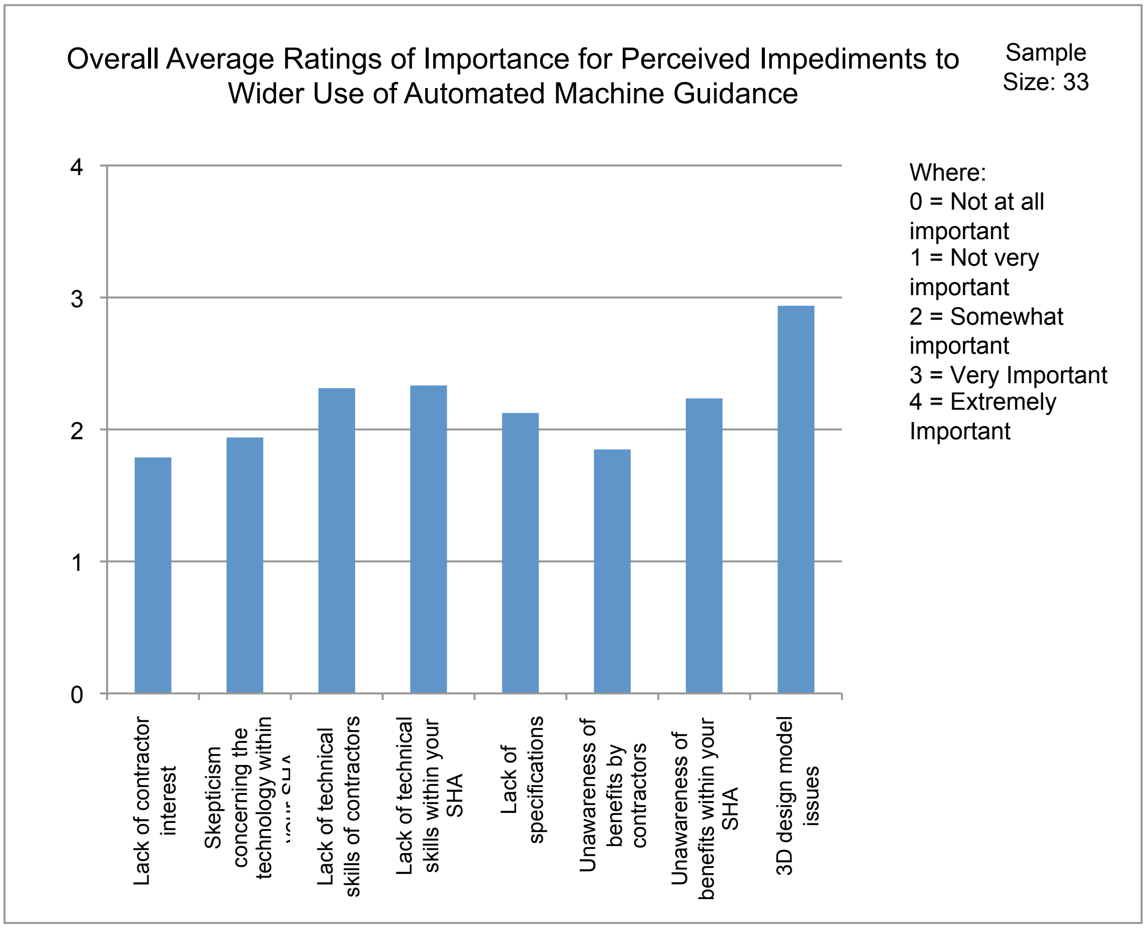


Figure 3.35

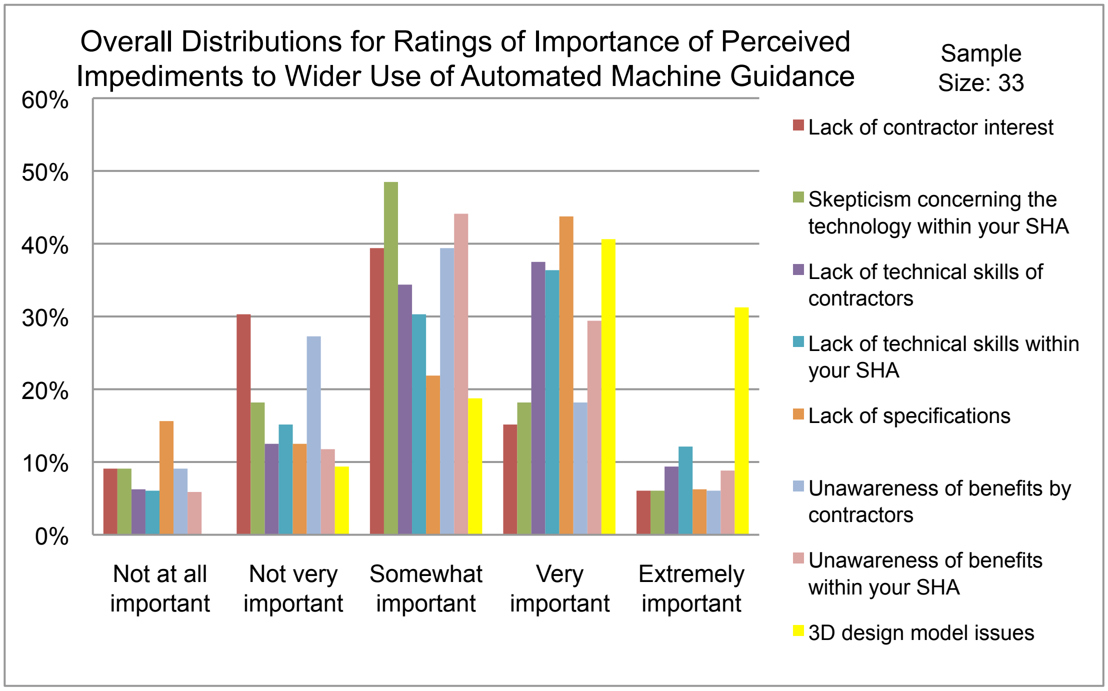


Figure 3.36

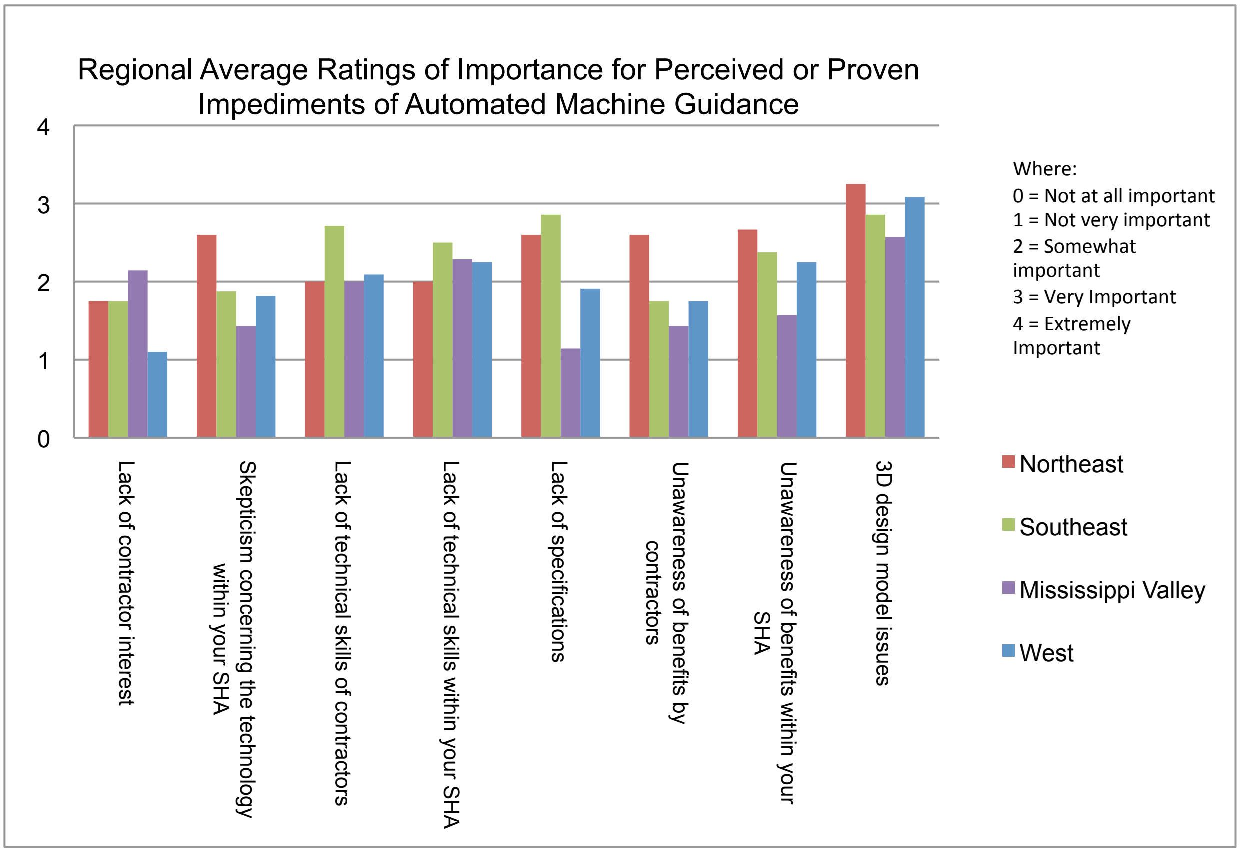


Figure 3.37

For all regions, 3D design model issues have the highest rating of all impediments to wider use of AMG with 72 percent of all respondents stating that they are either very or extremely important. Many respondents also selected lack of contractor and SHA technical skills as being significant. Forty-eight percent of respondents perceive agency lack of technical skills to be a very or extremely important impediment and 46 percent of respondents feel contractor lack of technical skills is a very or extremely important impediment. The Southeast Region has the highest average rating with respect to importance of both contractor and SHA lack of technical skills, with the differences being less for lack of agency skills than for lack of contractor skills.

Fifty percent of respondents feel lack of specifications is either very or extremely important as an impediment to wider use of AMG. This is significant because only 32 percent of SHAs using AMG have specifications. Unawareness of benefits within the agency has an average rating above somewhat important while unawareness of benefits by contractors is considered to be less important. Lack of contractor interest and skepticism concerning technology within the agency are not considered to be especially important barriers.

The Northeast Region has the highest average rating of importance for half of the impediments to wider use of AMG. This is also the region with the lowest percentage of states using AMG, which could indicate that these barriers are significant. Similarly, the Mississippi Valley Region has the highest use of AMG of any region and generally has lower ratings of importance for impediments to wider use of the technology. This suggests that either impediments to wider use of AMG have been overcome in much of the Mississippi Valley Region or these impediments are non-issues in many Mississippi Valley states.

The percentage of agencies using AMG that feel individual impediments are very or extremely important was compared to the percentage of agencies not using AMG that feel the same. The results appear in Figure 3.38. Percentages were calculated similar to the manner for evaluating the difference in perception of benefits (above). A significantly higher percentage of agencies that do not use AMG feel lack of contractor interest, agency skepticism concerning technology, lack of contractor and agency technical skills, and contractor unawareness of benefits are very or extremely important. Lack of specifications and agency lack of technical skills were also rated as being very or extremely important by a higher percentage of agencies not using AMG. However, these impediments were rated as being either very or extremely important by considerably closer percentages of respondents using and not using AMG than the previously discussed impediments. Three-dimensional design model issues are rated as being very or extremely important by a considerably higher percentage of agencies using AMG.

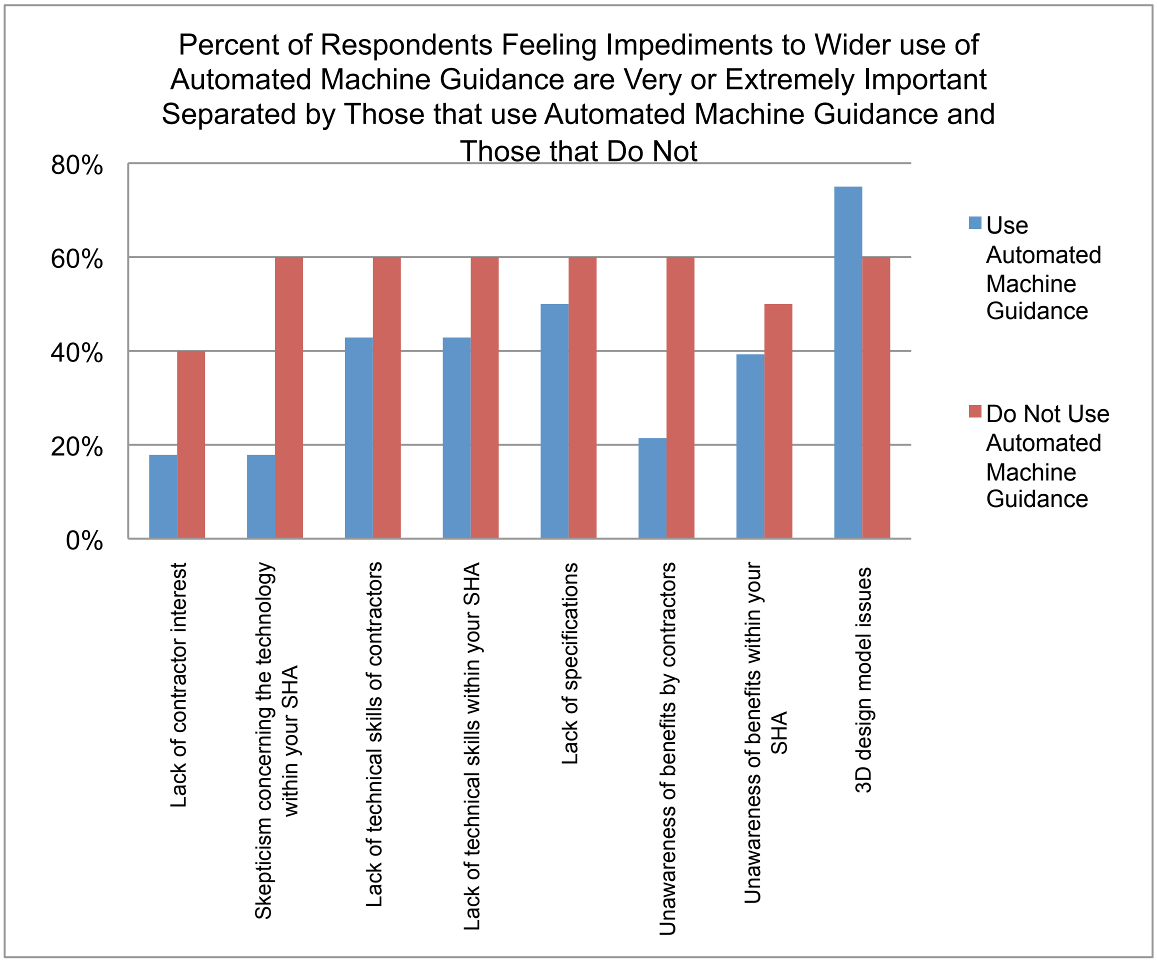


Figure 3.38

3.3.4. Earthwork

Several related questions within various sections of the survey focused on earthwork. As discussed in the literature review, 3D surface models allow determination of earthwork via the surface-to-surface method in addition to the traditionally used average-end-area method. Thus, an additional goal of the survey was to determine the extent of use of the surface-to-surface method for calculating earthwork quantities.

Respondents were questioned on what field survey method is used most often during data collection for final quantities. Distributions of overall and regional responses are provided in Figures 3.39 and 3.40, respectively. Cross sections by ground survey is the most frequent response for all regions. Approximately 67 percent of responding SHAs use cross sections by ground survey as their primary method of data collection for final quantities. Mass points and breaklines are the most common survey method for 18 percent of all responding SHAs. Twenty-five percent of respondents from the Southeast Region use photogrammetry as their primary method, which is considerably higher than other regions. The West is the only other region to have respondents indicate photogrammetry is the most common data collection method for final quantities.

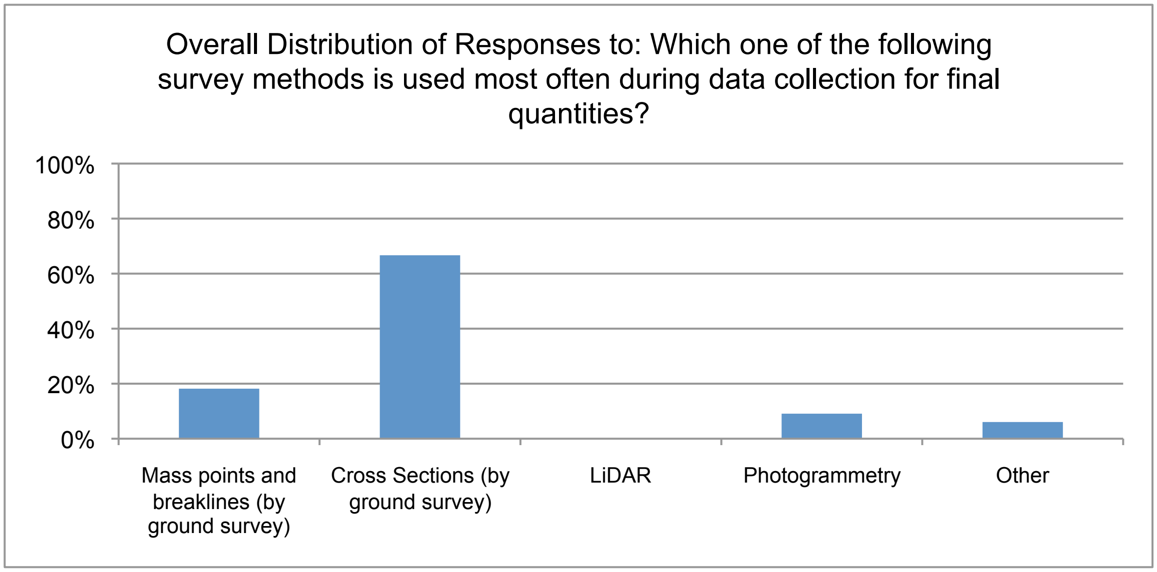


Figure 3.39

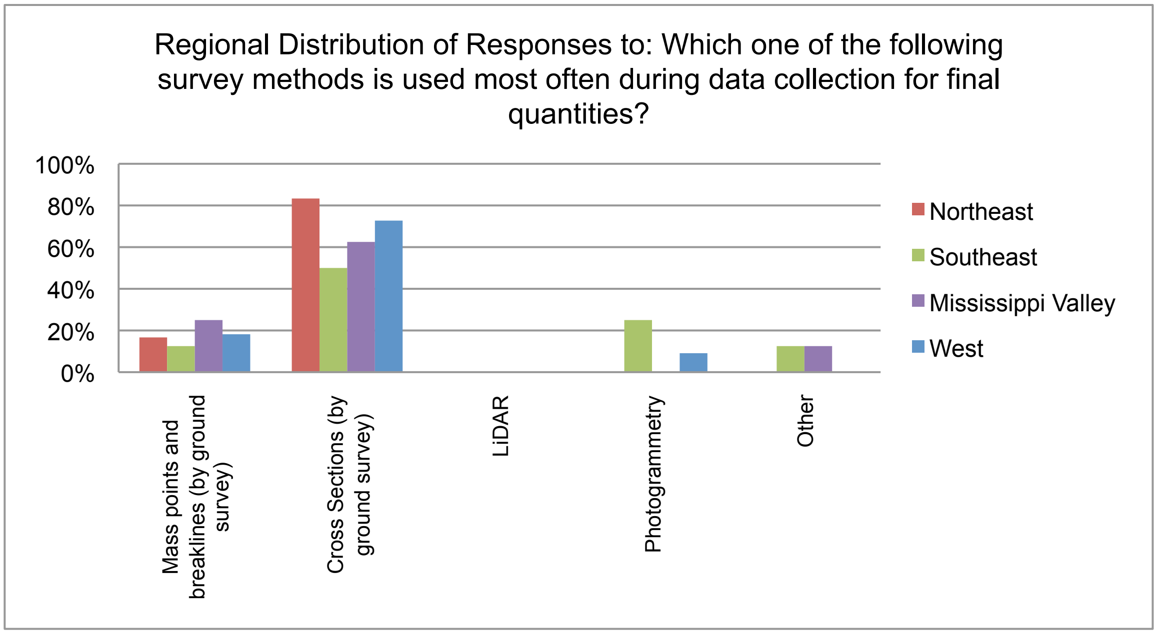


Figure 3.40

Respondents were asked which method is used most often for estimating earthwork quantities during design. The overall and regional distribution is provided in Figures 3.41 and 3.42, respectively. Approximately 87 percent of all responding SHAs primarily use average-end-area to compute earthwork quantities during design. However, two thirds of responding agencies from the Northeast Region most often use the surface-to-surface method. All responding agencies within the Southeast and Mississippi Valley Regions state average-end-area is most common.

Approximately 86 percent of responding agencies within the West Region use average-end-area in computing earthwork volume during design.

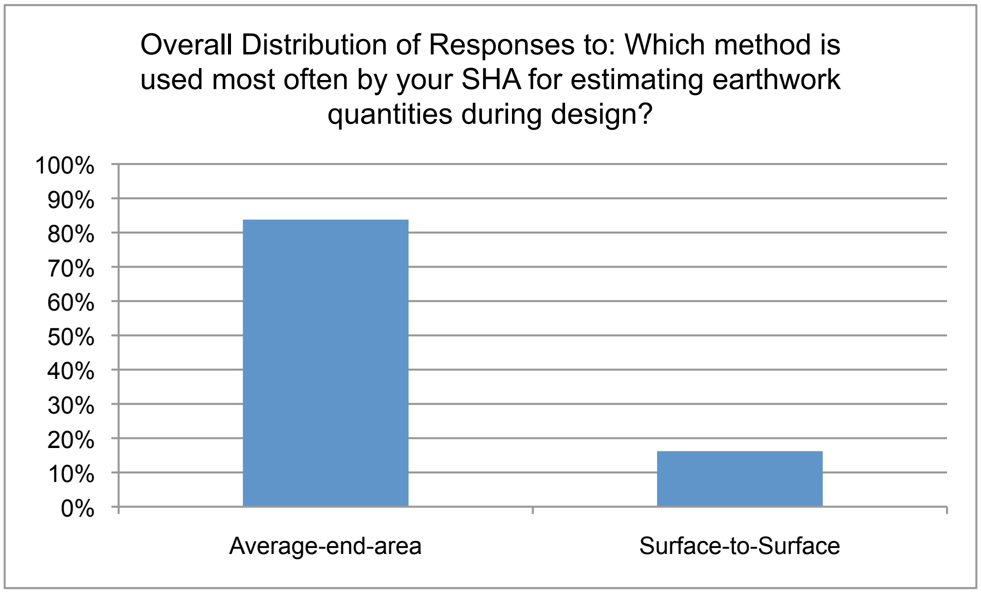


Figure 3.41

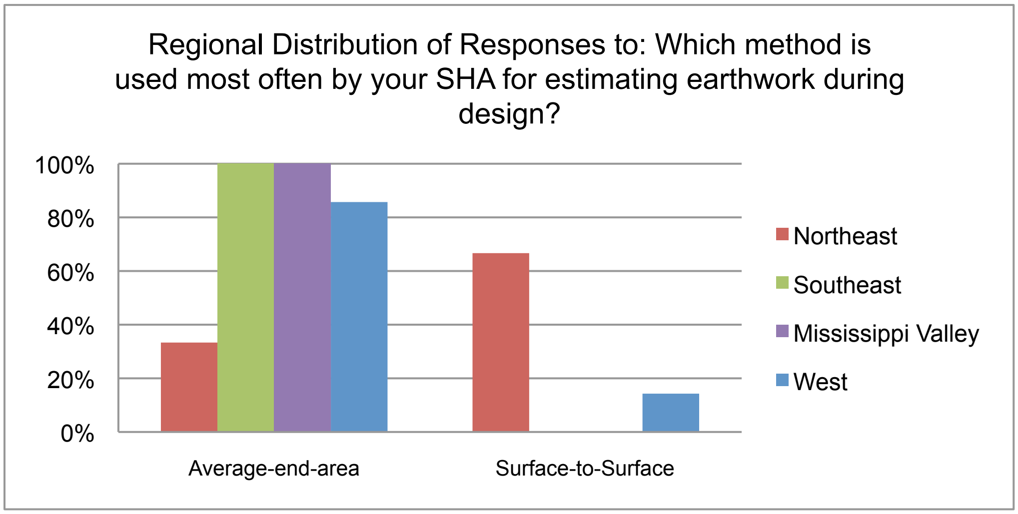


Figure 3.42

Respondents were also asked which earthwork computational method is specified most often in their SHAs' policy, standards, or procedural documents. Figures 3.43 and 3.44 provide the overall and regional distributions. While 84 percent of all responding agencies state average-end-area is used most often when computing earthwork quantities during design, 97 percent state average-end-area is specified most often in policy, standards, and procedural documents. All respondents from the Northeast, Southeast, and Mississippi Valley Regions state they primarily specify average-end-area for use for computing earthwork volumes. Recall that two thirds of Northeast respondents use surface-to-surface most often during design. One responding SHA from the West Region specifies surface-to-surface most commonly in policy, standards, and procedural documents.

