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Use of Automated Machine Guidance within the Transportation Industry

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SUMMARY

Automated machine guidance (AMG) links sophisticated design software with construction equipment to direct the operations of construction machinery with a high level of precision, and improve the speed and accuracy of the construction process. AMG technology has the potential to improve the overall quality, safety, and efficiency of transportation project construction. This research project was undertaken to study AMG implementation barriers and develop strategies for effective implementation of AMG technology in construction operations. Early in the research effort, an expert contact group was established to obtain perspectives from agencies, contractors, designers, and equipment manufacturers. An AMG workshop was conducted to develop a list of capabilities that must exist and obstacles that must be overcome to facilitate seamless electronic data transfer—from the initial surveying, to the development of digital terrain models (DTMs), through design and construction, to final inspection and verification. The synthesis from the workshop helped provide a framework and content for completing the research. Summarized here are some of the key findings from this research project.

AMG WORKFLOW PROCESSES

Integrating AMG into transportation projects involves complex decision-making and workflow processes, including selection of surveying methods and technologies, software design and engineering analytic tools, machine systems, sensor technologies, data interoperability and transfer mechanisms, and human-machine interaction during construction and training. A set of simplified workflow diagrams and narratives of processes and technologies have been provided by organizing the topics as follows:

1. Surveying preparation workflow processes,
2. Roadway design workflow processes,
3. Contractor data preparation workflow processes, and
4. Overall integrated AMG workflow processes.

The accompanying narrative attempts to concisely describe the processes involved with the workflow steps first to establish a baseline for the remainder of the report, and, second, to appreciate that AMG is best positioned to succeed when survey, design, and construction processes are properly coordinated. Understanding these AMG workflow processes is also important for developing guide specifications for effectively implementing AMG where critical roles and responsibilities can be defined.

In discussions with stakeholders in AMG processes, data interoperability was identified in virtually all the workflow processes as a key factor in providing an efficient AMG process. In the future, data interoperability will continue to be an area of desired AMG technology advancement.

AMG INFORMATION REVIEW

The research team constructed a searchable electronic library of information related to AMG and supporting technologies. The project's bibliography currently contains more than 370 documents that range from peer-reviewed academic papers to specifications to transportation agency directives to manufacturer specific videos and others.

The use of AMG technology is relatively new, and our study confirmed that the AMG literature base is not as mature as that of more-established technologies and procedures. As such, academic papers accounted for only 28% of the information sources in the AMG project bibliography. Even though information on AMG does not appear to have a large base of formally published papers, significant information was garnered through AMG-specific and related websites and from slides from presentations at meetings held by transportation agencies, software and hardware vendors, and contractors. A detailed annotated bibliography and list of AMG specifications was generated from the information and literature review. In addition, a lexicon of terms used in AMG was developed and is reported herein and is used throughout the report.

One of the key outcomes from the information and literature review was that there is very limited independently studied information that quantifies AMG machine-level performance or site-level construction efficiency gains for AMG projects. These areas require more research in order to fully understand the benefits of using AMG and related technologies in construction processes.

SURVEY OUTCOMES

The project survey garnered information from a sample of all major AMG stakeholder groups, helping to define the current state of the industry. The project team developed separate survey questions for the various stakeholder groups, based on internal collaboration and the literature collected to date.

The survey covered the following topics:

- Current computer-aided drafting (CAD) software capabilities
- Types of electronic files that are submitted to contractors (such as .dgn, .dwg, .dtm, .tin, and LandXML files)
- When these files are made available to the contractors (such as pre-bid or post-award)
- Equipment capabilities and reliability
- Perceived benefits and challenges regarding AMG processes

More than 5,000 survey respondents were solicited. Key survey outcomes are presented in the report. The full survey report is provided as a separate Appendix. The analysis results are primarily descriptive statistics and provide new insights into the development of this newly emerged technology.