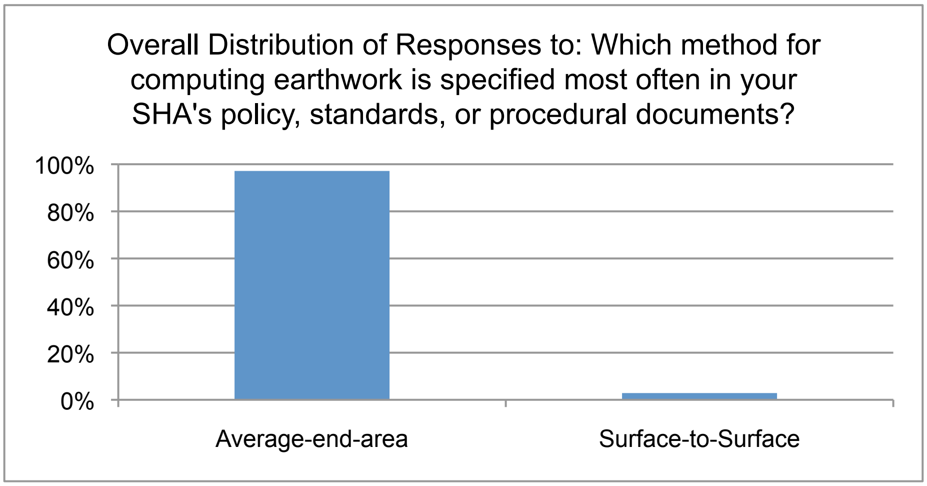


Figure 3.43

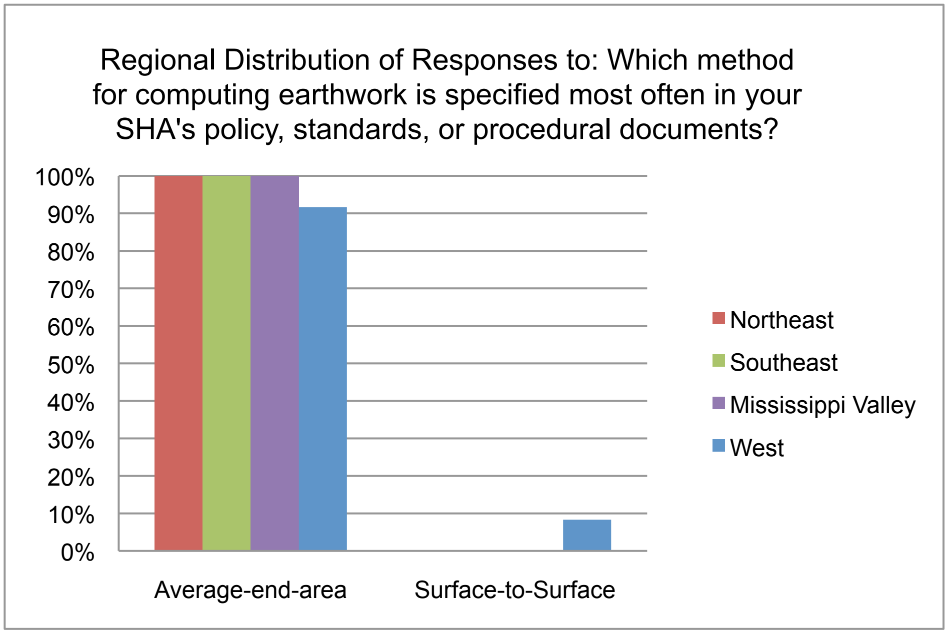


Figure 3.44

The same question was asked concerning methods for computing final quantities. The overall and regional distributions appear in Figures 3.45 and 3.46, respectively. Ninety-one percent of all responding agencies state average-end-area is the most common method. Thus, more agencies use average-end-area for computing final earthwork quantities than for design. One hundred percent of respondents from the Southeast and Mississippi Valley Regions primarily use average-end-area for computing final earthwork quantities. Thirty-three percent of responding agencies from the Northeast Region primarily use surface-to-surface to compute final earthwork volumes. Eight percent of respondents from the West Region usually use surface-to-surface.

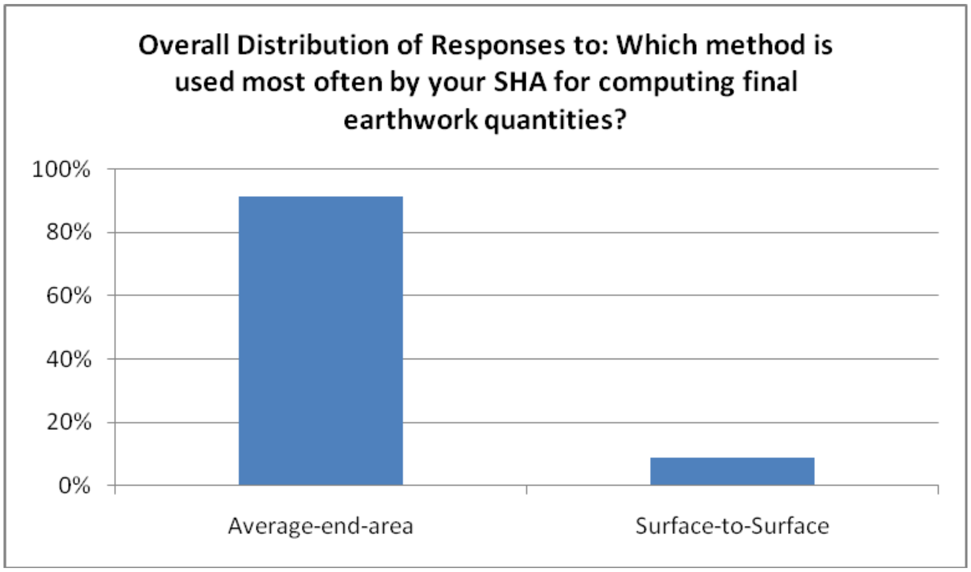


Figure 3.45

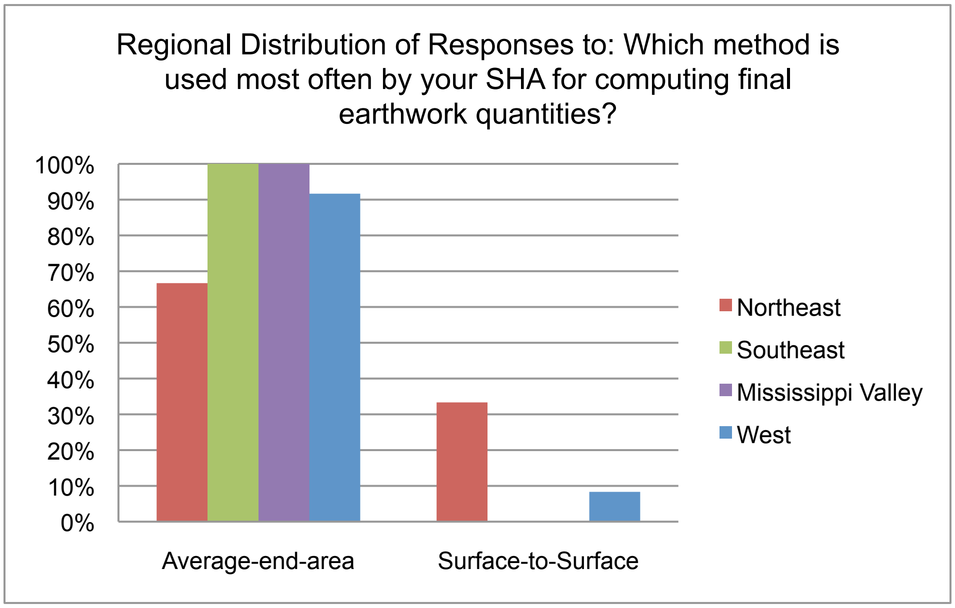


Figure 3.46

3.4. Railroads

The survey was distributed to seven class 1 regional railroads: 1) BNSF, 2) Canadian National, 3) Canadian Pacific, 4) CSX, 5) Kansas City Southern, 6) Norfolk Southern, and 7) Union Pacific. The number of respondents to survey questions varied from one to five throughout the survey. Only selected questions with three or more respondents will be discussed.

Figure 3.47 provides the distribution of responses of the percentage of design work done in-house as opposed to being contracted to engineering design consultants. There is widespread distribution among railroads in the percentage of work completed in-house with 40 percent indicating 60 to 79 percent of design work is completed in house. Eighty percent indicate they have content standards such as features, layers, colors, and line types for digital design files. Additionally, 80 percent of respondents have format standards for transferring digital data. Seventy-five percent of those that have formats for transferring digital data use MicroStation Design Files (.dgn) as their standard. One respondent indicated that AutoCAD Drawing File (.dwg) is their standard.

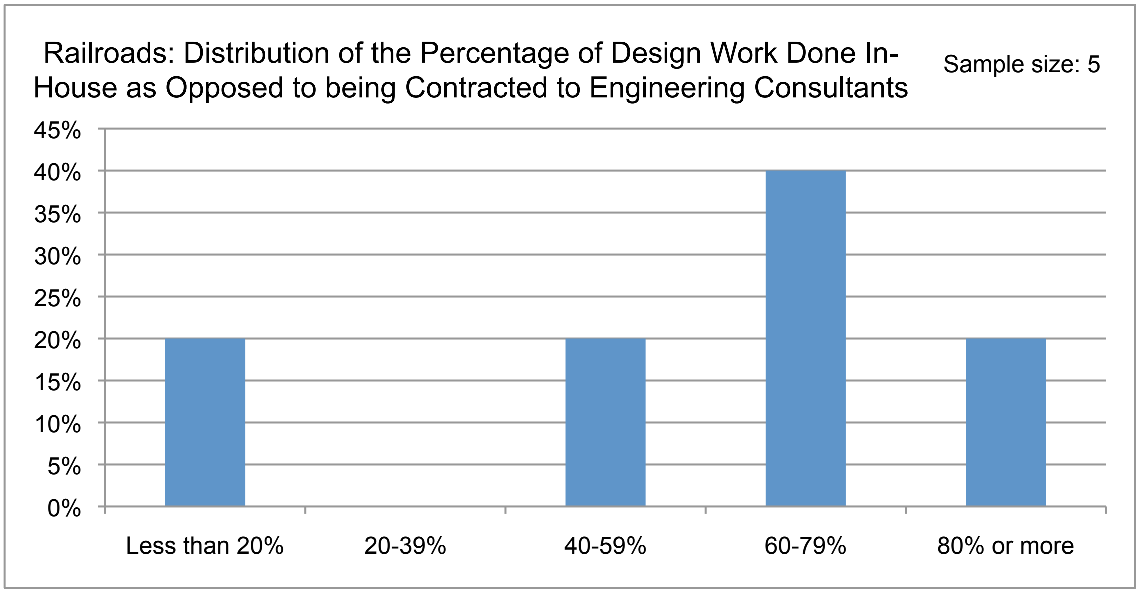


Figure 3.47

Figure 3.48 shows the distribution of adoption status for design methods that produce a 3D model. Twenty percent of responding railroads have fully adopted design methods that produce a 3D model. Forty percent of railroad respondents indicate their agency is not considering such methods. Additionally, 20 percent of respondents indicate they are planning for adopting such methods and 20 percent state they are considering adopting such methods.

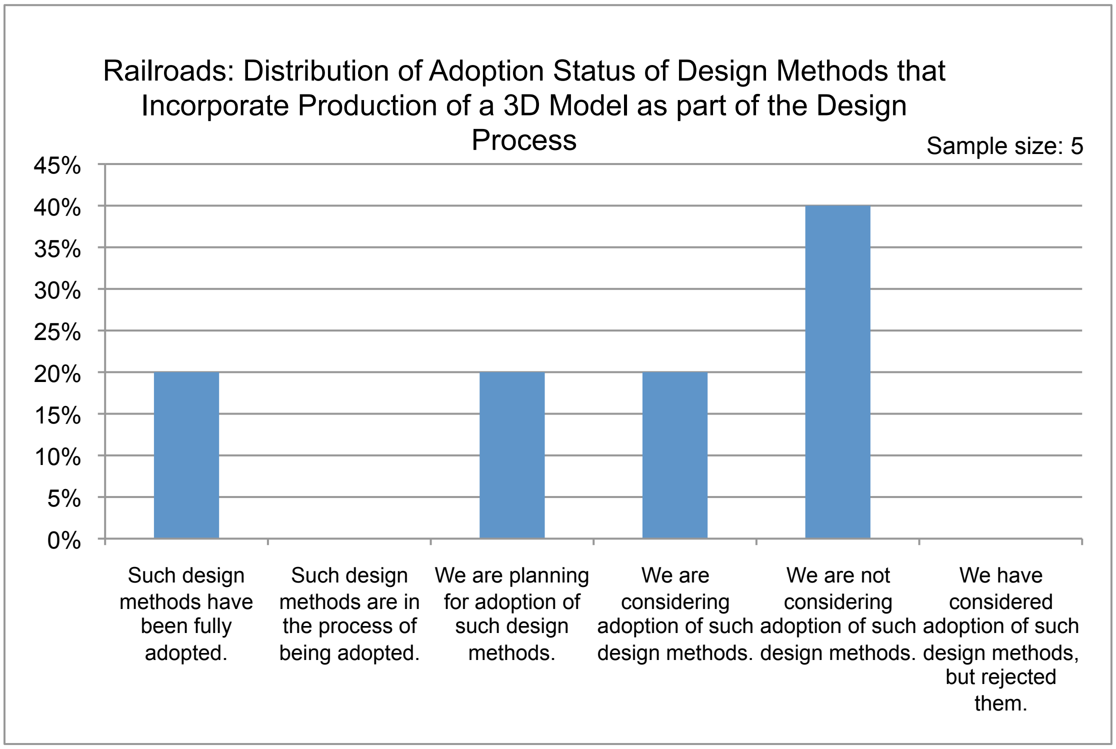


Figure 3.48

Two-thirds of respondents indicate their railroad uses automated machine guidance in construction. However, none of these respondents have AMG specifications. All respondents that use it at all use AMG for subgrade construction. Additionally, one railroad indicated that it uses AMG for excavation.

Twenty-five percent of responding railroads give 3D digital data some legal standing. One-third of respondents indicate engineering design consultants are required to provide 3D digital data to construction contractors upon request to aid in 3D model development. Ironically, as shown in Figure 3.49, none of the respondents indicate engineering design consultants always provide 3D design model data to construction contractors upon request. This is inconsistency between requirements and what is actually done, concerning provision of design data by consultants, is in line with responses from the SHAs.

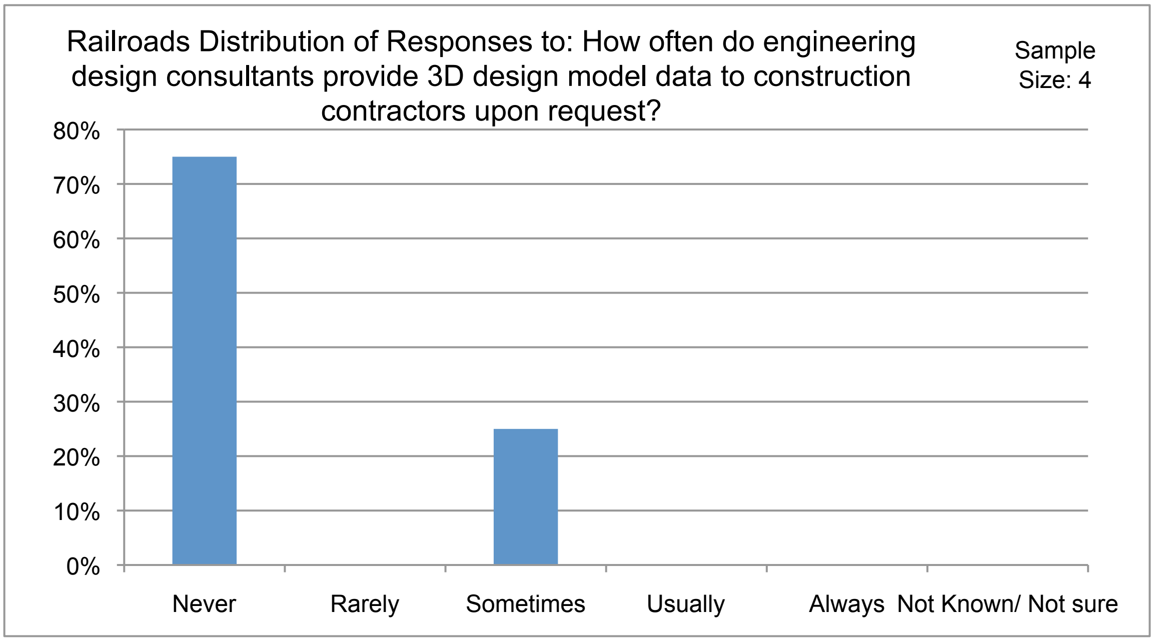


Figure 3.49

All responding railroads state that average-end-area, (as opposed to surface-to-surface), is the most common method for determining earthwork quantities during design, during final quantity determination, and specified in standards, policies, and procedural documents.

3.5. General Survey Conclusions

Significant issues associated with use of 3D design and construction technologies were identified through survey results. While advancements in these technologies are clear, there are still major technological and legal impediments that must be overcome for seamless transfer of data and complete implementation of these technologies.

Eight-two percent of all responding SHAs currently use AMG for some aspect of highway construction. Lower costs for construction, greater accuracy, contractor productivity gains, less repeat work, and less staking are all perceived or proven benefits that the majority of respondents feel are very important.

Eighty percent of responding SHAs give contractors primary responsibility for producing 3D design models for use in AMG. Only 19 percent of all responding SHAs have fully adopted design methods that produce a 3D model. Furthermore, 60 percent of respondents assert that engineering consultants rarely or never provide 3D digital data to construction contractors for aid in 3D model development.

Many agencies are in the process of adopting or are planning for adopting design methods that produce a 3D model. The necessity of 3D models for use in AMG is a likely driving factor in the decisions of these agencies. However, there are benefits associated with 3D design methods beyond use in AMG. Improved ability to detect and eliminate design errors prior to construction is recognized as being an exceptionally important benefit by 89 percent of agencies. Furthermore, the majority of respondents feel improved visualization and having a more comprehensive representation of design intent are significant benefits.

Survey respondents recognize three-dimensional design model issues as the most important impediment to wider use of AMG, which provides additional evidence of the importance of 3D design methods. However, implementing design methods that produce a 3D model is not an easy task for SHAs. There are many important impediments. The majority of respondents recognize lack of resources, agency lack of knowledge, entrenched business practices, lack of functionality in currently installed software, and required staff training as major obstacles. Translation of data across different software platforms has historically been a problem, but AASHTO and TRB continue to strive for data compatibility standards and vendors have reported to be cooperating.

It is appropriate to consider the size of SHAs in comparison to most engineering consulting firms when evaluating the difficulty of implementing 3D design methods. The resources required to purchase the required design tools and the number of employees that need to be trained in an engineering consulting firm make the goal more attainable. Due to the size of SHAs, internally implementing 3D design technologies might not be feasible at the present time particularly for agencies that primarily contract design work to engineering consultants. Thus, for the 46 percent of responding agencies that complete less than 40 percent of design work in-house, it could be more economical to contract 3D design work to engineering consultants rather than adopt the methods internally.

There are also legal factors hindering the transfer of 3D digital data between designers and construction contractors for use in AMG. Three-dimensional digital data have some legal standing in only 11 percent of responding SHAs. Primary issues include electronic signatures, transfer of liability as related to data exchange, data security, and auditability of plans.

Only 32 percent of responding SHAs that use AMG have associated specifications. Fifty percent of respondents feel lack of specifications is a very important impediment to wider use of the technology.

Use of the surface-to-surface method to compute earthwork quantities becomes possible when three-dimensional models are available. However, survey results indicate a large majority of SHAs are still using average-end-area.

There are significant differences in the extent of use of AMG among regions. While 100 percent of responding agencies from the Mississippi Valley Region are using it, only 33 percent of responding agencies from the Northeast Region are. The majority of states in the Mississippi Valley and Southeast Regions deliver more construction projects annually than the Northeast and West Regions. There is also a higher percentage of states using AMG in those two regions.

Considerable variation exists in the adoption status of 3D design methods among regions. There is widespread distribution in the Southeast and West Regions. However, in the Northeast and Mississippi Valley Regions, a high percentage of agencies fall into a single category of adoption status. In the Northeast Region, there are far more agencies in the process of adopting 3D design methods than there are in other categories of adoption status. There are appreciably more agencies in the Mississippi Valley Region planning for adoption of 3D design methods than there are in other categories of adoption status.

4. Case Studies

Based upon the survey responses, three SHAs were selected for more in-depth case studies: 1) Minnesota DOT (MnDOT), North Carolina DOT (NCDOT), and Wisconsin DOT (WisDOT). These agencies are exemplary in their support and commitment to 3D design, AMG, and their integration. The case study information was developed by site visits to MnDOT and WisDOT and by telephone conference with key staff at NCDOT. In addition to the interviews and discussions, each of these SHAs provided additional documents and or electronic materials concerning their adoption status and directions.

4.1. Minnesota DOT

MnDOT was an early adopter and advocate for automated machine guidance, with the technology being used for pond excavation as early as 2001. The agency had a visionary division director who understood the potential for significant savings in construction and spurred a department-based effort to encourage contractors to adopt the technology. By 2004, MnDOT had a specification for AMG construction of subgrade that required use of AMG on selected projects. Contrary to the Minnesota experience, it is contractors who have taken the lead in most other states and the SHAs are responding to the direction taken by industry when developing specifications and providing digital data.

Under MnDOT's specification, the agency prepares all 3D models for AMG. Models are provided to contractors without guarantee of accuracy. The plans are the basis for the contract and the 3D models are developed from them. As checks, 3D models are overlaid with cross sections and contoured to 0.10 foot. Visual inspection and numerical differencing of the overlays are performed. If errors in a model are discovered in the field, MnDOT has three days to update the model. Models are prepared in both the central office and the districts. Contractors must reformat the 3D models for use with their equipment if MnDOT's MicroStation® GEOPAK® format is not readily usable. The agency worked closely with Associated General Contractors to form ideas on 3D model content and detail (e.g., layers and resolution).

As of fall 2009, many Minnesota contractors had adopted AMG and MnDOT's specification is no longer required as a mandate on selected projects. The agency is still preparing 3D models, but not for all AMG projects. An agency goal for 2010 is to provide 3D models prior to bid for selected projects. Contractors are now often preparing the models from plans. When contractors prepare 3D models, they perform their own checking and use them at their own risk. AMG has been used not only for subgrade but also for base course on some projects. The technology saved eight days of ramp construction on a particular pilot project.

In the field, MnDOT has done some completely stakeless projects except at bridges and intersections where 3D models might have problems. Field checking has consistently shown final grades to be within ±0.05 ft of design. Checking frequency is at the discretion of the project engineer. Typically, surveyors follow a grader and do spot checks every 100 ft on straight-aways and every 50 ft on curves. Total stations or RTK GPS are used for the check surveys. Checks are made against plans. When using RTK GPS for checking, base stations and site calibrations that are independent of the contractor's are used. MnDOT made no modification to its allowable tolerances for grade checks: 1) within 0.1 foot of design when subgrade is prepared for placement of a aggregate wearing course; 2) within 0.05 foot above or 0.1 foot below design when prepared for placement of aggregate base course; and 3) within 0.05 foot of design when prepared for placement of a surface course (MnDOT, 2005).

MnDOT identified more uniform surfaces in the final product, greater accuracy, and increased safety (fewer people on active construction sites) as extremely important benefits of AMG. Lack of contractor interest (in the initial years) and 3D design model issues were identified as extremely important impediments.

MnDOT is in the process of implementing Corridor Modeler® for GEOPAK®. This software has extended 3D design functionality and is expected to make the modeling process much easier. In fact, MnDOT's intent is to develop and implement a 3D design process for AMG and modeling support. They are beginning to explore options that allow design of parallel surfaces instead of seams with varying thickness. Such and approach will expedite 3D design.

MnDOT identified the following benefits of 3D design as extremely important: 1) detection and elimination of design errors prior to construction, 2) more comprehensive representation of design intent, and 3) improved support for construction. In addition implementation planning is recognized as an extremely important prerequisite for adoption of 3D design. Traditional ways of thinking, limited resources, and complexity of the task are extremely important impediments. These are best addressed, internally, in a top-down fashion by leadership teams with buy-in from upper-level management. Eventually, entrenched business practices and ways of thinking will evolve with time and experience. MnDOT would like to see 3D design and AMG incorporated into the curricula of two-year civil technology educational programs from which they recruit many of their incoming employees.

To build upon its experiences and successes to date, MnDOT is undertaking an integrated 3D initiative with one or two pilot projects in 2010 or 2011 that will demonstrate the utility and benefits of operating and managing data in three dimensions from design, through public presentations, to construction. The initiative began as an implementation plan for AMG only (Henry & Thompson, 2009), but the agency decided to extend the plan to include an overall 3D initiative. The cited document states that AMG needs a champion, QC/QA processes need to be identified, and training needs to be developed, as do both short-term and long-term implementation strategies. It is recommended that full implementation be guided by four teams: 1) Management, 2) Leadership, 3) Implementation, and 4) Communication, with their roles, responsibilities, membership, goals, and timelines described in the cited document.

4.2. North Carolina DOT

Construction contractors in North Carolina began using AMG as early as 2003. By 2006, NCDOT was actively working with contactors to help implement AMG. The agency began providing 3D data, derived from plans, on selected large projects. By 2007, seventy-five percent of North Carolina's regions had had at least one project upon which AMG was used. Potentially lower costs, better products, and faster completion of construction projects motivated the agency.

NCDOT has a draft specification for AMG construction of subgrade and base course, which is expected to be used statewide by 2011. For fine grading and base course placement, the draft specification requires GNSS technology to be supplemented with laser or robotic total stations. Contractors are required to provide grade stakes at critical points on the alignment and on cross sections at 500-foot intervals. Under the specification, NCDOT provides a 3D model of the design surface. The plans are the contract documents and contractors assume the risk of using the electronic data. NCDOT does not intend to inspect 3D models that might be developed by contractors. Rather, quality assurance checks are made on the constructed product in the field. It is expected that 3D model development must be under responsible charge of a registered engineer or surveyor.

NCDOT cited less repeat work, more uniform surfaces in final product, greater accuracy, and contractor productivity gains as extremely important benefits of AMG. No impediments were designated as extremely important, but lack of technical skills on both the contractors' and agency's part, lack of an in-place specification, unawareness within the agency of benefits, 3D design model issues were identified as very important.

Creation of 3D models on the front end is perceived as having design-side costs and construction-side benefits. Performance evaluation for designers is based upon the number of plans that are produced. This number decreases if effort is devoted to 3D model development. Surveyors need 3D models for verification of AMG work in the field and existing arrangements, with lack of integration, complicate the process. In addition, NCDOT uses a different technology for managing payments. NCDOT recognizes potential benefits in development and management of 3D data throughout design, construction, and payment, to include comprehensive project information on not only roadways but also utilities, drainage, and other aspects, both existing and proposed. However, their existing data flows, workflows, technologies, and ways of doing business are not seamless and need much better integration. This will not happen without well-designed and delivered education and training at many levels within the agency.

NCDOT does a considerable amount (60-79 percent) of their roadway design in-house. The agency is transitioning to Corridor Modeler® 3D design software. Introductory training on the software has been completed within the roadway design section and an implementation plan is being executed during 2010. The plan begins with simple two-lane undivided bridge projects in January, moves through four-lane divided roadways with ditch medians in March through September, and leads to four-lane divided roadways with raised medians beginning in September. The CADD support group is developing templates and training documents to accompany each phase of the implementation process.

NCDOT identified detection and elimination of design errors prior to construction, more comprehensive representation of design intent, and improved support for construction as extremely important benefits of 3D design. Extremely important prerequisites include perceived and proven benefits and implementation planning. Complexity of the task was the only impediment to adoption of 3D design methods identified as extremely important, although six other listed in the survey were identified as very important. Among these, entrenched business practices could be the most critical. Staff needs to become comfortable with change.

4.3. Wisconsin DOT

In 2006, WisDOT began a 2.5-year process to develop, test, refine, and implement a specification for AMG construction of highway subgrade (Vonderohe et al., 2009). Among other things, the process included a stakeholder workshop and two construction seasons of pilot projects. The specification is a statewide option on all 2010 construction projects that include grading. The agency developed the specification in response to adoption of AMG technology by contractors within the state. Early versions of the specification required WisDOT to provide 3D design model seed data (e.g., breaklines) for the pilot projects. Contractors developed the full 3D models, which were then inspected by the agency. The plans are the contract documents and it is the contractors' ultimate responsibility to ensure that 3D models conform to the plans. In the final version of the specification, WisDOT provides electronic design data but not in the form of breaklines. These data are the same as those provided on any project whether or not AMG is to be used. The contractor's 3D model is provided to the agency, but there is no inspection or approval process.

The contractor in the presence of the project engineer performs quality assurance checks of the constructed subgrade. A minimum of 20 checks must be made per roadway mile, project, or stage. The checks are made against plan elevations at random full stations. Four of any five consecutive checks must be within 0.1 foot of the design elevation. This aspect of the specification is intended to address both acceptable bounds on random error and any systematic effects that might be present in the constructed subgrade. The specification also requires a GPS work plan that addresses site calibration, equipment calibration, and control configurations. The agency recognized the need for education and training of its project engineers and consultants on GNSS, AMG, and the specification. Training classes were developed and delivered in 2008 and 2009.

WisDOT identified less repeat work, contractor productivity gains, and lower costs for construction as extremely important benefits of AMG. Three-dimensional design model issues were the only impediment ranked as high as very important.

Even before undertaking their AMG specification development effort, WisDOT had begun to address 3D design issues, methods, and technology. This was driven by an announcement in 2004 that the agency's design software was being placed in "maintain only mode" by its vendor (Zogg, 2009). Being aware of the emergence of advanced building information modeling (BIM) technology and the use of AMG by construction contractors, the agency developed a list of design process and workflow improvement objectives prior to doing any software evaluation. These included improvement of design and construction documents, better communication of design intent, full implementation of AMG in construction, and sharing of engineering model information with other functional areas in the agency (i.e., operations, maintenance, and planning). These objectives were later incorporated in a comprehensive implementation plan for 3D technologies in general (see below). WisDOT ultimately selected Autodesk® Civil 3D® as their new software and developed new workflows, training materials, and a staged implementation plan. An innovative approach to training was driven by the realization that written documentation, specific to WisDOT's workflows, could not be kept current with software versioning. The decision was made to use video training with the vendor's material supplemented with agency-specific needs. User training is currently underway.

WisDOT identified detection and elimination of design errors prior to construction and improved support for construction as extremely important benefits of 3D design. Implementation planning was identified as an extremely important prerequisite. For impediments, entrenched business practices was identified as extremely important and entrenched technology, traditional ways of thinking, limited resources, and complexity of the task were identified as very important.

WisDOT AMG and 3D design efforts were always linked, but became even more dovetailed at a 2008 stakeholder workshop intended to explore more extensive use of 3D model information throughout design and construction. The most fundamental outcome of the workshop was agreement that 3D design and AMG are components of a larger group of technologies and processes having interrelated dependencies, synergistic benefits, and shared implementation issues (Vonderohe et al., 2010). Hence, an effort was undertaken to develop a comprehensive implementation plan for 3D technologies for design and construction. The plan includes six initiatives that are underway or proposed:

1. Height modernization and real-time network for RTK GPS.
2. Digital terrain model data collection and analysis.
3. 3D design process.
4. AMG.
5. Field technology and inspection.
6. Infrastructure lifecycle uses of 3D data.

The plan identifies short-term and long-term goals, benefits, impediments, timelines, priorities, levels of effort, and responsible parties for each of the initiatives. Perhaps most importantly, interdependencies among the initiatives, caused by relationships among their goals are identified, thus portraying the larger picture of over-arching, cross-cutting needs among business areas driven by 3D technologies and methods. Because of this, the plan goes on to recommend appointment of a higher-level management team to oversee and coordinate the six initiatives, provide a reporting mechanism, and advocate for the overall effort.

4.4. General Case Study Conclusions

The case studies make it clear that 3D design, AMG, and other 3D technologies (e.g., LiDAR, RTK GPS, etc.) have individual merit that could be used to make cases for individual adoption.

However, synergistic benefits and broader support for agency mission and goals can be expected if they are viewed as interrelated components of a larger whole that needs not only understanding but also advocacy at multiple levels in multiple business areas. Some keys to overcoming impediments are:

1. Buy-in and support from upper-level management.
2. Crosscutting, well-executed implementation planning, with short-term and long-term objectives. Implementation planning teams need broad representation and the plans themselves need thoughtful means of presentation and dissemination. Good implementation plans are often phased with simple tasks and changes taken on initially, then leading to more complex efforts as understanding and experience are gained. Pilot projects, selected for their desired aspects, are often critical for testing and refining ideas.
3. Management-level oversight and coordination of large, interdependent initiatives.
4. Champions: individuals or small groups with vision and commitment who take leadership roles and are persistent at moving forward.
5. Timely, well-designed and delivered education and training at multiple levels within the SHA.
6. Internal and external stakeholder participation in the planning and implementation process.

5. Comparison between Surface-to-Surface and Average-End-Area Calculations

5.1. Description of Earthwork Study

One of the incentives for adoption of 3D design methods is production of DTMs, which enable computations of earthwork quantities using the surface-to-surface method. To evaluate this incentive for adoption of 3D design methods, a study of the difference between earthwork quantities calculated using the average-end-area method and the surface-to-surface method was conducted. Earthwork volumes were computed for six different sites using both techniques. For each data set, volumes were calculated using average-end-area at cross section intervals of 10, 30, 50, and 100 feet. Volumes calculated using the average-end-area method at each cross section interval were compared to those calculated by the surface-to-surface method. The percent difference between the two methods at each cross section interval is reported in the analysis below. In addition, cost discrepancies between methods for both cut and fill is included. These are based on Wisconsin DOT average unit cost listings. All volume analyses were conducted using Autodesk AutoCAD Civil 3D 2009®. The majority of data acquired for this study were native to software other than Civil 3D. Such data are typically not recognized by Civil 3D. Therefore, LandXML was used to translate non-native data to Civil 3D. LandXML provides a non-proprietary data standard, developed by an industry consortium, to aid in transferring data between software.

It was hypothesized that as cross section intervals are decreased, quantities calculated using the average-end-area and surface-to-surface methods would converge. This hypothesis was based on two assumptions: 1) average-end-area calculations become more accurate as cross section intervals are decreased and 2) surface-to-surface is a more accurate method for computing quantities than average-end-area as asserted by other sources (U.S. Army Corps of Engineers, 2002; Cheng, 2005). It should be noted that this volume study is not intended to evaluate the accuracy of the two volume computation methods, as no “true” values for the volumes were available; it is strictly a comparison between the results produced by the methods. Results for two of the available data sets appear in Sections 5.2 and 5.3. Results for the remaining four data sets appear in Appendix C.

5.2. Long Stretch of Divided Roadway

The first data set was for a five-mile section of divided highway. The existing ground surface was developed by the Wisconsin DOT from photogrammetric data consisting of a grid of spot elevations (mass points) and breaklines. These data were native to Bentley MicroStation® and were transferred to Civil 3D via LandXML. A maximum triangle length of 300 feet was set for the existing ground surface to reduce the number of erroneous triangles around the perimeter of the surface.

The design surface data consisted of a drawing (.dwg) file containing the TIN structure of a DTM created by Hoffman Construction, a Wisconsin contractor. Drawing files are recognized by Civil 3D. However, the TIN structure in the drawing file was not recognized as a surface by Civil 3D. Rather, the line segments forming the triangular structure were recognized as polylines. These polylines were used as breaklines to generate the final design surface for volumetric analyses.

Visualizations of the existing and design surfaces appear in Figures 5.1 and 5.2. A boundary was created for the design surface by tracing the exterior of the design data set used in DTM generation. Without a well-defined boundary for the design surface, results of volume computations produced large differences between the methods and thus signified a problem with overlay of the existing ground and design surfaces. The software computes volumes near the perimeters of the data sets, where one surface has already ended, unless a distinct boundary is defined.

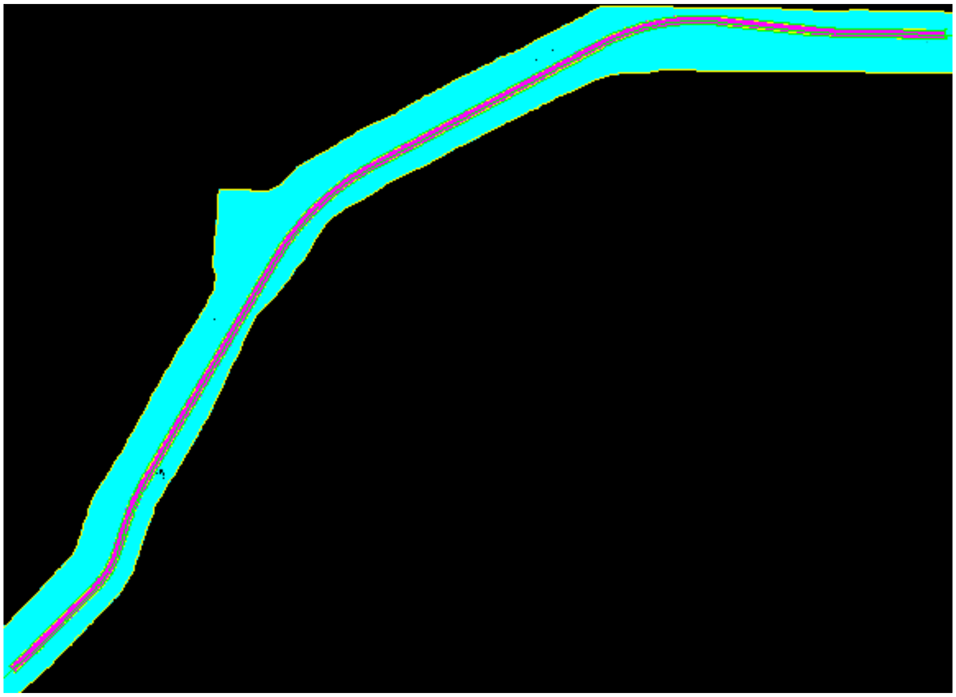


Figure 5.1: Plan View of the Surfaces Used in Volume Analysis of Long Stretch of Divided Roadway

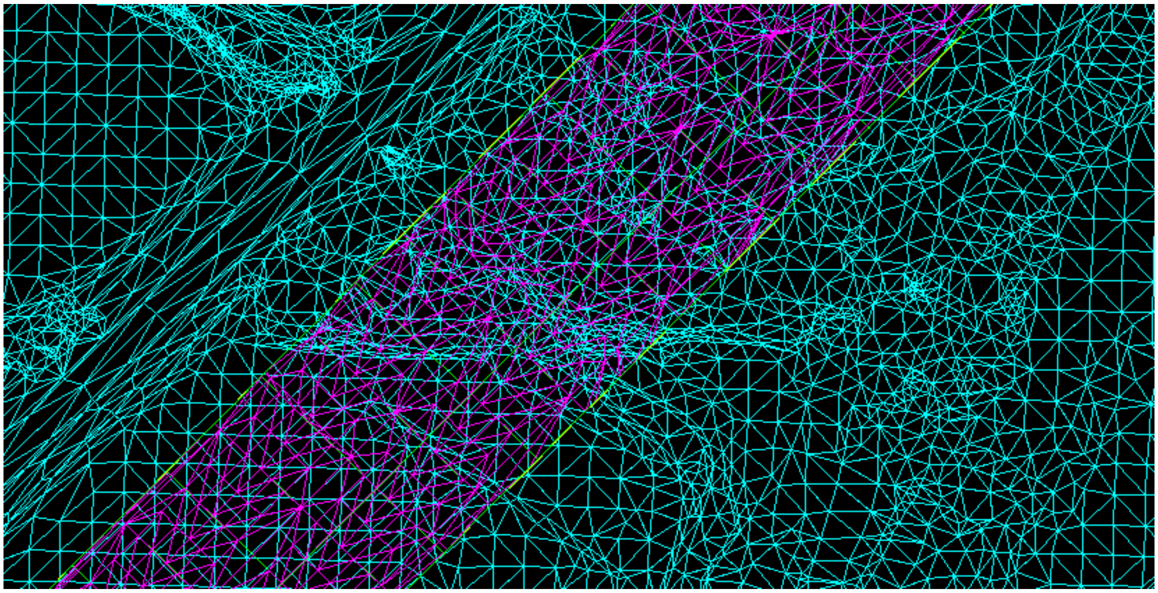


Figure 5.2: Close-Up Depiction of Surfaces Used in Volume Analysis of Long Stretch of Divided Roadway

Results from the two earthwork calculation methods appear in Figure 5.3 and Table 5.1. Both cut and fill volumes were considerably large for this project. Figure 5.3 shows that as the interval between cross sections used in average-end-area computations increases, the percent difference between the surface-to-surface and average-end-area calculation becomes larger for both cut and fill volumes. It is also noteworthy that the percent differences for cut and fill follow the same trend as the cross section interval is changed. There is only a small increase in the percent difference between when the interval is increased from 10 to 30 feet. However, intervals beyond 30 feet produced significant increases in percent differences.

Due to the large sizes of the analyzed surfaces, cost differences even when using small cross section intervals are considerable. When the spacing between cross sections is 10 feet, there are cost differences between computation methods that exceed $16,000. These differences do not change considerably when the cross section interval is increased from 10 to 30 feet. However, cost differences more than double for both cut and fill material when the cross section interval is increased from 30 to 50 feet. They nearly double again when the interval is increased for 50 to 100 feet. The maximum cost difference between earthwork computation methods occurs in fill material when the cross section interval is 100 feet. While a 4.54 percent difference between methods for fill at 100-foot cross section spacing might not seem extreme, it amounts to a difference of $112,514.99 in cost estimates.

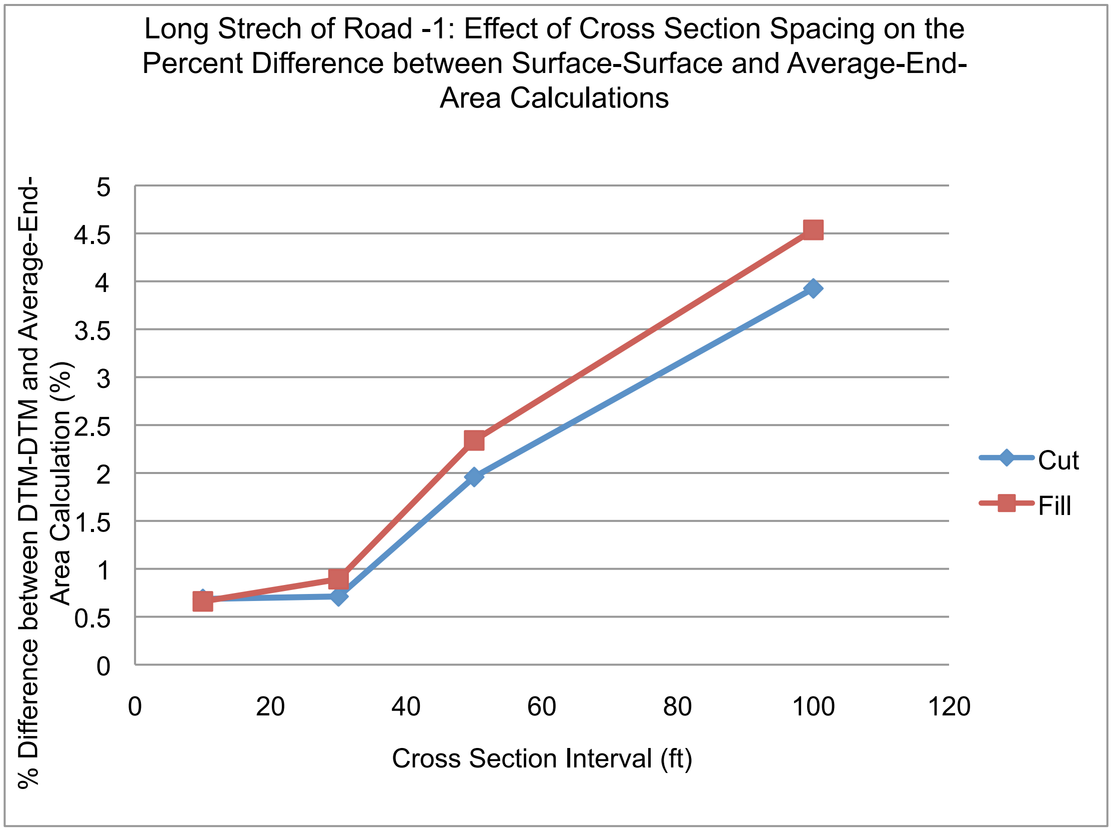


Figure 5.3

Table 5.1: Volume Comparison Results for Long Stretch of Divided Roadway

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Surface-Surface	n/a	674027.6	-------	--------	685150.3	-------	--------
Average-End-Area	10	669402.9	0.69	$16,741.41	680625.8	0.66	$16,378.80
Average-End-Area	30	678825.2	0.71	$17,367.31	679037.6	0.89	$22,128.01
Average-End-Area	50	660828.2	1.96	$47,781.83	669120.3	2.34	$58,028.53
Average-End-Area	100	647566.3	3.93	$95,789.91	654068.8	4.54	$112,514.99

5.3. Short, Hilly Section

A comparison between volume techniques was conducted on a short section of hilly terrain. The segment of roadway analyzed was approximately 1000 feet long. Data for this analysis was provided by the North Carolina Department of Transportation. Data for both the existing ground and design surfaces consisted of breaklines and mass points on 4.5-meter grid. Alignment data were also provided. The data were native to MicroStation and were transferred to Civil 3D using LandXML, where the surfaces were created. Figure 5.4 is a plan view of the existing and design surfaces and Figure 5.5 is a 3D depiction.