LEGAL BARRIERS

The use of AMG technology in construction contracting has created changes in business work processes and contract delivery processes, affecting all the contract stakeholders. Some legal mechanism is needed to bridge the implied design warranty concerns (Spearin doctrine) and the ability to include electronic engineered data (EED) as part of the contract documents. Currently, liability waivers and clauses are performing this function, in part, but they are yet to be tested in the courts.

The work process changes, resulting in functional role changes, have proceeded faster than the regulatory and legal systems have accommodated. A standard definition of professional roles is needed across all of the state license boards, which would help define the "responsible charge" of the various professional stakeholders. Results of this project should be communicated to the National Council of Examiners for Engineering and Surveying (NCEES) for consideration in the Model Law document (NCEES, 2009), which is intended to be used as a reference work in the preparation of amendments to existing legislation or in the preparation of newly proposed laws. The intent of NCEES in preparing this document is to present to the jurisdictions a sound and realistic guide that will provide greater uniformity of qualifications for licensure, to raise these qualifications to a higher level of accomplishment, and to simplify the interstate licensure of engineers and surveyors."

Defining professional roles will also require a standardized definition of EED, including what it is *not* to be used for. The Proposal for Use of EED in Construction created in 2008 by a joint Associated General Contractors (AGC) of America and Departments of Transportation (DOT) subcommittee does not address professional roles or duties, nor does it address the contractual context.

The good news, according to the project surveys, is that despite the legal hurdles; those with AMG experience perceive that it improves the spirit of cooperation between the contract stakeholders, through improved constructability communications. The project surveys have also indicated that the perception of liability regarding the exchange of EED is quite low.

AMG TRAINING OPPORTUNITIES

Good training programs will be necessary for stakeholders to maintain productivity and accuracy on AMG projects. An especially critical need exists for training (and possibly certification) on 3D modeling and the use of project control points during construction. Currently, training is provided by various sources; however, no one source provides all of the training necessary for AMG.

A considerable number of self-paced online opportunities are available, especially for learning about software. Meanwhile, hands-on, instructor-led opportunities exist predominately for equipment operation and using positioning hardware. Educational institutions are beginning to include AMG in their curriculums; however, educational goals are more general than training goals. Therefore, AMG stakeholders must continue to train personnel as new members are incorporated into their AMG teams.

BEST PRACTICES AND CHALLENGES FOR DESIGN MODEL DEVELOPMENT

The development of fully-integrated, electronic 3D models was more common for building design and construction projects than transportation projects for a variety of reasons. Recently, however software and hardware tools have been developed that have considerable capability and intelligence along with workflows and policies that support them. Therefore, electronic 3D models of transportation projects are appearing with levels of integration that rival those found in the building construction industry. Available online training tools strongly supplement more traditional face to face option and will further facilitate electronic transportation model development.

Wise choices regarding data collection during the initial surveying activities are an important part of the effort to improve the development of transportation design models. Transportation corridors are often long enough so that the curvature of the earth and other effects that cannot be address in a strictly Cartesian coordinate system will come into play. However, proper reference to geodetic surveys and/or state plane coordinates during both initial and construction surveys will address some of the challenges of developing and using electronic transportation models. Modern survey tools, including the use of global positioning system (GPS) surveying are available to increase the efficiency and lower the cost of such surveys.

IMPACT OF AMG ON EARTHWORK QUANTITIES

Proper use of digital information for AMG can result in less confusion and more accuracy than traditional methods of earthwork pay item quantification and payment. Survey responses from contractors indicate that majority of the responding contractors are already using DTMs for estimating quantities, means and methods, constructability, quantity of the progress of work, and payment.

Most of the equipment vendors indicated potential productivity gain of around 40% and potential cost savings of about 25 to 40% using AMG. On the other hand, most of the contractors indicated potential productivity gains of about 10 to 25% and potential cost savings of about 10 to 25% using AMG. The literature suggests productivity gain ranged from about 5 to 265% and cost savings ranged from about 10 to 68%, depending on the position measurement technology used and the application. Only a few case histories provide project specific productivity estimates for AMG for applications involving road construction, pipe trench excavation, and paving. A cost model is described in this report that relates productivity to cost savings.