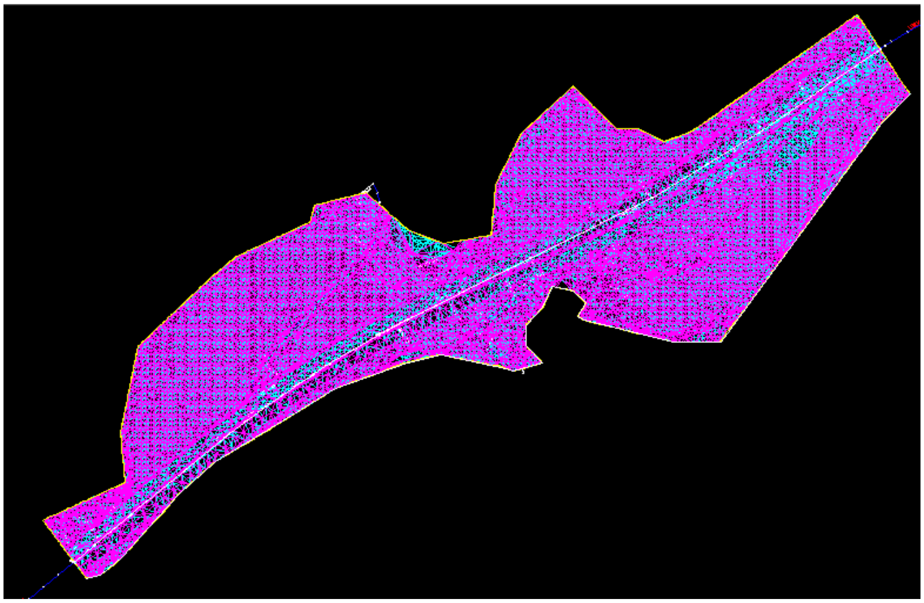


Figure 5.4: Plan View of Short, Hilly Section Surfaces

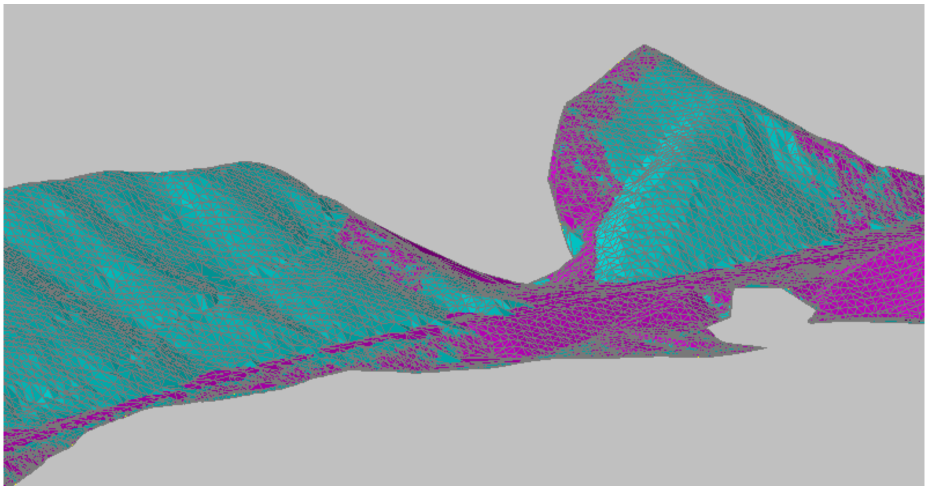


Figure 5.5: 3D View of Short, Hilly Section Surfaces

Table 5.2 and Figure 5.6 provide the results of the comparison between volume calculation methods at varying cross section intervals. Table 5.2 shows that the cut and fill volumes are fairly balanced in this example. As shown in Figure 5.6, there is are increases in percent differences between volume calculation methods, for both cut and fill, when increasing the cross section interval used in average-end-area computation, with one exception. The fill volume found using the average-end-area with a cross section interval of 50 feet is closer to the surface-to-surface result than the average-end-area result at both 10 and 30-foot intervals. Therefore, an additional calculation was performed using a 40-foot interval. It was found that the percent difference between computational methods at 40-foot cross section spacing is greater than at the 30-foot interval, indicating calculations using a cross section interval of 50 feet are inconsistent with the data at the other cross section intervals. However, this inconsistency can be explained by the random variability in the surfaces and the fact that the 50-foot interval, by coincidence, captured that variability in this particular case.

Due to the short length of this section of roadway, (approximately 0.2 miles), cost discrepancies were not overly large. However, they are not negligible when using a cross section interval of 100 feet. At a 100-foot interval, the cost difference for cut and fill are $4,034.82 and $1,408.76, respectively. These differences are significantly larger than those found when using smaller cross-section intervals.

Table 5.2: Volume Comparison Results for Short, Hilly Section

Source	Cross Section Spacing (ft)	Cut (yd^3)	% Difference Surface-to-surface	Cost Difference for Cut	Fill (yd^3)	% Difference Surface-to-surface	Cost Difference for Fill
Surface-to-surface	n/a	25249.0	-------	---------	18076.9	-------	---------
Average-End-Area	10	25262.1	0.05	$47.42	18077.9	0.01	$3.87
Average-End-Area	30	25268.6	0.08	$70.84	17953.7	0.68	$445.84
Average-End-Area	40	25073.3	0.7	$636.18	17936.2	0.78	$509.30
Average-End-Area	50	24974.7	1.09	$992.82	18079.4	0.01	$9.09
Average-End-Area	100	26363.6	4.41	$4,034.82	17687.7	2.15	$1,408.76

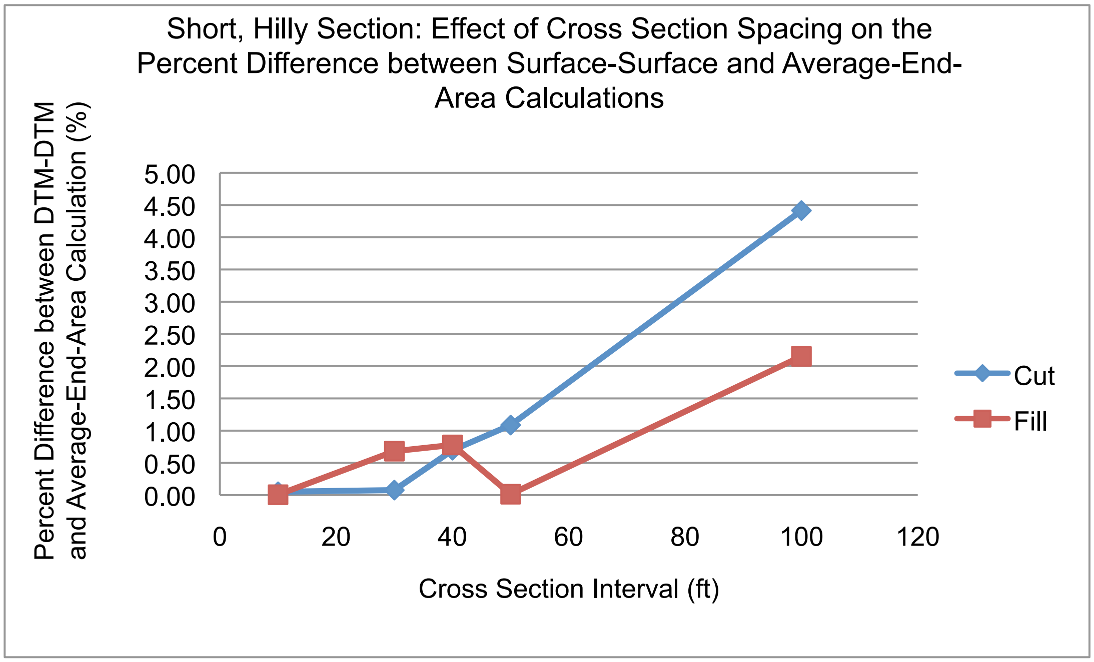


Figure 5.6

5.4. General Earthwork Calculation Methods Conclusions

From the results presented in Sections 5.2, 5.3, and Appendix C, it can be concluded that, typically, increasing the cross section interval used in average-end-area earthwork calculations leads to larger percent differences between average-end-area and surface-to-surface methods. This is expected due to two primary assumptions. Firstly, it has been asserted by others that surface-to-surface calculations are more accurate than average-end-area. Secondly, average-end-area calculations theoretically become more accurate as the cross section interval is decreased. The expected trend of larger percent differences with larger intervals did not always hold true. The outliers are explainable by random variability in the surfaces and the fact that associated errors can tend to cancel.

For large projects, differences in earthwork estimates can result in significant cost discrepancies, particularly at larger cross section intervals. However, it is important to note that the method of calculation is not the only source of error in earthwork estimation. A given quantity of soil does not have constant volume. When moisture is added to a soil, it swells. Conversely, soil shrinks as it dries. Additionally, soil volume increases when it is loosened or disturbed during excavation and soil volume decreases when soils are compacted. Thus, when estimating earthwork quantities, one needs to account for changes in soil volume by multiplying initial volumes by shrink and swell factors. Shrink and swell factors are heavily dependent on soil type and can range from 0.78 (shrinkage) to 1.65 (swelling) (Burch, 1997). Clearly, selection of inappropriate shrinkage or swell factors can produce erroneous results.

6. Methods and Examples for Describing Highway Design Software Functionality

As transportation organizations begin to explore adoption of 3D design software, there are faced with the considerable task of assessing alternative software products. Among the primary considerations is software functionality: what it is capable of doing and what is required of users to make it happen. Three-dimensional design software functionality is extensive and adopters need methods for describing it so that assessments can be performed. Here, we present three methods, with examples, for describing 3D design software functionality to user-operational-level detail.

6.1. User Interface

This approach builds a tree of what appears to the user as options are selected at various levels within the software. It assists in understanding linkages between functions and how to navigate among them.

To implement the method, one begins with the initial screen in the user interface and observes the available options. Each option might lead to sub menus or directly to functions within the software. Sub menus might have further embedded sub menus to many levels. Each successive menu or function should be examined in a hierarchical manner. Examinations should address what is needed as input from the user and what options exist. Help menus within the software can be used to assist in describing options and functions that are unfamiliar to the user. This method allows for determination of what functions exist, how they are organized within the software, and if there are any desired functions that are unavailable. The result is a representation of how the software is structured from a user-interface perspective.

The following example describes the user interface below the main menu when “Surfaces” is selected from the task bar in AutoCAD® Civil 3D (2009)®. The menu in Figure 6.1 is displayed. The options within the menu allow the user to create a surface in several ways, edit an existing surface, add labels to the surface, add a legend, and various utilities.

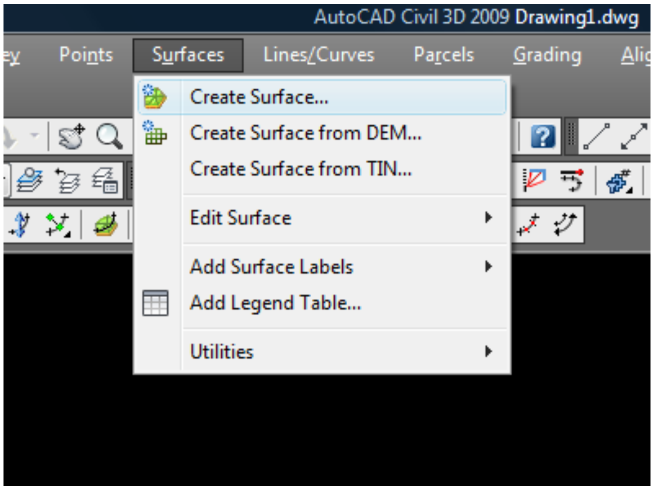
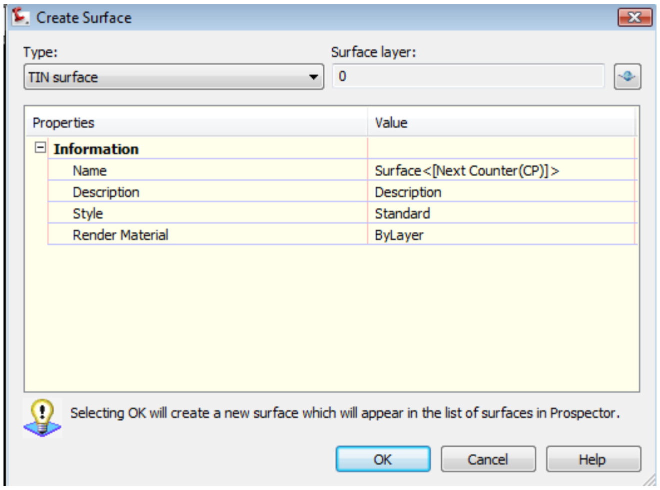


Figure 6.1: Surfaces Menu

The first option on the “Surfaces” menu is “Create Surface.” When this option is selected, the “Create Surface” dialog box in Figure 6.2 appears. Here, the user enters a surface name and description and selects the surface style which encompasses how the surface will be displayed on the screen including features such as contours, triangles, and borders. In this box, the user can also select the level of display of render materials from the list in Figure 6.3. Examples of render materials include asphalt, concrete, and gravel. The surface type and layer also can be specified in the “Create Surface” dialog box. Options for surface type are shown in Figure 6.4.



Type: TIN surface

Surface layer: 0

Properties	Value
Information	
Name	Surface<[Next Counter(CP)]>
Description	Description
Style	Standard
Render Material	ByLayer

Selecting OK will create a new surface which will appear in the list of surfaces in Prospector.

Figure 6.2: Create Surface Dialog Box

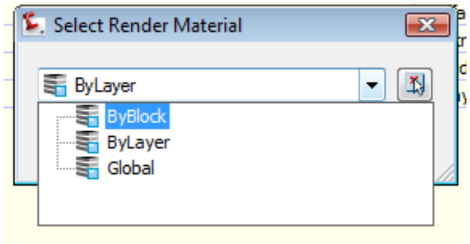


Figure 6.3: Render Material Options

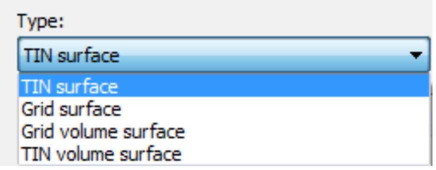
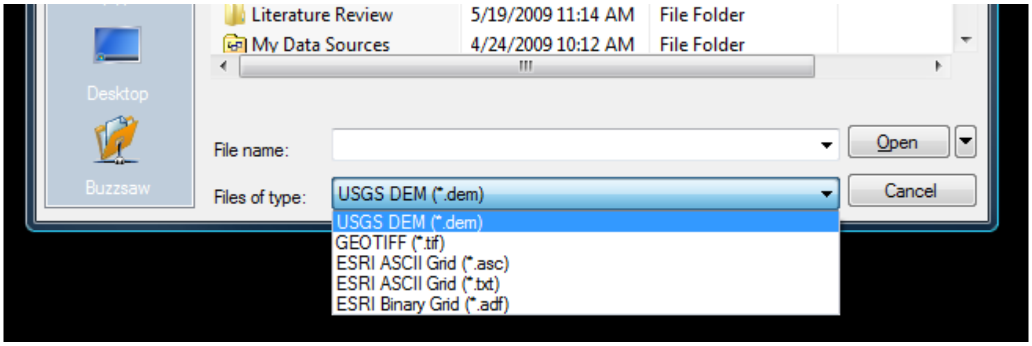


Figure 6.4: Surface Type Options

In addition to creating a surface from objects within the drawing file, one can import a DEM or TIN using the options “Create Surface from DEM” and “Create Surface from TIN,” which are the next options under the “Surface” menu (Figure 6.1). These options require input of a file containing a surface. In the “Create Surface from DEM” option, the user is prompted to browse for a file of the types displayed in Figure 6.5. Similarly, in the “Create Surface from TIN” option, the user is prompted to browse for a .tin file.



Literature Review	5/19/2009 11:14 AM	File Folder
My Data Sources	4/24/2009 10:12 AM	File Folder

File name:

Files of type: USGS DEM (*.dem)

Figure 6.5: File Options for Importing DEM

The fourth option on the "Surface" menu is "Edit Surface," which offers many options as shown in Figure 6.6. The first option is "Edit Surface Style." This option produces a prompt to select the surface for which the style is to be edited. Once a surface is selected, a menu appears with tabs for editing display features:

Information: The name of the surface style, creator, and date of creation.

Borders: Interior and exterior display settings for borders and datums.

Contours: Settings for display of major, minor, and depression contour lines.

Grid: Settings for primary and secondary grid display.

Points: Options for selecting the display of points and 3D geometry.

Triangles: Options such as vertical exaggeration for triangle display.

Analysis: Settings for display of directions, elevations, slopes, and slope arrows.

Watersheds: Customization of watershed display.

Display: Allows layers to be turned on and off so that if a view of only triangles and border is desired, contours and other features can be turned off. Feature colors can also be selected here.

Summary: All display settings from the other tabs.

The second option on the "Edit Surface" menu is "Edit Surface Properties." Here, there are four tabs: 1) information, 2) definition, 3) analysis, and 4) statistics. In the information tab the user is given the same elements as in the "Create Surface" dialog box. The definition tab is used to turn data and edit items on and off or to eliminate surface definition items. A surface edit option in this tab includes setting a maximum triangle length. The analysis tab controls contours, directions, elevations, slopes, slope arrows, user-defined contours, and watershed analysis properties. The user cannot make edits in the statistics tab, but it includes a summary of the surface such as maximum elevation and number of triangles.

The remaining "Edit Surface" options appear in Figure 6.6. These encompass various edits that can be made to a surface.

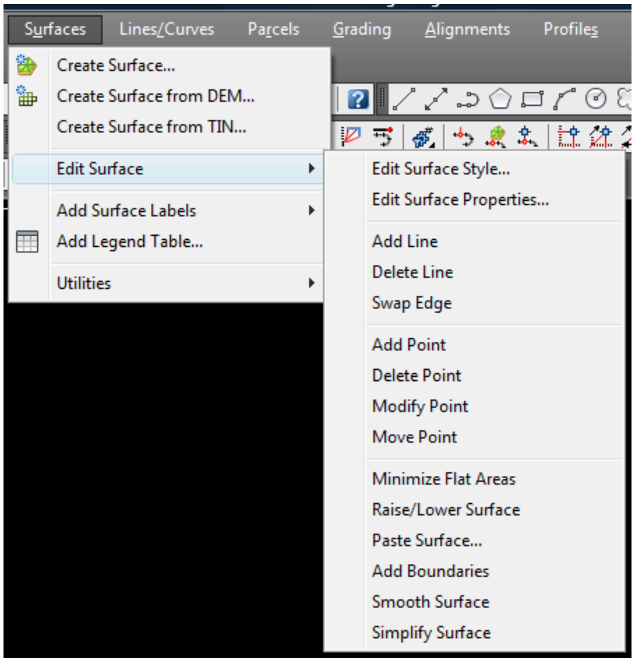


Figure 6.6: Edit Surface Menu

The fifth option under the "Surface" menu is "Add Surface Labels," with options as shown in Figure 6.7. The first option under this menu is to "Add Surface Labels," which has the dialog box shown in Figure 6.8. The user can specify the feature from the options shown in Figure 6.9. The label type can also be specified. Figure 6.10 shows label type options for surfaces. The label type, which determines how the display will appear, can also be controlled from the add labels menu. The reference text object prompt method options are also included in the "Add Surface Labels" dialog box as shown in Figure 6.11. The remaining items under the main "Add Surface Labels" menu allow for insertion of the various labels at points specified by the user.

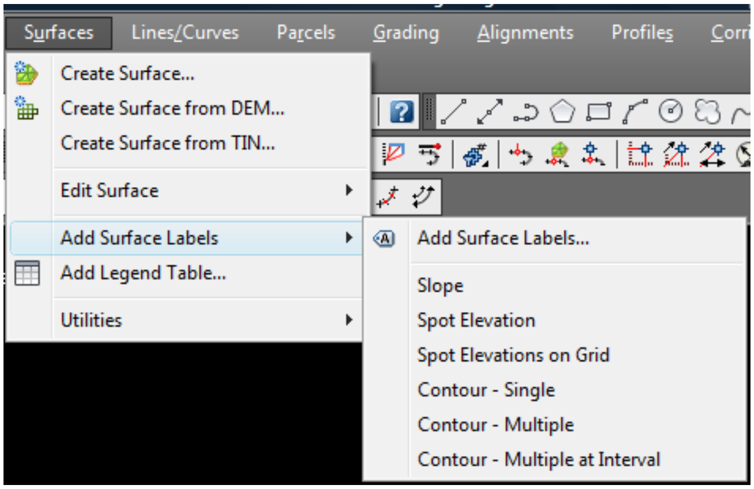
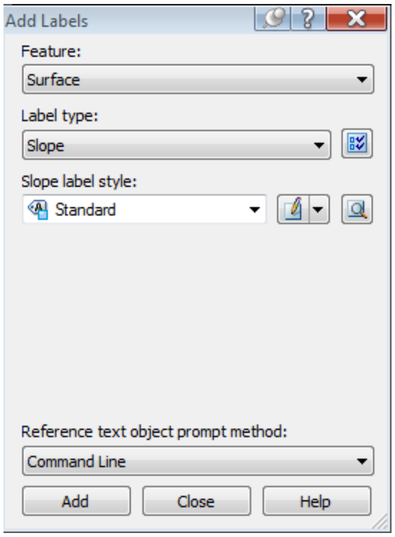


Figure 6.7: Add Surface Labels Menu


Add Labels

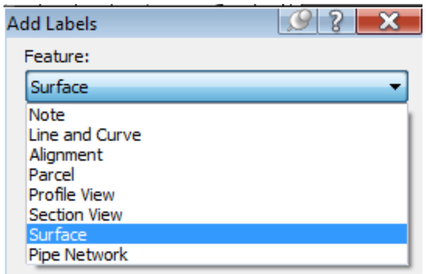
Feature:
Surface

Label type:
Slope

Slope label style:
Standard

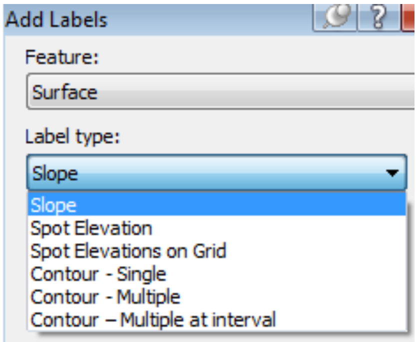
Reference text object prompt method:
Command Line

Figure 6.8: Add Labels Dialog Box


Add Labels

Feature:
Surface

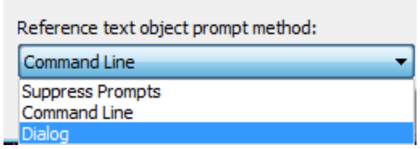
Figure 6.9: Feature Options



Feature: Surface

Label type: Slope

Figure 6.10: Label Type



Reference text object prompt method: Command Line

Figure 6.11: Reference Text Object Prompt Method Options

The sixth option under the “Surface” menu is “Add Legend Table.” This option leads to choice of a surface and then specification of a table type from the options shown in Figure 6.12. The user must also choose if the legend is static or dynamic. (Dynamic tables update when the surface is updated).