ACCURACY OF AMG PROCESS

The accuracy of the AMG process is primarily influenced by three variables: position measurement technology, construction process, and human errors. These parameters are application-specific or machine-specific, and have not been thoroughly studied and or documented in the technical literature. The research team conducted interviews with various contractors to get feedback on various error detection and mitigation strategies.

Survey results indicated that a majority (> 70%) of contractors, software/hardware vendors, and agencies who responded believe that the number of elevation data points used in creating the DTM is an important factor in the accuracy of the DTM. A grid of data points was analyzed using six different interpolation methods to determine the absolute mean error (calculated as the average of absolute value of the difference between the actual and the estimate value). Results show that the interpolation method and spatial density of data points are factors.

A summary matrix was developed with attributes of accuracy, coverage range, measurement principle, and relative cost of various position measurement technologies that are typically used in construction applications. Laser, ultrasonic, robotic total station, GPS, augmented GPS, assisted GPS (via mobile phones), locata (pseudolites), and infrared laser technologies were studied. Typical precision requirements and vertical accuracy requirements for earthwork and paving equipment/operations are summarized from sources identified in the literature.

AMG GUIDE SPECIFICATION

As part of the research effort, specifications from several transportation authorities were collected. To compare the contents of the specifications, various attributes were identified and compared between the specifications. After reviewing all of the collected specifications, it was observed that although the layout of each specification was different, similar topics were addressed and similar language was used. After a critical review of the phrase and heading tables, the following six headings were identified to best characterize the specification language from all of the specification documents — general, liability, equipment, responsibilities, measurement, and payment. These headings were selected for inclusion in an AMG guide specification tool. To use the AMG guide specification tool, it would ideally be reviewed and discussed by agency design and contracting groups and provided to contractors for review and comments. The guide tool is formatted so that it can be printed, marked for items to include, marked to add additional items, and space for adding comments.

THE FUTURE OF AMG

Rapid technological developments are propelling AMG towards new capabilities that are radically expanding and shifting the roles and identities of traditional surveyors, design engineers, agencies, contractors, and equipment providers. New paradigms are emerging for conceptualizing sites, designing new and different projects, constructing projects, and ultimately using and maintaining them. The future of AMG is one that will likely be abundant with new technologies, with advanced software, improved data interoperability, and new autonomous machine capabilities. To fully benefit, these developments must be stewarded proactively by a broadly inclusive AMG owner-designer-surveyor-engineer-construction community. How this community should interact and work together is yet to be defined, but may require new models, training, and even development of new educational disciplines/professions.

Whatever the future AMG landscape looks like, it will require planning and new ways of interaction to garner the full potential of this technology. New partnerships, research and development, and training across the AMG community will be key to accelerating AMG innovation. The concept for an AMG professional is introduced in this context. Also, building on discussion elsewhere in this report on the topic of data interoperability, future needs are presented. A futuristic description of an AMG land drone is also presented in the context of some of the technical challenges that exist in advancing AMG capabilities to yet an even higher level than exists today.

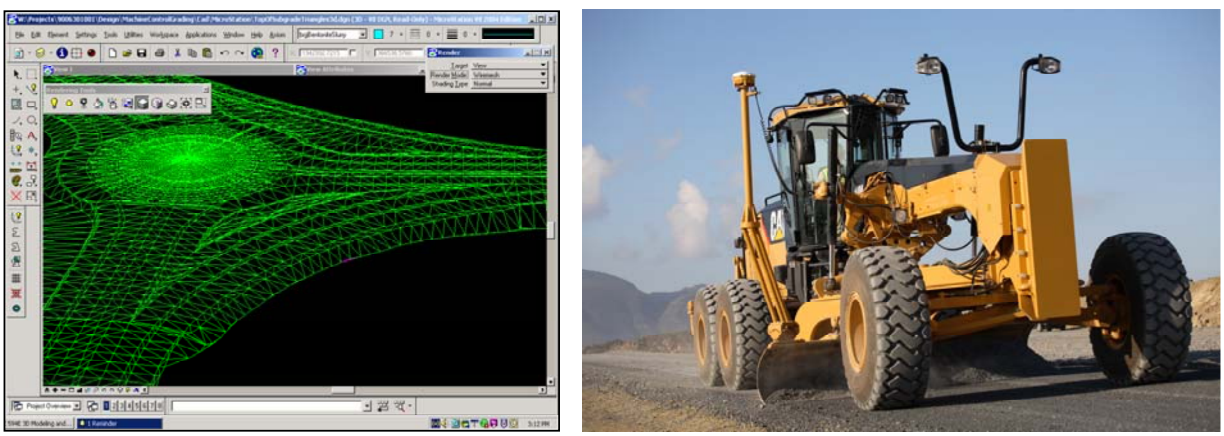
CHAPTER 1: INTRODUCTION

Using automated machine guidance (AMG) technology in transportation construction projects allows state agencies and contractors to deliver projects better, safer, faster, and more cost-effectively. This research project, NCHRP 10-77, Use of Automated Machine Guidance (AMG) within the Transportation Industry, was initiated to advance the integration and implementation of AMG. This report summarizes the findings and outcomes of this project.

PROBLEM STATEMENT

AMG technologies are continuing to be adopted by contractors because it improves construction efficiency and quality. Agencies are improving electronic design processes that support AMG construction and deliver higher quality products to the public. Equipment providers are rapidly advancing software tools and machines systems to increase automation in the design and construction process. Motivation to more widely integrate and adopt AMG processes therefore exists. However, the framework for adoption of AMG into the complex framework of design to construction has not been comprehensively documented in one source and it would be desirable to more fully develop some details of the framework. Technical, equipment, software, data exchange, liability/legal, training, and other barriers limits progress with AMG implementation into construction projects. This study was designed to understand and develop guidelines to improve AMG implementation.

Figure 1-1 shows what might be considered as common design rendering and equipment on modern construction projects now, yet the workflow processes to fully benefit from AMG processes is complex. Also, the spectrum of AMG technologies is now wider than ever with advancements in software tools, machine technologies, position equipment and sensors. In the future, AMG has the potential to be integrated well beyond basic earthwork operations. Guidance is needed on how best to advance and benefit from these technologies.



(a) **(b)**

Figure 1-1. AMG Applications involving (a) Three-Dimensional (3D) Design and (b) Application of AMG in Earthwork Grading (images curtesy of Iowa DOT and Caterpillar)

RESEARCH OBJECTIVES AND SCOPE

The project focused on three outcomes:

1. Guide specifications for AMG technology
2. Guidance on the use of such technology in construction projects

3. Strategies for implementing AMG technology into construction projects

Key obstacles that need to be addressed:

- Development and transfer of three-dimensional (3D) electronic files
- General lack of knowledge of the subject matter
- Overcoming legal barriers
- Understanding the impact of AMG technology in terms of both benefits and liabilities

RESEARCH APPROACH

The project team believed it would serve the project well to establish an expert contact group early in the project, so they could seek its advice throughout the project. The expert contact group included a full range of experts such as:

- Earthwork and paving contractors
- Equipment manufacturers and dealers
- Software developers
- State agency representatives
- Academics

Due to the broad and complex nature of the AMG technologies and process, the project research team convened the expert contact group for an intense workshop during the second month of the study. One objective of the workshop was to accomplish an initial review of survey questions planned for distribution to garner national and international feedback on implementation of AMG. The other main objective of the workshop was to develop a list of capabilities that must exist and obstacles that must be overcome to facilitate seamless electronic data transfer—from initial surveying, to the development of digital terrain models (DTMs), through design and construction, to final inspection and verification.