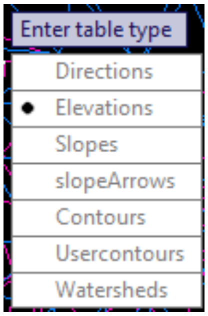


Figure 6.12: Legend Table Types

The final option under the “Surface” menu is “Utilities,” which offers the sub menu in Figure 6.13. The first option in the sub menu is “Export to DEM” which generates the dialog box in Figure 6.14. Here, the surface to be exported, file name, exporting coordinate zone, and grid spacing are specified. There are also options to use a custom null elevation and to add a description of the DEM.

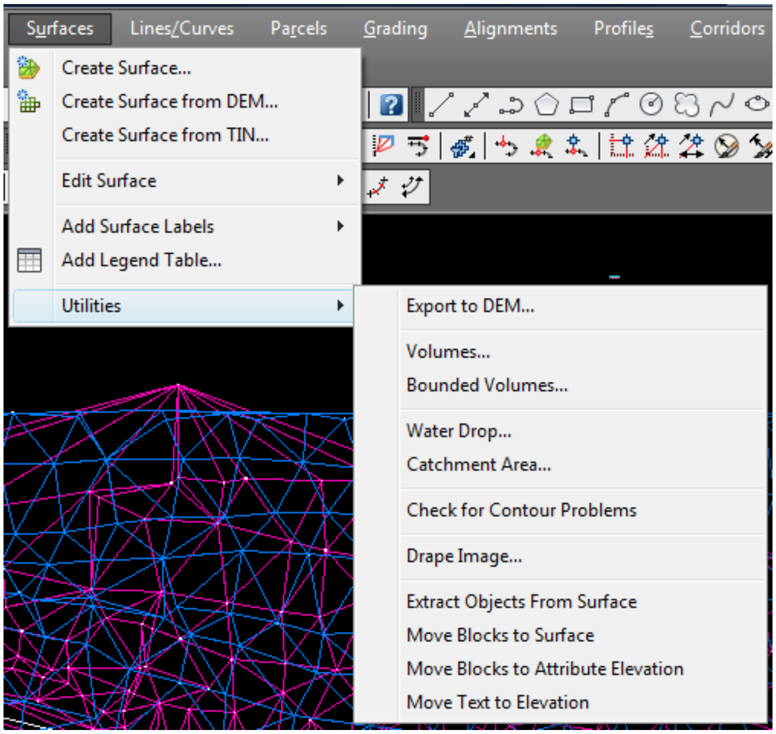
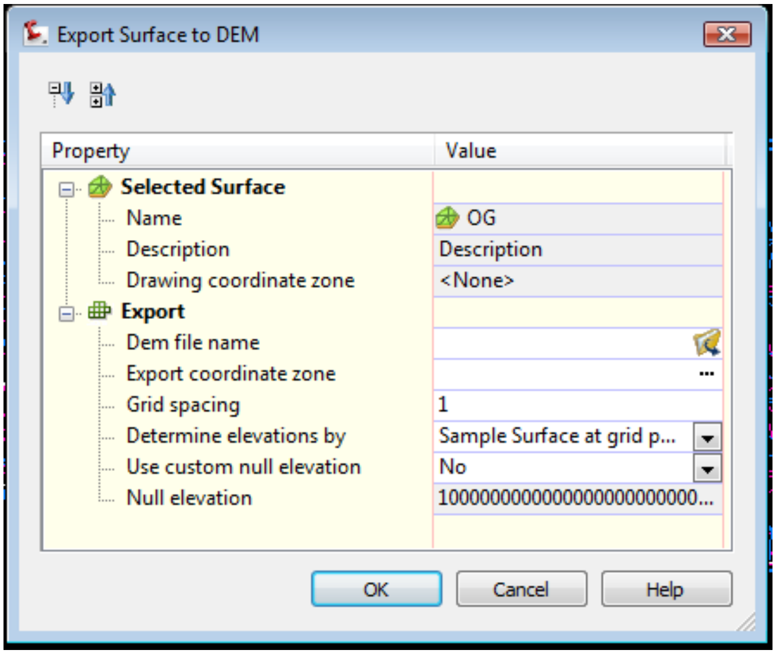


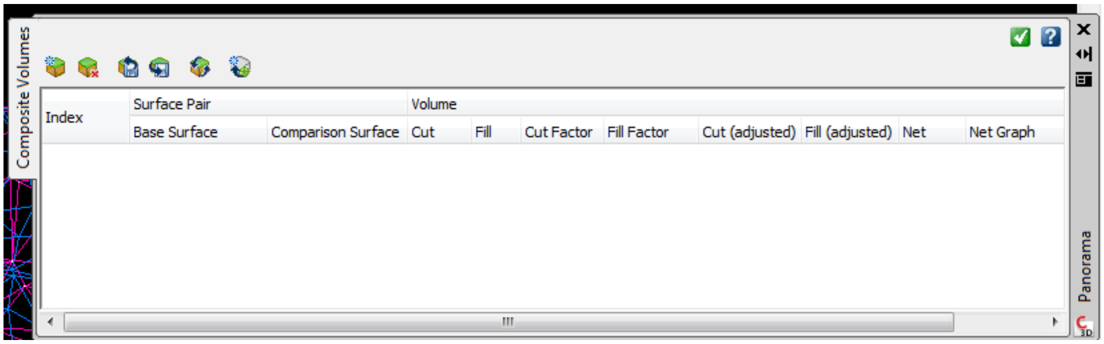
Figure 6.13: Utilities Menu



Property	Value
Selected Surface	
Name	OG
Description	Description
Drawing coordinate zone	<None>
Export	
Dem file name	
Export coordinate zone	...
Grid spacing	1
Determine elevations by	Sample Surface at grid p...
Use custom null elevation	No
Null elevation	1000000000000000000000000...

Figure 6.14: Export Surface to DEM Dialog Box

The next option under the “Utilities” menu is “Volumes,” which allows computation of volumes using the composite DTM-DTM method and generates the dialog box shown in Figure 6.15. Here, new volume entries can be created by selecting surfaces on screen, selecting from a list of surfaces, import volume entries from file (.xml format), and export volume entries to file (.xml format). The base surface is the existing ground surface and the comparison surface is the design surface. Once these are entered, the cut, fill, and net volumes are displayed, including adjustments if a cut factor and fill factor were used. A net graph also appears showing a red bar if net volume is cut and green bar if net volume is fill.

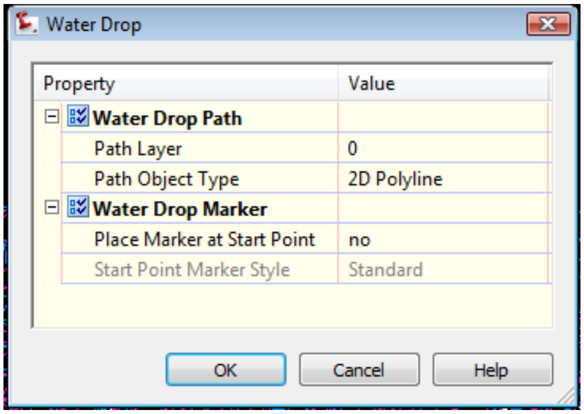


Index	Surface Pair		Volume							
	Base Surface	Comparison Surface	Cut	Fill	Cut Factor	Fill Factor	Cut (adjusted)	Fill (adjusted)	Net	Net Graph

Figure 6.15: Composite Volume Dialog Box

Also under “Volumes” in the “Utilities” menu is “Composite Volumes,” which computes composite volumes within a boundary. The user must first select an existing polyline, polygon, or parcel to act as the boundary within which volumes will be computed. The net, cut, and fill volumes are displayed in the command line.

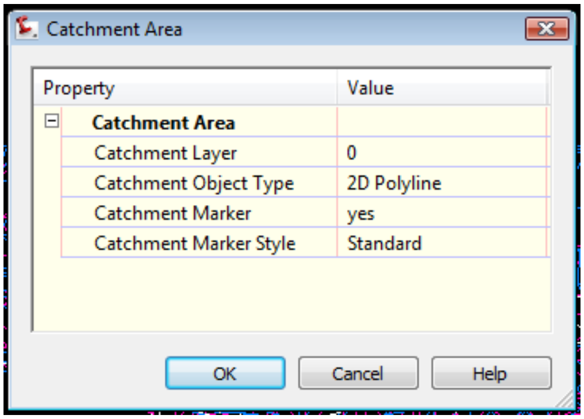
The next item in the “Utilities” menu is “Water Drop,” which has the dialog box shown in Figure 6.16. It is used to specify the parameters for drawing water drop paths on a surface. Before the dialog box appears, the user must specify a surface on which to perform the water drop analysis. In the dialog box, the user must input the “Path Layer” where the water drop paths will be drawn. The “Path Object Type” specifies whether 2D or 3D polylines are to be drawn. There are also options for placing a marker at the starting point of the water drop path and the style of the start point.



Property	Value
Water Drop Path	
Path Layer	0
Path Object Type	2D Polyline
Water Drop Marker	
Place Marker at Start Point	no
Start Point Marker Style	Standard

Figure 6.16: Water Drop Dialog Box

The next option in the “Utilities” menu is “Catchment Area,” which is used to analyze water runoff and display surface drainage area. A surface must be identified after selecting “Catchment Area.” Then the dialog box shown in Figure 6.17 appears. Here, the layer, object type, and marker options are selected similar to the “Water Drop” dialog box.



Property	Value
Catchment Area	
Catchment Layer	0
Catchment Object Type	2D Polyline
Catchment Marker	yes
Catchment Marker Style	Standard

Figure 6.17: Catchment Area Dialog Box

The sixth option on the “Utilities” menu is “Check for Contour Problems.” After selection, the user is prompted to select a surface. Any detected contour problems are displayed in the Event Viewer, which pops up in a window.

“Drape Image” is the next choice on the “Utilities” menu. This brings up the dialog box in Figure 6.18. The user must select an image, such as an aerial photo, the surface, and a render material name so that an image can be placed in the background of the drawing.

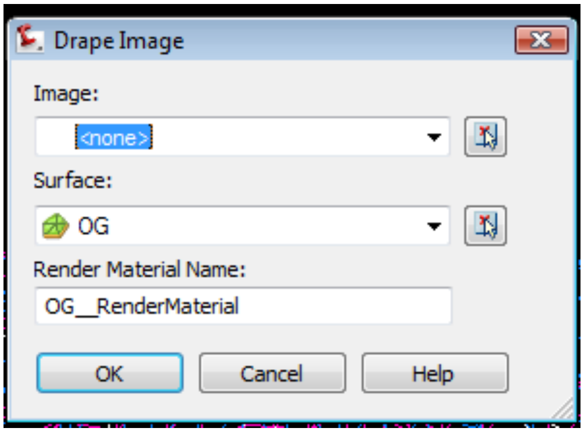


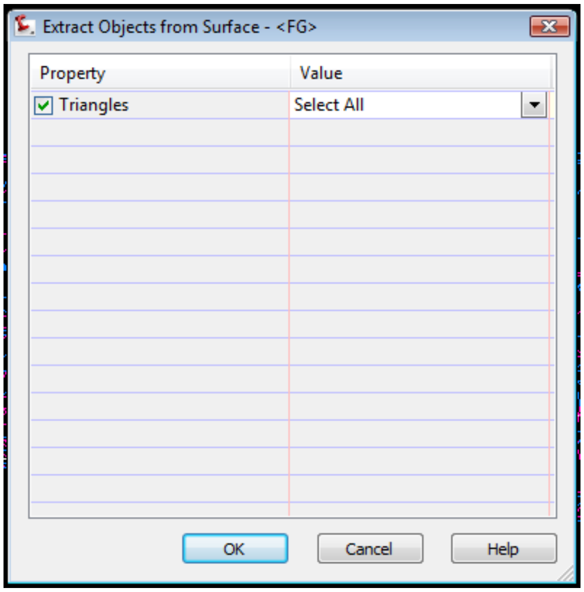
Image: <none>

Surface: OG

Render Material Name: OG__RenderMaterial

Figure 6.18: Drape Image Dialog Box

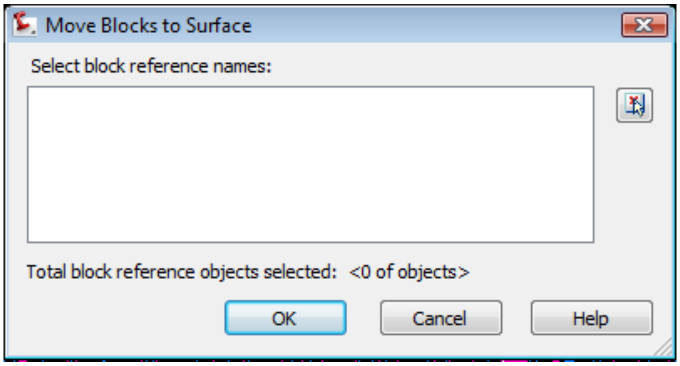
The next choice on the “Utilities” menu is “Extract Objects from Surface.” When selected, the user is prompted to select a surface, which brings up the dialog box shown in Figure 6.19. The property from which to extract objects must be selected (triangles are shown in Figure 6.19) as well as whether the extraction is to be global or designated individual objects.



Property	Value
☑ Triangles	Select All

Figure 6.19: Extract Objects from Surface Dialog Box

Next on the “Utilities” menu is “Move Blocks to Surface.” The user must select a surface to which blocks are to be moved, generating the dialog box shown in Figure 6.20. “Move Blocks to Surface” is used to move selected block reference objects to the elevation on the selected surface. The icon can be used to select individual objects from the screen.



Total block reference objects selected: <0 of objects>

Figure 6.20: Move Blocks to Surface Dialog Box

The tenth option on the “Utilities” menu is “Move Blocks to Attribute Elevation.” This function moves block objects with attributes at their insertion point to the elevation of one of the block’s attribute objects. When selected, the dialog box in Figure 6.21 appears. The block reference name and elevation attribute tag must be selected, and the chosen reference objects are moved to the elevation of the specified attribute.

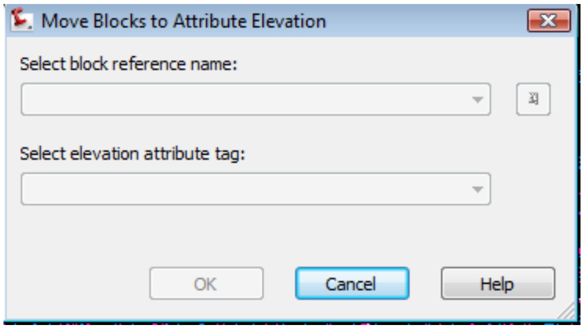


Figure 6.21: Move Blocks to Attribute Elevation Dialog Box

The final option on the “Utilities” menu is “Move Text to Elevation.” Once chosen, the user must select a text object from the screen. This utility moves text objects at their insertion point to the elevation of their numeric text values.

6.2. Business Process Hierarchy

An alternative to describing highway design software functionality through the user interface is to develop a hierarchical structure of business processes used in highway design and then to describe the steps in the software necessary to execute the business processes. This approach might facilitate comparisons between software choices more readily than the user interface approach because the ease or complexity of applying alternative software packages to established business processes will become apparent. Of course, developing a detailed business process hierarchy for 3D highway design and then detailing the necessary steps in each software package can be a challenging task. Figure 6.22 is an example of what might be contained in a “Create 3D Alignment” component of a highway design process hierarchy. The level of abstraction in the figure decreases from left to right. Software steps would typically be described only for the lower levels of abstraction. Further lower levels of abstraction might appear below “Create Horizontal Curve” and “Create Vertical Curve” as there are various methods for executing these processes.

- **Create 3D Alignment**
  - **Create Alignment Termini**
    - **Create BOJ (N, E, Elev)**
    - **Create EOJ (N, E, Elev)**
  - **Create Horizontal Components (Repeatable and Iterative)**
    - **Create PI (N, E, Elev)**
    - **Create Back Tangent (Bearing)**
    - **Create Forward Tangent (Bearing)**
    - **Create Horizontal Curve (Parameters)**
    - **Create POT (N, E, Elev)**
  - **Create Vertical Components (Repeatable and Iterative)**
    - **Create VPI (N, E, Elev)**
    - **Create Back Tangent (G_1)**
    - **Create Forward Tangent (G_2)**
    - **Create Vertical Curve (Parameters)**
    - **Create POT (N, E, Elev)**
  - **Assemble Horizontal and Vertical Components**
  - **Assign Stationing**

Figure 6.22: Business Process Hierarchy for Alignment Component of 3D Highway Design

6.3. Software and Database Architectural Model

Perhaps even more fundamental than the user interface and execution of business processes is the underlying makeup of highway design software and the manner in which it represents data elements, complex objects, and the relationships among them. Representations of these characteristics are referred to as “architectural models” and can be presented as narrative descriptions, diagrams, formal symbolic languages, or combinations of these. Low-level descriptions of software architectures are often proprietary and, even if available, might be difficult to interpret by persons other than software engineers and programmers. However, higher-level descriptions of the manner in which software and data interact provide insight into the power, effectiveness, and longer-term utility of alternative software products. As a diagrammatic example, Figure 6.23 is an activity diagram, provided by Bentley®, for the steps in GEOPAK® going from a survey point to the system database.

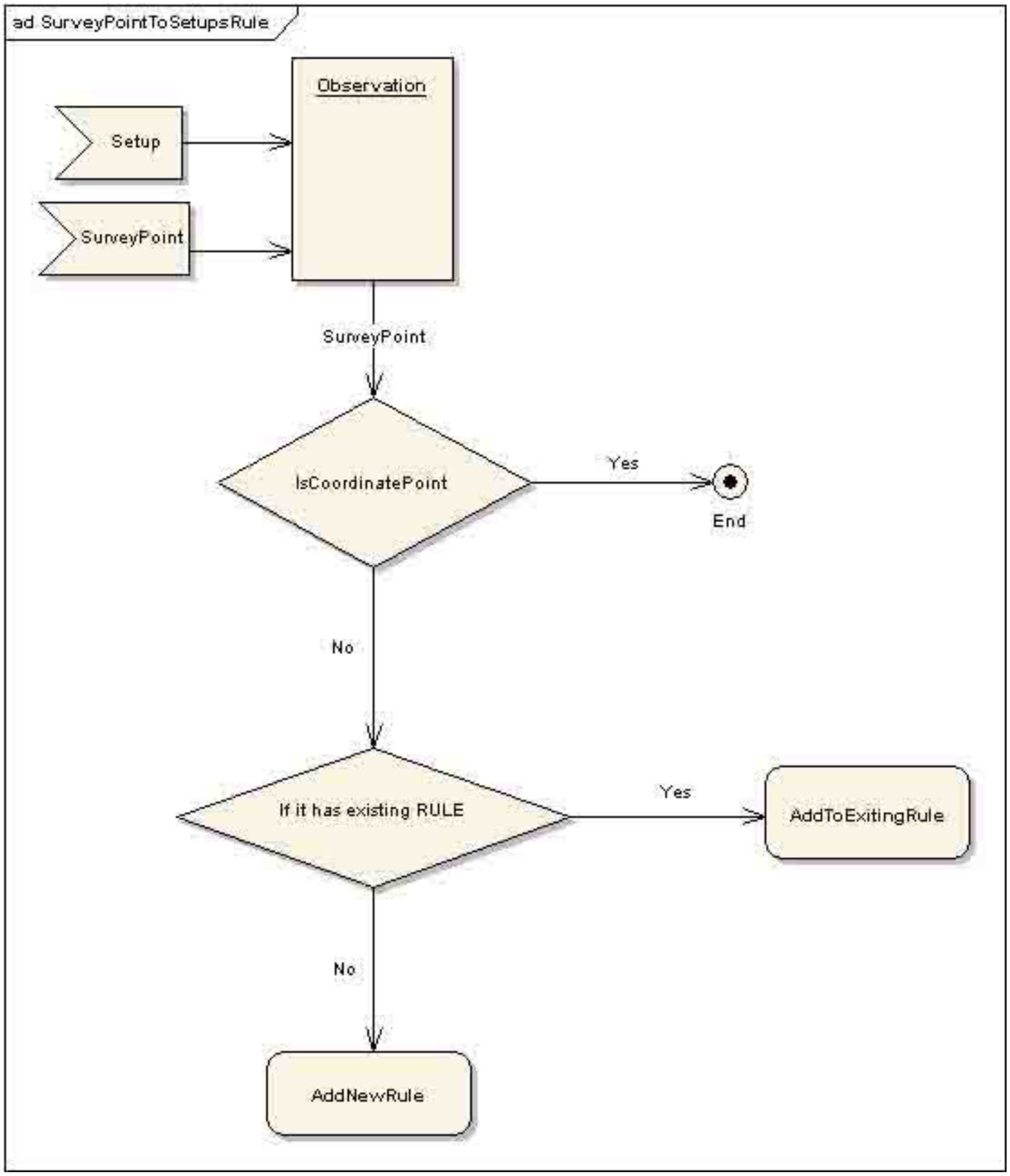


Figure 6.23: Activity Diagram for Process in GEOPAK® (Courtesy of Bentley®)

7. Summary, Conclusions, and Recommendations

7.1. Summary and Conclusions

A survey was constructed with the objectives of identifying and characterizing both benefits and technological, institutional, cultural, and legal impediments to the adoption of 3D design and construction technologies, data flows, and workflows. The survey was administered to all 50 SHAs and seven class one regional railroads. The survey was divided into three sections: design, contracting, and construction. This allowed multiple responders from a single organization to reply only to questions reflecting their area(s) of competency. The survey response rate was 70 percent.

Significant issues associated with adoption of 3D design and construction technologies were identified through survey results. While advancements in these technologies are clear, there are still major technological, institutional, and legal impediments that must be overcome for seamless transfer of data and complete implementation of these technologies.

Eight-two percent of all responding SHAs currently use AMG for highway construction. At the present time, 80 percent of responding SHAs give contractors primary responsibility for producing 3D design models required for AMG. It can be inferred that a primary underlying reason for this is that most SHAs have not fully adopted 3D design methods. Approximately 19 percent of all responding SHAs have fully adopted design methods that produce a 3D model. Furthermore, 60 percent of respondents assert that engineering consultants rarely or never provide 3D digital data to construction contractors to aid in 3D model development.

Although the majority of SHAs have not fully implemented 3D design methods, many agencies are in the process of, or planning for, adoption of them. The need for 3D models for use in AMG is a likely driving factor for adoption of 3D design methods. However, there are valued benefits associated with 3D design methods beyond use in AMG. The highest ranked additional benefit is detection and elimination of design errors prior to construction, followed by improved visualization and having a more comprehensive representation of design intent.

Survey respondents recognize three-dimensional design model issues as the most important impediment to wider use of AMG, which provides additional evidence of the importance of 3D design methods. However, there are impediments that must be overcome by agencies prior to adopting 3D methods. The majority of respondents recognize the lack of resources, agency lack of knowledge, entrenched business practices, lack of functionality in currently installed software, and required staff training as major obstacles to implementing 3D design methods. Inevitable technological advances are addressing lack of functionality, but the other identified impediments beg for education, training, and shared perspectives of agency missions. In addition, translation of data across different software platforms has historically been a problem, but AASHTO and TRB continue to strive for data compatibility standards and vendors have reported to be cooperating.

There are also legal factors hindering the transfer of 3D digital data between designers and construction contractors. Only 11 percent of responding SHAs provide any legal standing for 3D digital data in contract documents. Primary issues associated with this include electronic signatures, transfer of liability as related to data exchange, data security, and auditability of plans. Professional licensure for those in responsible charge of 3D model development is also an issue. Although the long-term goal of seamless data transfer might not be realized until 3D design models have legal standing equal to that of 2D plans, there are many other aspects of achieving the goal that are less complex, less fraught with obstacles, and far easier to address in the short term.