The workshop commenced with a presentation about the objectives of the research project and the workshop, then participants were assigned to one of the following breakout groups.

1. Legal impacts
2. Development of 3D files
3. Accuracy best practices and inputs/outputs
4. Bid item quantity
5. Review of the proposed survey objectives and questions
6. Training information requests

Participants in each group brainstormed lists of challenges and opportunities in their areas. Participants reviewed the breakout session lists and identified other topics, then combined and organized the topics into a list. The participants voted on the priority order of the topics, and a list of the top 10 challenges/opportunities was developed. Discussions in subsequent sessions provided details and synthesized contexts for the top 10 list items (see Table 1-1). Participants also gave feedback about the survey. The complete Workshop Report is included as Appendix A.

Table 1-1. Synthesized and Ranked Priorities – General Session from AMG Stakeholder Workshop

Rank	Topic and Synthesis
1	**Data:** There is a need to improve data management and electronic data exchange formats, such as xml and LandXML. These data exchange formats are not sufficiently robust to be appropriate for wide adoption. Improvement of data exchange procedures between design and construction entities is an opportunity for improvement.
2*	**Training and Education:** Training and education is needed for all types of participants, including agency and contractor professional engineers, designers, and field personnel.
2*	**Standardization:** In general, it would be desirable to modernize specifications. Non-standardized AMG specs among states and the lack of standards for software and hardware are hindering the implementation of AMG. Areas for improvement include better definition of project survey control (set and maintain) and development of standard data feedback loops as bases of payment (quantities) for accurate pay estimates.
4	**Quality/Improvements:** AMG provides opportunities to provide grade checks that cover essentially 100% of the surface. In addition, it is possible to incorporate utilities in models, in their as-built locations, by referencing them before they are covered. Effective model verification will result in better QA/QC. Procedure error and clash detection will result in a better final product. Other possible benefits include increased productivity and improved industry perception and image, due to the use of higher technology solutions. However, to obtain these benefits, it will be necessary to carefully identify the proper technology for each specific implementation.
5	**3D Model:** By conducting initial discussions with stakeholders early in the project using 3D designs, it is easier to obtain understanding and agreement. Performing virtual construction, before actually building, results in improved plans and fewer mistakes. Errors become readily apparent during a 3D video fly-through. Designers can visualize subgrades and find utility conflicts. An opportunity for this group is to coordinate with the Associated General Contractors Build Information Modeling (AGC/BIM) group that is working on horizontal construction. Software developers have already started developing a horizontal construction version of BIM.
6	**Benchmark Case Studies:** There is an opportunity to develop a set of case studies that demonstrate the use of AMG through the design and construction process. Contracting authorities and others may be more willing to adopt and encourage the use of AMG after they have read the case studies.
7	**Legal Challenges:** Requiring licensed surveyors or engineers to perform the conversion of 3D models into machine control files could delay the adoption of AMG technology. The question exists about who is responsible for the design, if plans are stamped twice by two different people: the original designer and/or the person who was responsible for the conversion. Another question is, “What becomes of the legal record of the design?” Can a 3D model be part of the contract documents? Is it possible to make electronic plans the legal document that represent the design?
8	**Safety:** Considerable increases in safety are possible, because fewer people are working on the ground around the equipment as they set and reference stakes.
9	**Real-Time Network Support for Virtual Real-Time Network to Work for AMG:** An opportunity for improvement would be to enhance virtual real-time networks so that they can replace base stations for use with AMG applications. Currently, signal latency issues compromise the accuracy to such an application.
10	**AMG Applications for Subgrades/Paving/Overlays:** There are some unique challenges and unique opportunities for AMG applications on subgrades, paving, and overlays.

** Equal number of votes*

Building on the knowledge gained from the early workshop outcomes, the research team deployed surveys that targeted private industry and transportation agencies. More than 5,000 survey respondents were solicited. The results of the survey findings were used to pinpoint industry needs and shortcomings within AMG processes. Legal aspects, specifications, training, accuracy, impacts, and other aspects were studied. The research team also constructed a searchable electronic library of information related to AMG and supporting technologies. The project's bibliography contains more than 370 documents organized into categories and sub-categories.