Eight-two percent of all responding SHAs use AMG, but only 32 percent of these have associated specifications. The majority of respondents indicate lack of specifications is a significant impediment to wider use of AMG. Procedures followed without specifications could easily vary among projects and there is potential for poor use or poor practices. A particular difficulty is lack of guidelines for quality assurance or inspection of AMG work. Many SHAs that do have AMG specifications leave their inspection component as is, thus requiring frequent subgrade staking that has been shown by some to not be necessary.

There are significant differences in the extent of use of AMG among regions. In the Mississippi Valley Region, 100 percent of responding SHAs use it. On the contrary, only one-third of Northeast Region respondents indicate that they do. There is also considerable variation in the adoption status of 3D design methods among regions. In the Southeast and West Regions, there is a fairly even distribution in the number of agencies that have fully adopted, are planning for adoption, or are considering adopting 3D design methods. However, in the Northeast Region, there are far more agencies in the process of adopting 3D design methods than there are in other categories of adoption status. Also, there are appreciably more agencies in the Mississippi Valley Region planning for adopting 3D design methods than there are in other categories of adoption status.

In follow-up to the survey, in-depth case studies of Minnesota, North Carolina, and Wisconsin DOTs revealed some keys to overcoming impediments to adoption of 3D design methods and AMG:

1. Buy-in and support from upper-level management.
2. Crosscutting, well-executed implementation planning, with short-term and long-term objectives.
3. Management-level oversight and coordination of large, interdependent initiatives.
4. Champions: individuals or small groups with vision and commitment who take leadership roles and are persistent at moving forward.
5. Timely, well-designed and delivered education and training at multiple levels within the SHA.
6. Internal and external stakeholder participation in planning and implementation processes.

The majority of SHAs are still using average-end-area to compute earthwork quantities. The surface-to-surface method is possible when 3D models are available, and authoritative sources state that this method is more accurate than average-end-area. Moreover, if 3D models are available, the surface-to-surface method is easier than average-end-area because there is no need to generate cross sections.

A comparison between earthwork quantities, calculated using the surface-to-surface and average-end-area methods, was conducted for six different sites. Volumes were computed using the average-end-area method at cross section intervals ranging from 10 to 100 feet to determine what effect altering the cross section interval had on the difference between surface-to-surface and average-end-area results.

In most cases, increasing the cross section interval used in average-end-area earthwork calculations led to larger percentage differences between average-end-area and surface-to-surface earthwork results. For large projects, the differences in earthwork quantity estimates are large enough to cause considerable cost discrepancies among methods, particularly when 100-foot cross section intervals are used. Cross section intervals of 50 or 100 feet are commonly used in practice when computing earthwork quantities using the average-end-area. The expected trend of increasing percentage difference with increasing cross section interval did not always hold true. In some of the test cases, decreases in percentage differences were observed in a consecutive pair of increasing intervals. These were due to coincidence between the selected intervals and the random variability of the terrain.

Means for describing various aspects of 3D design software must be available when assessing alternative choices for implementation. Factors such as support for improved workflows and objectives, ease of use, and software and database structures and relationships need to be considered as well as cost, training, and complexity of implementation (technological and institutional). Three descriptive methods (i.e., user interface, business process hierarchy, and software and database architectures) were described by narrative and examples.

7.2. Recommendations for State Highway Agencies

For SHAs seeking buy-in and commitment from upper management:

1. Draw upon existing information sources for summaries of benefits and reasons for moving forward with adoption of integrated 3D technologies, including 3D design and automated machine guidance. Existing information sources include journals such as *Transportation Research Record* and *ENR*; proceedings of and presentations at conferences such as those of the Transportation Research Board (TRB) and the International Highway Engineering Exchange Program (IHEEP); documentation available from the AASHTO Technology Implementation Group on AMG; reports of projects such as this one and those appearing below in the list of references, particularly (Hannon, 2007) and (Hannon & Sulbaran, 2008); and soon-to-be-forthcoming documents from the research project NCHRP 10-77: *Use of Automated Machine Guidance (AMG) within the Transportation Industry*.
2. Document statewide use of AMG by contractors and their desires for 3D design data. In many cases, the construction industry is ahead of the SHAs in realizing benefits of 3D technologies.
3. Prepare and present executive summaries of the materials recommended in (1) and (2) and tailor them to the particular needs and circumstances of your SHA.
4. Encourage upper management to attend sessions on 3D technologies at TRB and IHEEP conferences, especially sessions that are designed for upper-management-level audiences.

For SHAs seeking specification development for AMG:

Recognizing that SHAs formulate and present their specifications in many different ways:

1. Draw upon the experiences and results of those SHAs that have gone through the process (e.g., Iowa, New York, Minnesota, Missouri, North Carolina, Wisconsin, and others).
2. Involve both internal and external stakeholders in the specification development process to obtain their insight and their sense of ownership.
3. Include pilot projects, selected for their diversity in extent, duration, management characteristics, and terrain types in the specification testing and refinement process.
4. Begin with rough grading and move on to fine grading, base course placement, and paving.
5. Include aspects of quality assurance and inspection. These should be given careful consideration during development and thorough testing on the pilot projects.
6. Look to soon-to-be-forthcoming documents from research project NCHRP 10-77 *Use of Automated Machine Guidance (AMG) within the Transportation Industry* for more detailed guidance.
7. Include education and training for office and field personnel as the specification is being implemented.

For those SHAs moving towards adoption of 3D highway design technology:

1. View and describe the process as “adoption of 3D design methods,” not “adoption of 3D design technology.” The technology is necessary, but not sufficient. Effective 3D design requires change (for the better) in the way of doing business.
2. Before embarking upon assessment of software alternatives, establish and agree upon business objectives and a structure for, if not details of, improved design processes.

3. Plan for phased implementation of the new methods and technology, beginning with simple steps and leading to more complex tasks and broader adoption.
4. Anticipate needs for training and retraining as new versions of software become available. Draw upon vendor training materials supplemented with examples specific to your SHA.

For those SHAs seeking to develop or improve 3D data flows from design to construction:

1. Document and understand existing data flows. Include internal (agency) and external (consultant and contractor) players.
2. Use the results from (1) to identify specific obstacles and bottlenecks (technological, institutional, and legal) that must be overcome.
3. Develop content, quality, and data exchange standards for 3D models. Include QC/QA procedures. Test and refine the standards. Involve key internal and external stakeholders in these processes.
4. Agree upon responsibilities for development and management of the data and changes to them. Include contractual priorities between 2D plans and 3D models. Consider adopting these aspects within specifications.
5. Consider revising policy documents and procedures that require the average-end-area method for earthwork calculations (both estimates and final quantities).
6. Establish a timeline for phased implementation (e.g., from selected projects to statewide; from pre-construction to pre-bid).

For those SHAs seeking broader integration of multiple 3D technologies:

1. Recognize that 3D is a way of thinking and doing business, not merely a collection of technologies.
2. Recognize that there are potential uses for 3D data beyond design and construction, into operations, maintenance, and planning.
3. Establish a vision statement describing the ultimate long-term goal of the undertaking.
4. Develop a high-level implementation plan for achieving the vision. The plan should identify business areas, technologies, and initiatives and the relationships and dependencies among them; include short-term and long-term goals; assign priorities and responsibilities; and include timelines and milestones. From the outset, involve internal and external stakeholders in the planning process.
5. Establish implementation teams at the operational level and a management team to oversee and coordinate the operational-level teams' efforts. Such teams should be identified in the implementation plan (3).
6. Develop a strategy for presentation and dissemination of the plan (3).

Acknowledgements

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Appendix A: Survey Instrument

P9734:

Questionnaire on Three-Dimensional Design and Automated Machine Guidance
for Highway Construction
Construction and Materials Support Center
University of Wisconsin - Madison

August 12, 2009

Three-Dimensional Design and Automated Machine Guidance for Highway Construction Questionnaire

The Construction and Materials Support Center at the University of Wisconsin – Madison is studying the relationship between design products and automated machine guidance for highway construction. Our study is funded by the National Center for Freight and Infrastructure Research and Education, also at UW-Madison.

Our objectives include identification and characterization of technological, institutional, cultural, and legal impediments to adoption of 3D design and construction technologies, data flows, and workflows. We hope to be able to identify and suggest strategies for overcoming these impediments and to outline high-level steps in implementation planning.

This study is structured into three sections:

Section 1: Design

Section 2: Contracting

Section 3: Construction

Initially, we are distributing the survey to members of the AASHTO Standing Committee on Design. However, this web survey is designed to allow multiple responders from a single SHA. Responders are requested to reply only to those questions with which they are most familiar. Each responder is requested to contact additional responders within their SHA until the questionnaire is completed. Once completed, the questionnaire should be submitted. The questionnaire should require 30-45 minutes to complete.

Your responses although not anonymous will be kept confidential. If you have any questions about the survey please contact Alan Vonderohe at email vonderoh@engr.wsic.edu or vonderohe@centurytel.net.

Please submit the completed survey no later than **September 18, 2009**.

Instructions to complete the survey:

To choose a response, click on the button that corresponds to your answer. If you would like to change your answer, click on a different button or for questions with multiple answers just click the same button.

You may go back to earlier pages by clicking the 'BACK' button at the bottom of the screen. To advance to the next page of the survey click the 'NEXT' button.

If you start the survey and are unable to finish it, you can exit and return to it later by clicking again on the link in your email. If you need to send the survey to someone else to complete a section or to review your SHA's answers, you should forward them the email with the link and the password that they will need to enter the survey.

After the entire survey has been completed and all the data are ready to be submitted, please click on the ‘SUBMIT’ button on the last page. It is important that the ‘SUBMIT’ button be used so we know your SHA has given permission to the researchers to use the data provided for analysis and reporting. Once you click ‘SUBMIT’ you will not be able to re-enter the survey.

We appreciate your time and effort in assisting us by completing this web-based questionnaire.

Terminology and Acronyms Used in this Questionnaire

1. 2D: Two-dimensional.
2. 3D: Three-dimensional.
3. 3D design model: A digital 3D model of a highway design.
4. Automated machine guidance: Use of computers, survey technology, and sensors on construction equipment to automate the calculation and interpolation of position between the equipment and a 3D design model. This interpolation provides visual horizontal and vertical guidance to the operator of the construction equipment. Automated machine guidance is also referred to as “machine control”, “GPS machine guidance”, or “automated machine operations”. For purposes of this survey, intelligent compaction is out-of-scope and is not included in automated machine guidance.
5. CAD: Computer-aided design.
6. DTM: Digital terrain model.
7. SHA: State highway agency.

[PAGE]

Would your SHA like to receive a copy of the final report for this project?

○ Yes (1)

○ No (2) (Skip to Section selection screen)

[PAGE] [only shown if answer to the above question is “1” YES]

In the spaces provided below, please provide the full mailing address where we should send a copy of the final report for this project.

Name________________

Street1_______________

Street2_______________

City_______________

State______________

Zip________________

[PAGE]

Which section of the survey do you wish to go to?

○ Section 1 (1) (go to question 1 in section 1)

○ Section 2 (2) (go to question 14 in section 2)

○ Section 3 (3) (go to question 26 in section 3)

[PAGE]

Section 1: Design.

1. Approximately what percentage of your highway design work is done in-house as opposed to being contracted to engineering consultants?

O Less than 20% (1)

O 20-39% (2)

O 40-59% (3)

O 60-79% (4)

O 80% or more (5)

2. What is your SHA's designated CAD software package(s) for internal use? Please select all that apply.

O 2a. Geopak® (1 if checked)

O 2b. CAiCE®

O 2c. InRoads®

O 2d. Civil 3D®

O 2e. Other [go to question 2o]

O 2f. None designated [if checked "none" make sure no other items are checked]

[PAGE]

[ask only if q2e = 1 "checked"]

2o. Please specify what other CAD software package(s) your SHA has designated for internal use.

[**[PAGE]**

3. Are design consultants required to use a particular CAD software package?

O Yes (1)

O No (2) (skip to question 5)

[PAGE]

4. What CAD software package(s) are design consultants required to use? Please select all that apply.

O 4a. Geopak® (1 if checked)

O 4b. CAiCE®

O 4c. InRoads®

O 4d. Civil 3D®

O 4e. Other [go to question 4o]

[PAGE]

[ask only if q4e = 1 "checked"]

4o. Please specify what other CAD software package(s) design consultants are required to use.

[PAGE]

5.Does your SHA have content standards (e.g., features, layers, colors, line types) for digital design files?

O Yes (1)

O No (2) (skip to question 7)

[PAGE]

6. Are design consultants required to conform to your SHA’s content standards for digital design files?

O Yes (1)

O No (2)

7.Does your SHA have a format standard(s) for digital design data transfer?

O Yes (1)

O No (2) (skip to question 9)

[PAGE]

8. What is your SHA’s format standard(s) for digital design data transfer? Please select all that apply.

O 8a. LandXML. (1 if checked)

O 8b. .dwg.

O 8c. .dgn.

O 8d. .dxf.

O 8e. Other [go to question 8o]

[PAGE]

[ask only if q8e = 1 “checked”]

8o. Please specify your SHA’s format standard(s) for digital data transfer.

[PAGE]

9.Within your SHA, which <u>one</u> of the following best describes the status of adoption of design methods that incorporate development of a 3D design model as part of the design process?

O Such design methods have been fully adopted. (1)

O Such design methods are in the process of being adopted. (2)

O We are planning for adoption of such design methods. (3)

O We are considering adoption of such design methods. (4)

O We are not considering adoption of such design methods. (5)

O We have considered adoption of such design methods, but rejected them. (6)

[PAGE]

Please answer the following sets of questions with the scale from “not at all important” to “extremely important” shown below.

10.Within your SHA, how important are each of the following perceived or proven benefits of design methods that produce a 3D design model?

Code (not seen)	*1*	*2*	*3*	*4*	*5*
	Not at all important	Not very important	Somewhat important	Very important	Extremely important

10a. Improved visualization of project design (e.g., perspective views, fly-throughs).	○	○	○	○	○
10b. Detection and elimination of design errors prior to construction.	○	○	○	○	○
10c. More comprehensive representation of design intent (e.g., at intersections).	○	○	○	○	○
10d. Improved support for construction (e.g., automated machine guidance).	○	○	○	○	○
10e. Other (specify)	○	○	○	○	○

[PAGE]

[ask if q10e = any 2-5]

10e1. Please specify any other perceived or proven benefits of design methods that produce a 3D design model within your SHA.

[PAGE]

11.Within your SHA, how important are the typical prerequisites for adoption of design methods that produce a 3D design model?

Code (not seen)	*1*	*2*	*3*	*4*	*5*
	Not at all important	Not very important	Somewhat important	Very important	Extremely important
11a. Perceived (undocumented) benefits.	○	○	○	○	○
11b. Proven (documented) benefits.	○	○	○	○	○
11c. Feasibility studies.	○	○	○	○	○
11d. Cost / benefit studies and / or return-on-investment studies.	○	○	○	○	○
11e. Implementation planning.	○	○	○	○	○

[PAGE]

12.Within your SHA, how important are each of the following potential impediments to adoption of design methods that produce a 3D design model?

Code (not seen)	*1*	*2*	*3*	*4*	*5*
	Not at all important	Not very important	Somewhat important	Very important	Extremely important
12a. Entrenched technology (e.g., contracts with vendors, staff training).	○	○	○	○	○
12b. Entrenched business practices (e.g., policies and long-established procedures).	○	○	○	○	○
12c. Traditional ways of thinking about engineering design.	○	○	○	○	○
12d. Lack of perceived benefits.	○	○	○	○	○
12e. Lack of proven benefits.	○	○	○	○	○
12f. Limited resources.	○	○	○	○	○
12g. Benefits are on the construction side but costs are on the design side.	○	○	○	○	○
12h. Lack of knowledge and skills (agency).	○	○	○	○	○
12i. Lack of knowledge and skills (engineering design consultants).	○	○	○	○	○
12j. Lack of functionality in currently-installed software.	○	○	○	○	○
12k. Complexity of the task (e.g., mix of in-house and consultant-based design technologies and procedures).	○	○	○	○	○
12l. Other (specify)	○	○	○	○	○

[PAGE]

[ask if q12l = any 2-5]

12l1. Please specify any other potential impediments to adoption of design methods that produce a 3D design model.

[PAGE]

13. Which method is used <u>most often</u> by your SHA for estimating earthwork during design?

O Average-end-area (1)

O Surface-to-surface (DTMs) (2)

[PAGE]

Please provide the following information for the person who completed the above section of this questionnaire. If it is the same person who completed a previous section please enter the section for which you entered your information previously in the name line.

Name:___________________________________

E-mail Address:____________________________

Phone Number:____________________________

Job Title (Functional Role):___________________

There are additional questions please click the 'NEXT' button to continue.

[PAGE]

Section 2: Contracting.

14. Are 2D plans considered to be part of the construction contract documents for your SHA?

O Yes (1)

O No (2)

15. Do 3D digital data have any legal standing (e.g., versus 2D plans) in your SHA's construction contracts?

O Yes (1)

O No (2)

16. Has your SHA investigated implications of, and/or impediments to, adopting 3D models as contract documents?

O Yes (1)

O No (2)

17. Has your SHA identified any legal issues associated with adopting 3D models as contract documents?

O Yes (1)

O No (2) (skip to question 19)

[PAGE]

18. What legal issues associated with adopting 3D models as contract documents were identified by your SHA? Please select all that apply.

O 18a. Electronic signatures. (1 if checked)

O 18b. Transfer of liability, as related to electronic data exchange.

O 18c. Auditability of plans.

O 18d. Data security (e.g., protection against unauthorized changes, integrity of revision history).

O 18e. Unintended use of electronic location data

O 18f. Other

[PAGE]

[ask if q18e = 1 “checked”]

18o. Please specify any other legal issues associated with adopting 3D models as contract documents that were identified by your SHA.

[PAGE]

19. From January 1, 2007 to present, has automated machine guidance been used in your state for highway construction?

O Yes (1)

O No (2) (skip to question 22)

O Unknown (-1) (skip to question 22)

[PAGE]

20. When construction contractors use automated machine guidance, who has primary responsibility for developing the 3D design model?

O Contractor (1)

O Consultant on subcontract to the contractor (2)

O SHA (3)

O Consultant on subcontract to the SHA (4)

21. When construction contractors use automated machine guidance, who has primary responsibility for ensuring the 3D design model conforms to the contract documents?

O Contractor (1)

O Consultant on subcontract to the contractor (2)

O SHA (3)

O Consultant on subcontract to the SHA (4)

[PAGE]

22. Which forms of digital data, that might assist in 3D design model development, does your SHA provide to construction contractors? Please select all that apply.

O 22a. Slope stake reports. (1 if checked)

O 22b. Mass points and / or break lines derived from the plans.

O 22c. Alignment.

O 22d. Partial 3D design model (e.g., without intersection detail).

O 22e. Full 3D design model.

O 22f . Other

O 22g . None [if “none” is checked, make all other options blank]

[PAGE]

[ask if q22f = 1 “checked”]

22o. Please specify any other forms of digital data that might assist in 3D design model development that your SHA provides to construction contractors.

[PAGE]

23.Are engineering design consultants required to provide 3D design model data to construction contractors upon request?

O Yes (1)

O No (2)

24. How often do engineering design consultants provide 3D design model data to construction contractors upon request?

O Never (1)

O Rarely (2)

O Sometimes (3)

O Usually (4)

O Always (5)

O Not Known / Not sure (-1)

25. Which method for computing earthwork is specified <u>most often</u> in your SHA's policy, standards, or procedural documents?

O Average-end-area (1)

O Surface-to-surface (DTMs) (2)

[PAGE]

Please provide the following information for the person who completed the above section of this questionnaire. If it is the same person who completed a previous section please enter the section for which you entered your information previously in the name line.

Name:___________________________________

E-mail Address:____________________________

Phone Number:____________________________

Job Title (Functional Role):___________________

There are additional questions please click the 'NEXT' button to continue.

[PAGE]

Section 3: Construction.

26. Approximately how many construction projects does your SHA deliver annually?

Enter one number here: _________

27. From January 1, 2007 to present, has automated machine guidance been used in your state for highway construction?

O Yes (1)

O No (2) (skip to question 30)

[PAGE]

28. From January 1, 2007 to present, approximately what percentage of highway construction projects in your state have used automated machine guidance?

O Less than 20% (1)

O 20-39% (2)

O 40-59% (3)

O 60-79% (4)

O 80% or more (5)

29. From January 1, 2007 to present, which types of construction in your state used automated machine guidance? Please select all that apply.

O 29a. Sub grade construction. (1 if checked)

O 29b. Base course placement for asphalt paving.

O 29c. Base course placement for concrete paving.

O 29d. Asphalt paving.

O 29e. Concrete paving.

O 29f. Excavation (e.g., borrow pits).

O 29g. Other (specify)

[PAGE]

[ask if q29g = 1 “checked”]

29o. Please specify what other types of construction used automated machine guidance in your state from January 1, 2007 to present.

[PAGE]

30. Does your SHA have an automated machine guidance specification?

O Yes (1)

O No (2) (skip to question 33)

[PAGE]

31.For which types of construction does your SHA have an automated machine guidance specification? Please select all that apply.

O 31a. Sub grade construction. (1 if checked)

O 31b. Base course placement for asphalt paving.

O 31c. Base course placement for concrete paving.

O 13d. Asphalt paving.

O 31e. Concrete paving.

O 31f. Excavation (e.g., borrow pits).

O 31g. Other [specify]

[PAGE]

[ask if q31g = 1 “checked”]

31o. Please specify the other types of construction that your SHA has an automated machine guidance specification.

[PAGE]

32. Does your SHA’s automated machine guidance specification address preparation and / or responsibility for the 3D design model?

○ Yes (1)

○ No (2)

33. Has your SHA received lower than expected bids that can be attributed to use of automated machine guidance?

○ Yes (1)

○ No (2)

○ Not Known / Not sure (-1)

Please answer the following sets of questions with the scale from “not at all important” to “extremely important” shown below.

34.In your SHA’s experience, how important are each of the following perceived or proven benefits of automated machine guidance?

Code (not seen)	*1*	*2*	*3*	*4*	*5*
	Not at all important	Not very important	Somewhat important	Very important	Extremely important
34a. Less staking (e.g., blue tops, red tops, slope stakes)	○	○	○	○	○
34b. Less repeat work.	○	○	○	○	○
34c. Support for night work.	○	○	○	○	○
34d. More uniform surfaces in final product.	○	○	○	○	○
34e. Greater accuracy (e.g., closer to design grades before checking).	○	○	○	○	○
34f. Contractor productivity gains.	○	○	○	○	○
34g. Lower costs for construction.	○	○	○	○	○
34h. Other (specify)	○	○	○	○	○

[PAGE]

[ask if q34h = any 2-5]

34h1. Please specify what other perceived or proven benefits of automated machine guidance are important to your SHA.

[PAGE]

35.Within your SHA, how important are each of the following perceived impediments to wider use of automated machine guidance?

Code (not seen)	*1*	*2*	*3*	*4*	*5*
	Not at all important	Not very important	Somewhat important	Very important	Extremely important
35a. Lack of contractor interest.	○	○	○	○	○
35b. Skepticism concerning the technology within your SHA.	○	○	○	○	○
35c. Lack of technical skills of contractors.	○	○	○	○	○
35d. Lack of technical skills within your SHA.	○	○	○	○	○
35e. Lack of specifications.	○	○	○	○	○
35f. Unawareness of benefits by contractors.	○	○	○	○	○
35g. Unawareness of benefits within your SHA.	○	○	○	○	○
35h. 3D design model issues (e.g., responsibility, data exchange, approvals).	○	○	○	○	○

[PAGE]

36.Which method is used most often by your SHA for computing final earthwork quantities?

○ Average-end-area (1)

○ Surface-to-surface (DTMs) (2)

37.Which one of the following survey methods is used most often during data collection for final quantities?

○ Mass points and break lines (by ground survey) (1)

○ Cross sections (by ground survey) (2)

○ LiDAR (3)

○ Photogrammetry (4)

○ Other (specify) (5)

[PAGE]

[ask if q37 = 5 “other”]

37o. Please specify what other survey method is used most often during data collection for final quantities.

[PAGE]

Please provide the following information for the person who completed the above section of this questionnaire. If it is the same person who completed a previous section please enter the section for which you entered your information previously in the name line.

Name:___________________________________

E-mail Address:____________________________

Phone Number:____________________________

Job Title (Functional Role):___________________

There are additional questions please click the ‘NEXT’ button to continue.

[PAGE]

Does this survey need to be reviewed before the data can be submitted for use?

If, Yes. Please have the appropriate authority review and submit the survey.

If, No. Please click the ‘SUBMIT’ button to submit your answers.

It is important that the ‘SUBMIT’ button be used so we know your SHA has given permission to the researchers to use the data provided for analysis and reporting.

[PAGE] [only displayed after the ‘SUBMIT’ button has been clicked]

The survey is now complete and all of your answers have been submitted.

Thank you again for taking the time to complete this survey.

Appendix B: Additional Survey Results (Design Component)

Note: The text of the responses to the “Other” option for the survey questions listed below are reproduced here verbatim.

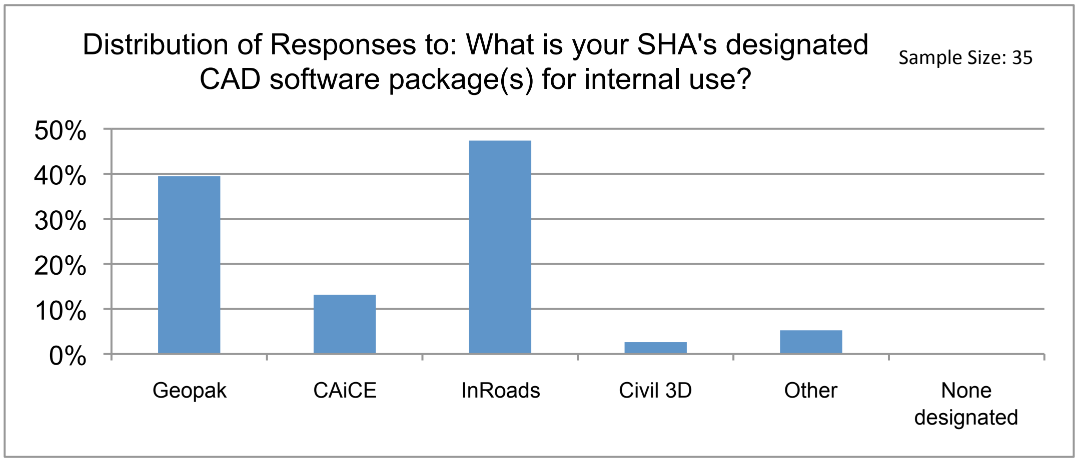

Figure B.1

Responses to *other*: Corridor Modeler, Bentley MicroStation, Quantity Manager, Storm and Sanitary.

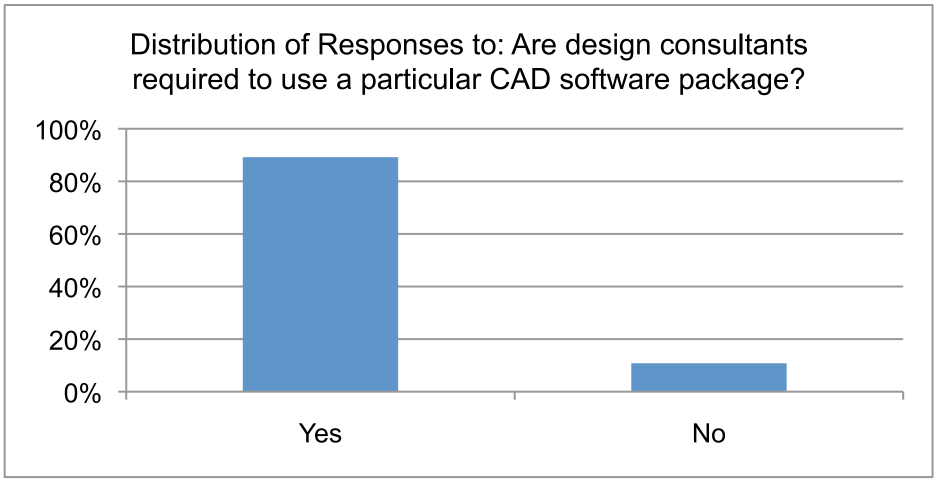

Figure B.2

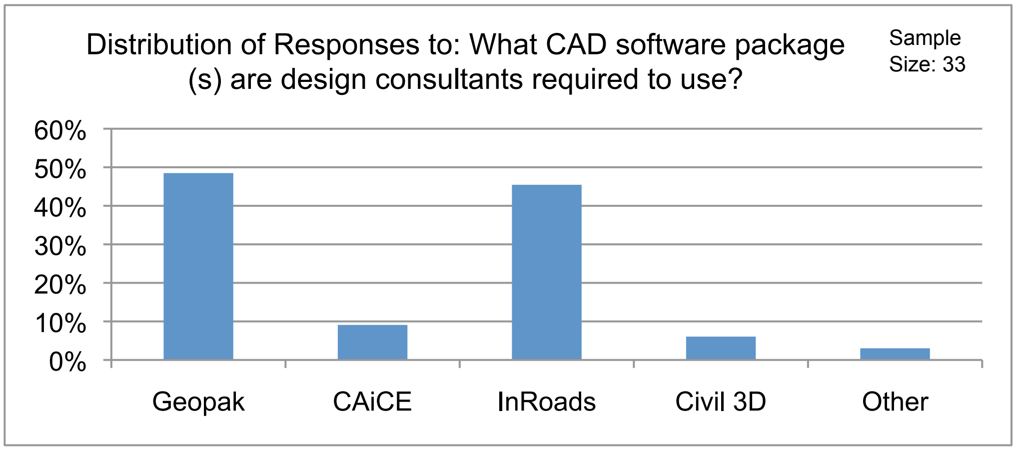

Figure B.3

Responses to *other*: Bentley MicroStation, Quantity Manager, Storm and Sanitary.

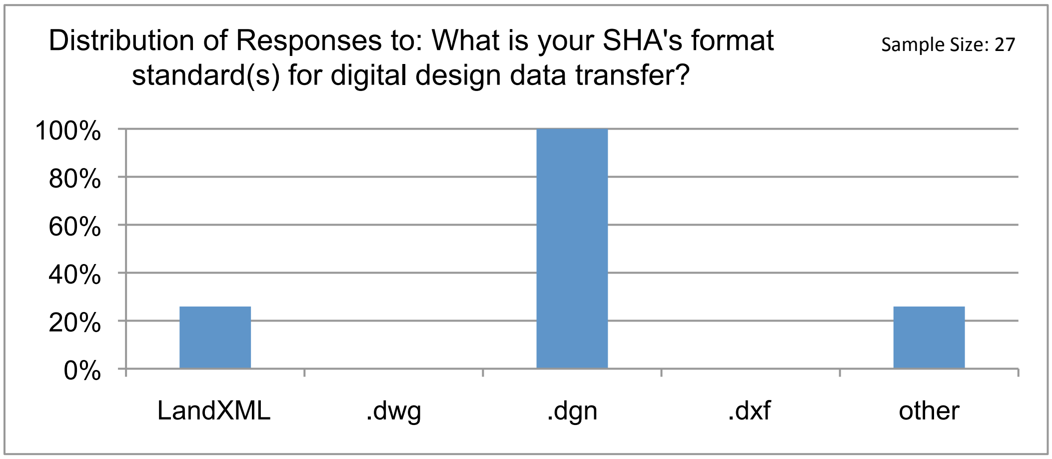

Figure B.4

Responses to *other*:

Plan Sets = .cal & .pdf Surface Data = .dtm, .dgn file with triangles only, LandXML or Trimble export Geometry Data = .dgn (alignment information only).

http://www.dot.state.fl.us/ecso/downloads/publications/CriteriaHandBook/CPCH2008MR1/CPCHMR1.shtm Note that on questions 3 and 4 that FDOT requires specific delivery formats, which are described in detail in the document linked above. If a data producer could use another software package to meet those format requirements it is acceptable. However, it is impractical to meet those formats, usually, without using the principal software that creates those formats, so the issue is moot.

MicroStation format for all CADD design files, proprietary GEOPAK format for coordinate geometry (*.gpk), drainage project file (*.gdf), site projects (*.gsf). 3D models can be GEOPAK format (*.tin) or Trimble (*.ttn) for AMG. We also provide *.dwg for AMG only, not general data transfer.

All final design plan view and profile view drawings must be submitted in 2D v8 dgn format, soon switching to v8i dgn format. All coordinate geometry must be submitted in native Geopak (gpk) format AND LandXML format. All cross sections must be submitted in their native dgn format with all the Geopak intelligence (cross section cell) in the drawing as well as in ASCII reports (Geopak Multiline and/or xs list reports). Topo survey data from consultants to the agency is submitted in dgn format and gpk format, and the model is TIN format.

.alg, .dtm

XML, DGN, InRoads file formats (ALG, DTM, FWD).

SDMS (AASHTO) CAiCE Proprietary.

SDMS (AASHTO) CAiCE Proprietary.

Appendix C: Additional Earthwork Comparisons

C.1. Borrow Pit

A borrow pit was available as one of the sites used for comparison between earthwork computation methods. Borrow pits by nature have large cut quantities. The borrow pit was approximately 580 feet long and 120 feet wide. The data were received from the Wisconsin Department of Transportation and were native to CAiCE®. These data, comprised of breaklines only, were transferred to Civil 3D using LandXML. An exterior boundary was created for both the existing and final ground surfaces to eliminate long, narrow erroneous triangles along surface exteriors. Figures C.1 and C.2 are visualizations of the two ground surfaces. Note: For all images, blue depicts the existing ground surface and pink depicts the final ground surface.

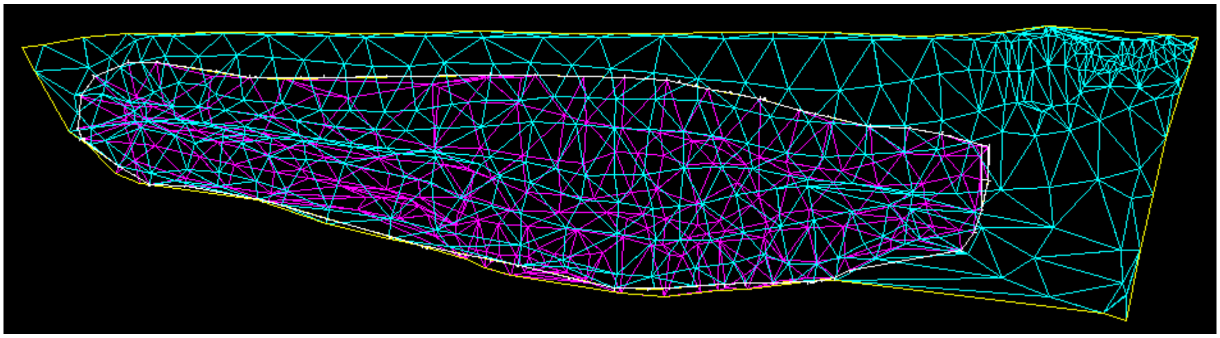

Figure C.1: Plan View of Surfaces Used in Borrow Pit Earthwork Computations

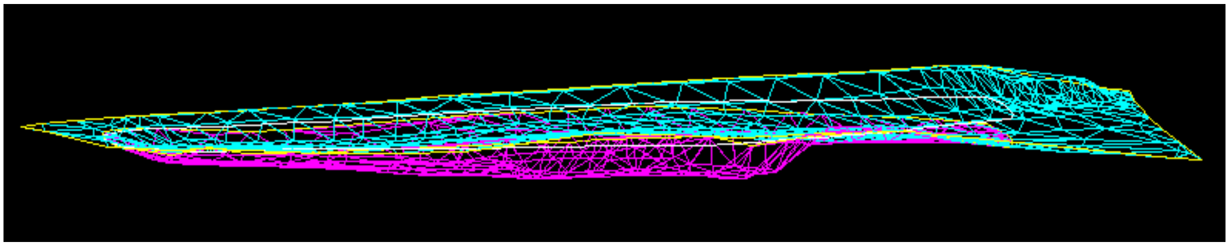

Figure C.2: 3D View of Surfaces Used in Borrow Pit Earthwork Computations

Results from the two computation methods appear in Table C.1 and Figure C.3. The figure shows that as the cross section interval increases there are larger percentage differences between the surface-to-surface and average-end-area results for both cut and fill quantities. There is only a small change in the differences when increasing the interval from 10 to 30 feet. However, when the interval is increased beyond 30 feet, there are considerable increases in the differences between the two computation methods. The increase of interval from 50 to 100 feet results in the largest increase in differences between earthwork quantities.

The largest cost discrepancy occurred in cut material when using a 100-foot cross section interval. This maximum cost difference is $4,742.41, which is approximately 10 times larger than the cost difference for cut material at a 50-foot interval. Also, when using a 10-foot cross section interval, there is only a $56.49 difference in cost estimates for cut material.

It also important to note that the percent differences between methods for fill computations are significantly larger than those for cut. However, due to the small amounts of fill, the maximum observed cost difference was only $45.07. The percent difference between results is more sensitive when the volume of material is small.

Table C.1: Results of Volume Comparison for a Borrow Pit

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-to-surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-to-surface	Cost Difference for Fill
Surface-to-surface	n/a	16931.6	-------	--------	76.7	-------	--------
Average-End-Area	10	16921.9	0.06	$56.49	74.8	2.49	$11.14
Average-End-Area	30	16910.0	0.13	$125.52	78.9	2.82	$12.59
Average-End-Area	50	16850.8	0.48	$470.71	72.8	5.03	$22.50
Average-End-Area	100	17745.0	4.80	$4,742.41	69.0	10.08	$45.07

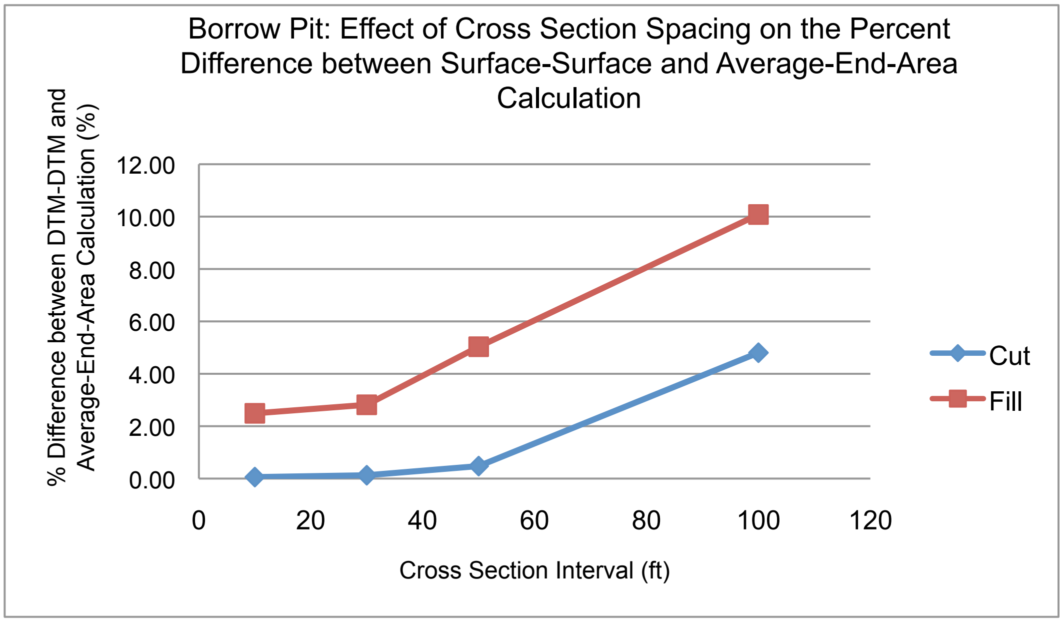

Figure C.3

C.2. Intersection

A data set for a two-lane intersection was available from the Wisconsin DOT for comparison of earthwork computation methods. Data for the intersection were native to Civil 3D and included a corridor model. A corridor model is created incrementally by registering typical 2D roadway sections and slopes with surface data at a defined frequency to create a 3D model of the roadway design. An existing ground surface was provided as part of the data set. A design ground surface was extracted from the corridor model. Figure C.4 shows the intersection.

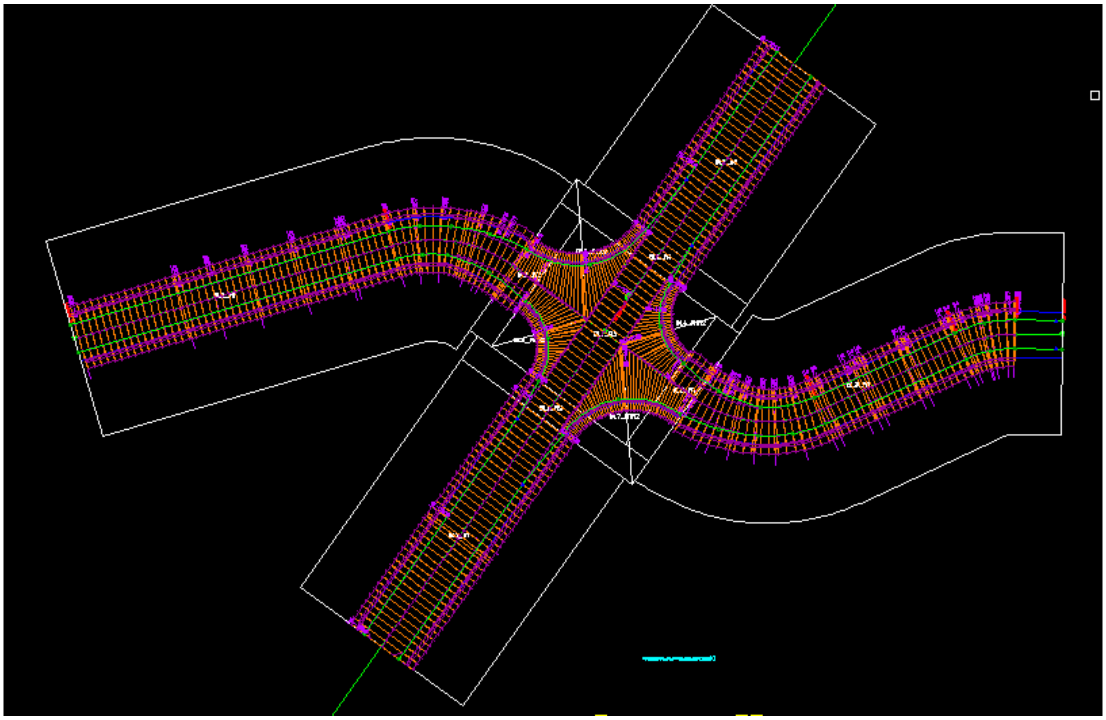

Figure C.4: Plan View of Intersection

Comparisons between surface-to-surface and average-end-area calculations at varying cross section intervals are provided in Figure C.5 and Table C.2. For both cut and fill volumes, larger percent differences between surface-to-surface and average-end-area arise when the cross section interval is increased. Percent differences between volume computation methods are higher for fill volumes. This larger percent difference for fill quantities likely follows the logic described in the borrow pit example; percent differences for smaller quantities are more sensitive to even small changes in absolute volume. The greatest increase in percent difference between computation methods for both cut and fill volumes occurred when increasing the cross section interval from 10 to 30 feet.

The quantities of both cut and fill material for the intersection are relatively small. Thus, the cost discrepancies between surface-to-surface and average-end-area results were not considerable. The maximum cost difference between methods occurred for cut material when using a cross section interval of 100 feet but this amounts to only $213.44. The largest cost discrepancy ($115.44) amongst methods for fill material occurred when using an interval of 100 feet.

Table C.2: Volume Comparison Results for Intersection

Source	Cross Section Interval (ft)	Cut (yd³)	% Difference Surface-to-surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-to-surface	Cost Difference for Fill
Surface-to-surface	n/a	2903.9	---------	--------	349.0	------------	--------
Average-End-Area	10	2904.8	0.03	$3.00	348.5	0.15	$1.95
Average-End-Area	30	2927.7	0.82	$85.90	333.7	4.38	$55.31

Average-End-Area	50	2940.7	1.27	$133.00	368.2	5.51	$69.61
Average-End-Area	100	2962.9	2.03	$213.44	380.9	9.14	$115.44

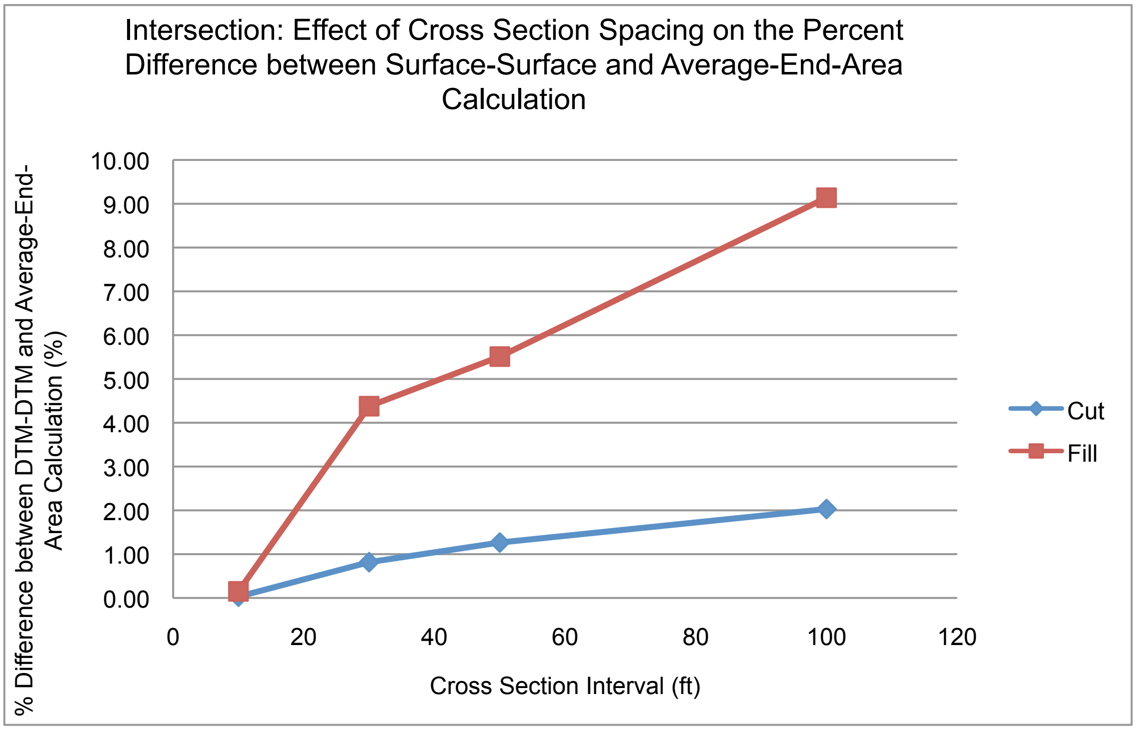

Figure C.5

C.3. Long Stretch of Bi-Directional Roadway

Data were available for a narrow two-lane roadway, approximately 4.25 miles in length. The existing ground data, provided by the Wisconsin DOT as a design (.dgn) file, consisted of photogrammetric mass points and breaklines. The data were transferred to Civil 3D using LandXML and a surface was generated with a set maximum triangle length of 300 feet to reduce the number of erroneous triangles near the surface's perimeter. The design data were provided by Wondra Excavation (a Wisconsin contractor) as a drawing (.dwg) file containing the 3D faces of a previously-created DTM. A final design surface was created by importing the 3D faces as drawing objects and manually creating a boundary around the perimeter of the faces. Figures C.6 and C.7 are visualizations of the existing ground and design surfaces.

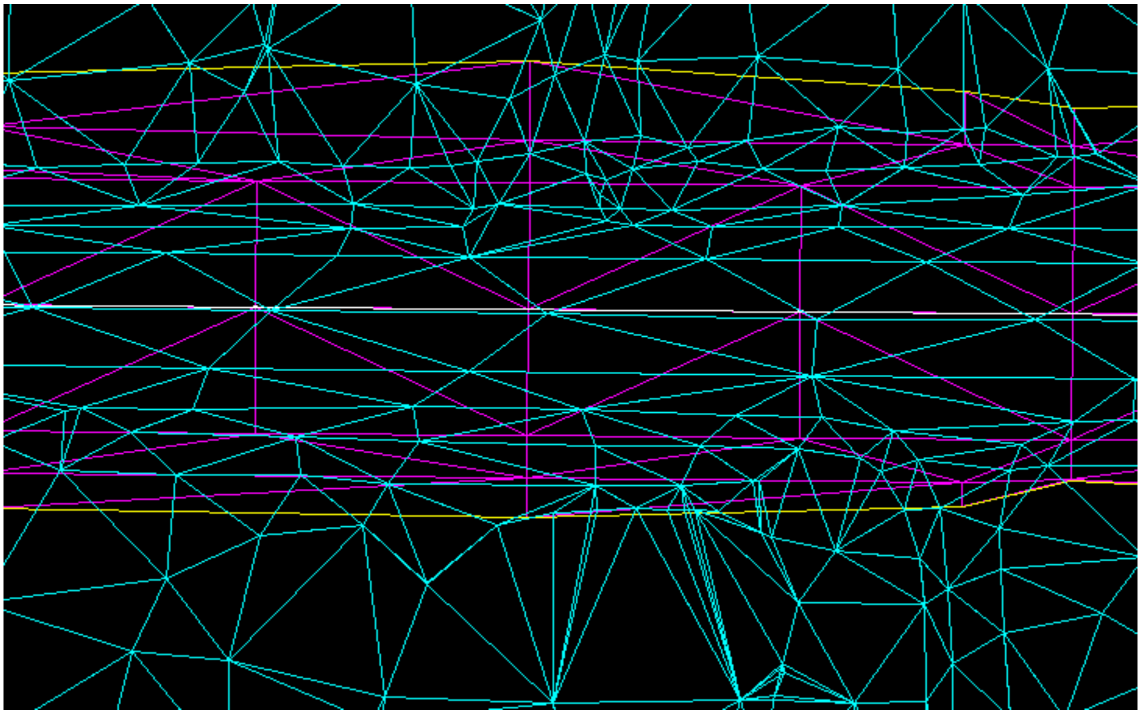

Figure C.6: Close-Up Plan View of a Section of Bi-Directional Roadway

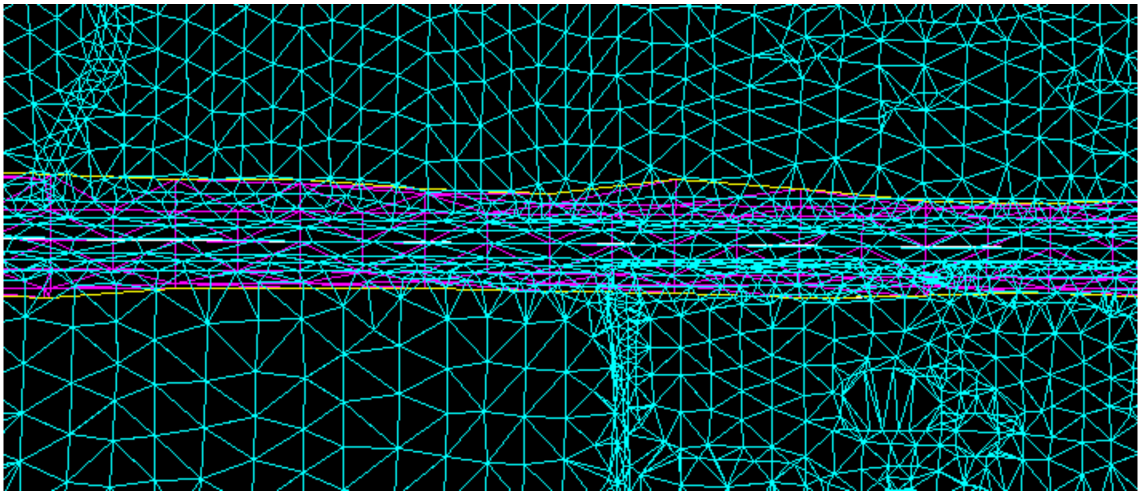

Figure C.7: Plan View of Bi-Directional Roadway

Table C.3 and Figure C.8 show the volume comparison between surface-to-surface and average-end-area methods. Volumes were computed via the average-end-area method at a cross section interval of 20 feet in addition to the usual 10, 30, 50, and 100-foot intervals. The 20-foot interval was included because there was an observed decrease in the percent difference between volume computations for fill when the cross section interval was increased from 10 to 30 feet. The increase in percent difference is fairly linear with the exception of fill volumes when using an interval of 30 feet.

The maximum cost difference between the two methods occurs for cut material when using a cross section interval of 100 feet. The total cost difference for cut at the 100-foot interval is $16,105.71, which is more than double the difference at the 50-foot cross section interval. The maximum cost difference for fill materials arises when a 100-foot interval is used. It is $8,236.59, which is nearly three times the cost discrepancy when a 50-foot interval is used. The cost difference when using an interval of 10 feet is $2,105.83 for cut and $641.21 for fill. Increasing the interval only 10 feet (from 10 to 20) causes the cost difference between methods to approximately double for both cut and fill.

Table C.3: Volume Comparison Results for Bi-Directional Roadway

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Surface-Surface	n/a	87691.9	-------	--------	39728.7	-------	--------
Average-End-Area	10	87110.2	0.66	$2,105.83	39551.6	0.45	$641.21
Average-End-Area	20	86455.0	1.41	$4,477.69	39426.9	0.76	$1,092.81
Average-End-Area	30	86139.9	1.77	$5,618.35	39681.5	0.12	$171.01
Average-End-Area	50	85511.3	2.49	$7,894.03	38947.2	1.97	$2,829.36
Average-End-Area	100	83242.8	5.07	$16,105.71	37453.4	5.73	$8,236.59

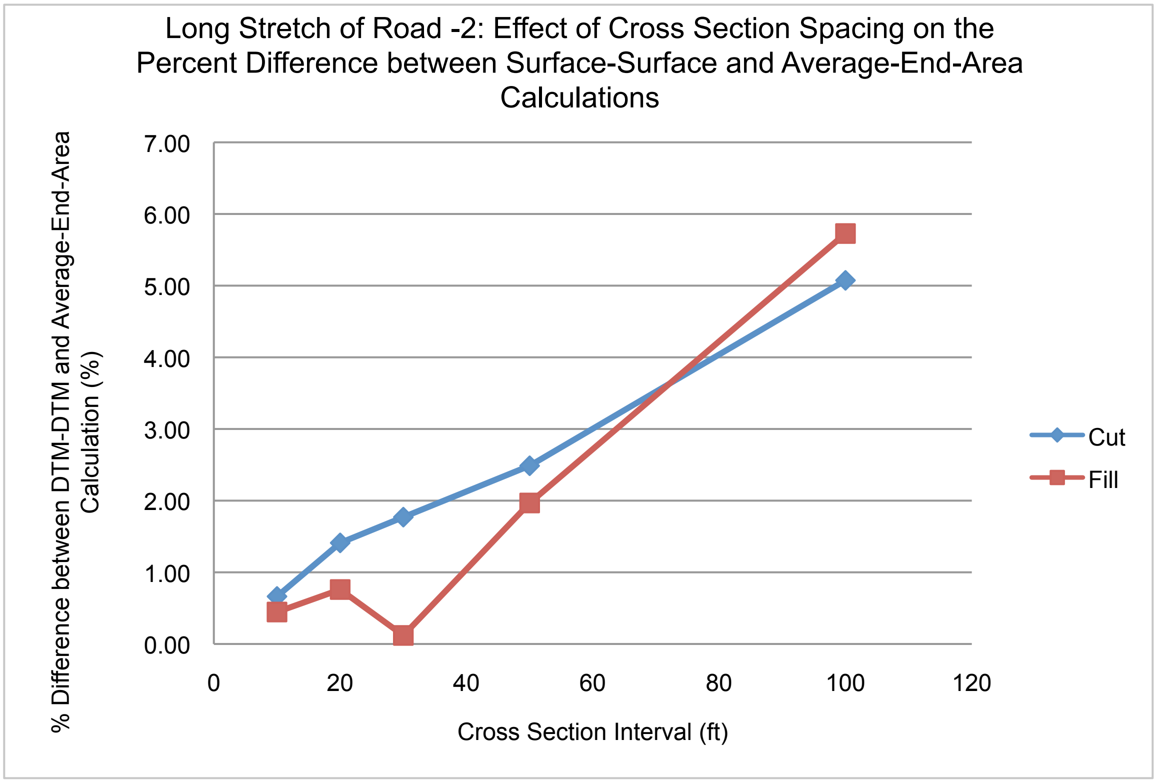

Figure C.8

C.4. Short Stretch of Roadway

Data at varying mass point densities (1.5, 3, 4.5, 6, and 12-meter grid spacing) were received from the North Carolina DOT for a short stretch of roadway, approximately 1100 feet in length. These data came from a separate study to determine the appropriate mass point density for creating surfaces. Determining the effect of mass point density on surfaces was beyond the scope of this study, but the data at all mass point densities were incorporated into the comparison between surface-to-surface and average-end-area results.

The data sets were native to MicroStation®. The data were transferred to Civil 3D using LandXML. An exterior boundary was provided with the data. This boundary was used for both the existing ground and design surfaces. Figures C.9 and C.10 are visualizations of the surfaces.

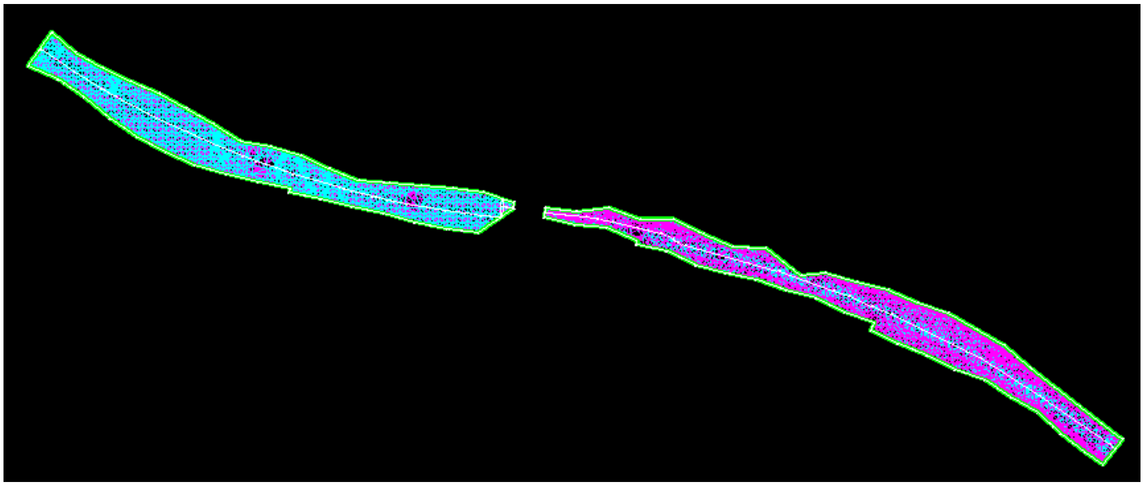

Figure C.9: Plan View of Surfaces Used in Study of Effects of Mass Point Density on Comparison between Volume Computation Methods

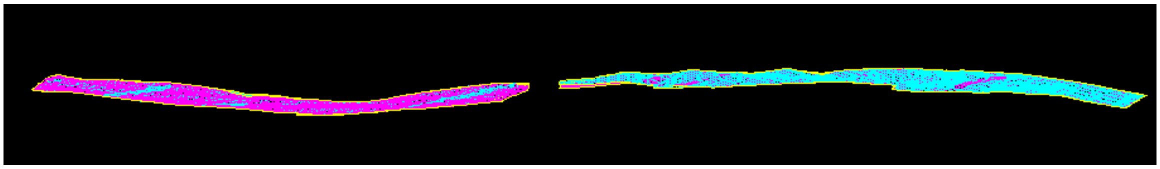

Figure C.10: 3D View of the Surfaces Used in Study of Effects of Mass Point Density on Comparison between Volume Computation Methods

Volumes were computed via the average-end-area method at the previously-used cross section intervals and compared to surface-to-surface results for all mass point densities. In addition to the previously-used intervals, average-end-area computations were made at 60 and 80-foot intervals because, with all mass point densities, there was a significant decrease in the percent difference between surface-to-surface and average-end-area results when increasing the cross section interval from 50 to 100 feet. Observing the average-end-area results at intervals between 50 and 100 feet enabled detection of a decreasing trend in fill differences when increasing the cross section interval beyond 50 feet.

Tables C.4, C.5, C.6, C.7, and C.8 provide the comparison between surface-to-surface and average-end-area computations at varying cross section intervals for each mass point density. Figures C.11 and C.12 are graphical depictions of the differences between volume computation methods for cut and fill, respectively. Note: All mass point densities are included in Figures C.11 and C.12. There is an increase in percent differences when the cross section interval increases for both cut and fill volumes, with one exception. As mentioned previously, the exception is a significant decrease for fill volumes when 100-foot intervals are used. There were also minor decreases in percent differences when moving from 50 to 60-foot intervals for 4.5, 6, and 12-meter grid spacings. However, there was not a trend of decreasing differences between the two methods as the interval was increased from 50 to 100 feet.

Figures C.11 and C.12 indicate that all mass point densities have the same trend of percent differences with increasing cross section intervals for both cut and fill volumes. However, there are larger deviations in percent differences for fill than for cut.

Since varying the mass point density generally did not affect the percent differences for both cut and fill, cost differences between point densities are negligible. The site was quite small, so cost differences were not large. The maximum cost difference between computational methods occurred at 100-foot cross section intervals. This cost difference was approximately $500 based on all point densities. However, if the percent difference for cut of approximately 11.5 percent that arose when using an interval of 100 feet occurred on a large project, cost differences between methods could be very high.

Table C.4: Volume Comparison for 1.5-Meter Grid Spacing

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Surface-Surface	n/a	1186.5	-------	---------	992.9	-------	---------
Average-End-Area	10	1183.8	0.23	$9.88	992.2	0.06	$2.24
Average-End-Area	30	1173.7	1.08	$46.34	999.4	0.66	$23.71
Average-End-Area	50	1156.1	2.56	$109.83	984.8	0.81	$29.07
Average-End-Area	60	1126.2	5.08	$218.25	973.8	1.92	$69.14
Average-End-Area	80	1085.6	8.50	$365.15	964.8	2.83	$101.54
Average-End-Area	100	1046.0	11.84	$508.50	988.3	0.46	$16.36

Table C.5: Volume Comparison for 3-Meter Grid Spacing

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Surface-Surface	n/a	1186.8	-------	---------	987.1	-------	---------
Average-End-Area	10	1186.3	0.05	$1.95	985.1	0.20	$7.28
Average-End-Area	30	1172.4	1.21	$52.13	992.8	0.57	$20.53
Average-End-Area	50	1150.8	3.04	$130.39	1019.0	3.23	$115.37
Average-End-Area	60	1127.2	5.02	$215.82	949.1	3.85	$137.42

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Average-End-Area	80	1083.6	8.70	$373.69	928.2	5.97	$213.40
Average-End-Area	100	1045.0	11.95	$513.46	977.9	0.93	$33.30

Table C.6: Volume Comparison for 4.5-Meter Grid Spacing

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Surface-Surface	n/a	1185.8	-------	---------	984.5	-------	---------
Average-End-Area	10	1185.1	0.06	$2.46	982.0	0.26	$9.16
Average-End-Area	30	1175.5	0.87	$37.18	992.3	0.79	$28.13
Average-End-Area	50	1151.4	2.90	$124.67	1023.6	3.97	$141.43
Average-End-Area	60	1128.5	4.83	$207.32	946.7	3.84	$136.98
Average-End-Area	80	1084.8	8.51	$365.44	934.6	5.07	$180.67
Average-End-Area	100	1053.6	11.15	$478.53	986.5	0.20	$7.13

Table C.7: Volume Comparison for 6-Meter Grid Spacing

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Surface-Surface	n/a	1184.4	-------	---------	979.8	-------	---------
Average-End-Area	10	1184.0	0.04	$1.59	977.6	0.22	$7.67
Average-End-Area	30	1172.3	1.03	$43.98	986.6	0.69	$24.62
Average-End-Area	50	1149.3	2.96	$127.03	1016.5	3.75	$133.04
Average-End-Area	60	1129.3	4.66	$199.61	943.3	3.72	$132.06
Average-End-Area	80	1084.5	8.44	$361.89	921.7	5.92	$210.07

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Average-End-Area	100	1051.2	11.25	$482.37	975.6	0.43	$15.24

Table C.8: Volume Comparison for 12-Meter Grid Spacing

Source	Cross Section Spacing (ft)	Cut (yd³)	% Difference Surface-Surface	Cost Difference for Cut	Fill (yd³)	% Difference Surface-Surface	Cost Difference for Fill
Surface-Surface	n/a	1176.2	-------	---------	971.3	-------	---------
Average-End-Area	10	1175.5	0.06	$2.43	969.2	0.21	$7.53
Average-End-Area	30	1166.4	0.83	$35.22	980.0	0.90	$31.49
Average-End-Area	50	1138.7	3.19	$135.71	1001.8	3.13	$110.23
Average-End-Area	60	1116.3	5.09	$216.58	941.3	3.09	$108.82
Average-End-Area	80	1058.6	10.00	$425.75	908.4	6.48	$227.70
Average-End-Area	100	1042.4	11.38	$484.39	952.1	1.98	$69.50

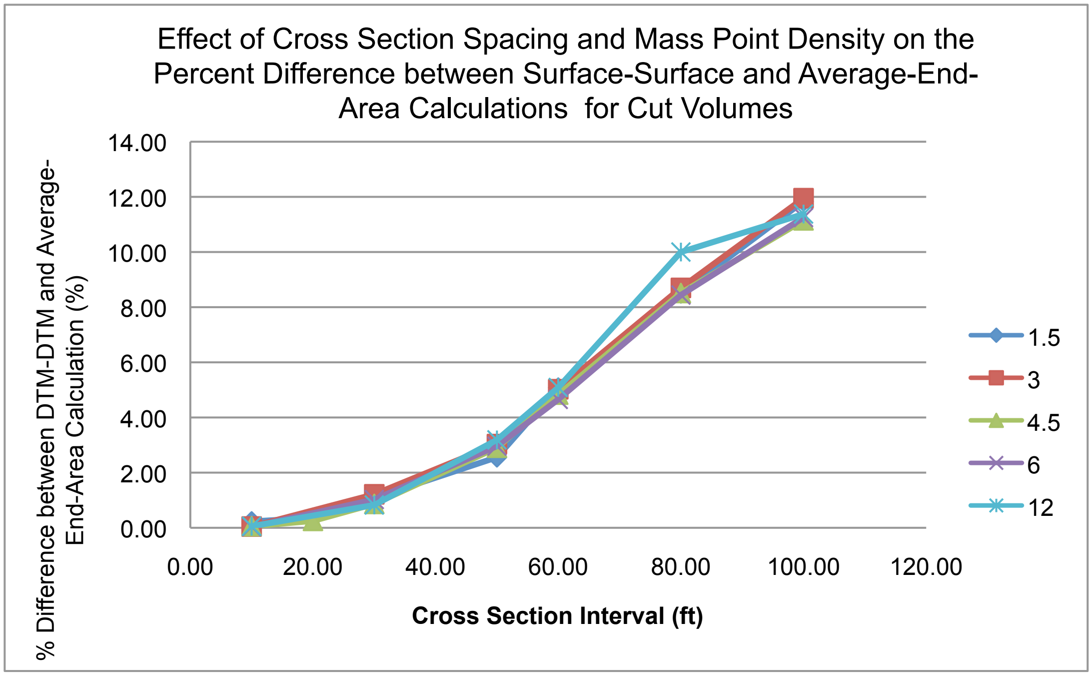

Figure C.11

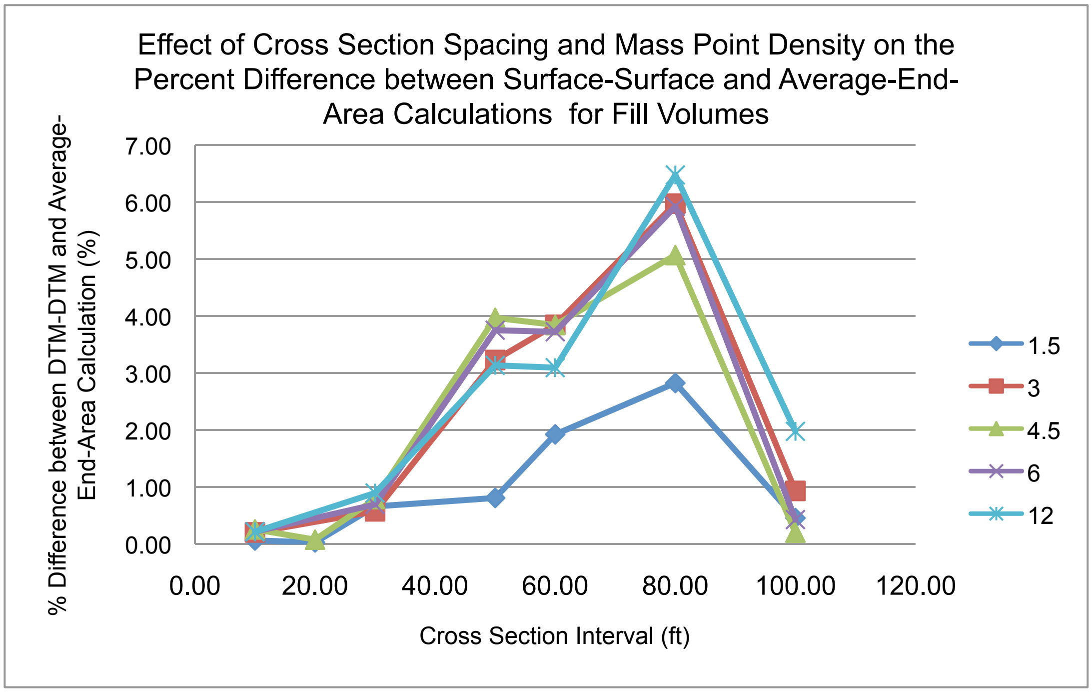
Effect of Cross Section Spacing and Mass Point Density on the Percent Difference between Surface-Surface and Average-End-Area Calculations for Fill Volumes
% Difference between DTM-DTM and Average-End-Area Calculation (%)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Cross Section Interval (ft)
1.5
3
4.5
6
12

Figure C.12