Because educational and training programs were identified as an especially critical need for stakeholders to maintain productivity and accuracy on AMG projects, this topic was studied in detail by using survey outcomes and collecting information from equipment providers, contractors, and academic intuitions on education and training offerings. An assessment of the findings was used to shows that education and training are provided by various sources; however, no one source provides all the preparation necessary for full AMG implementation.

The research team also worked on understanding and developing best practices for the creation of the electronic 3D models that are central to the success of AMG. To develop best practices, the research team approached this topic from the perspectives of designers, contractors, developers, and those who synthetize the information.

It is common knowledge that earthwork pay items are historically objects of great dispute between agencies and contractors, so the research team focused on studying AMG accuracy and its application to pay quantities. Several technologies were studied in terms of position accuracy. Using the expert contact group, the research team developed a detailed matrix that lists sources and frequencies of errors in the AMG process, and, equally importantly, associated error detection and mitigation strategies.

An earth-berm test bed was set up to capture position data to specifically quantify errors introduced from different terrain modeling methods. Further, field experiments were conducted on three project sites to evaluate Global Navigation Satellite System (GNSS) technologies mounted on roller compactors in terms of position reproducibility and repeatability. The experiments demonstrated the use of a proposed statistical analysis method to quantify machine-level measurement errors for different ground conditions, machines, and operational parameters. Because AMG covers a wide range of equipment and applications, a matrix of similar proposed field studies was developed.

The technology behind AMG can exist in "information silos" within different user functional areas, so the research team studied and developed detailed workflow process diagrams. The workflow diagrams were based on survey information, contractor and agency interviews, bibliographic content, and studies of product information. Although the workflows were developed during the later stages of the research effort, they are presented at the beginning of this report to establish a baseline for the reader. Near the end of this report, the results of a specification review and synthesis are presented. The research team relied upon the information obtained from the literature and specification reviews, the surveys, and the expert contact group workshop. Results were used to create guide specification tool.

Finally, a discussion of the future of AMG was developed by identifying the various workflow process and technologies used in AMG and overall needs for advancement discussed in this report.

REPORT ORGANIZATION

This rest of this report is organized into eleven chapters. Chapter 2 describes the basic processes of AMG in terms of the surveying process and the overall AMG design to site-level construction workflow. These narratives and flow diagrams provide a condensed explanation of the full AMG process.

Chapter 3 describes the literature review and bibliographic library of information sources related to AMG and establishes an updated AMG lexicon. The project's bibliography contains more than 370 documents.

Chapter 4 describes the results of a detailed survey that garnered information from key AMG stakeholders worldwide.

Chapter 5 presents the findings of a study of legal matters that may hamper the implementation of AMG processes, either by state transportation agencies or contractors, including electronic file use disclaimers, organized labor issues, and state statutes. Results were categorized into two areas (1) owner/agency reluctance to share electronic data design (EDD) with contractors and (2) definitions of functional roles with regard to 3D project delivery.

Chapter 6 lists and describes various AMG training programs and resources. Several on-line sources are referenced including university level and manufacturer level training. No one source provides all the training necessary for AMG.

Chapter 7 describes best practices for the development of design models and emphasizes that good modeling demands communication, training, teamwork, and patience.

Chapter 8 describes the impact of AMG on earthwork quantity estimates, which historically has been a source of great dispute between agencies and contractors. Information suggests that AMG will likely result in less confusion and more accuracy than traditional methods of earthwork payment.

Chapter 9 focuses on numerous factors that influence the accuracy of AMG processes.

Chapter 10 summarizes national specifications used for different AMG phases and provides a guide specification tool with basic language that represents the state-of-practice.

Chapter 11 discusses a range of topics with a focus on exciting future possibilities for AMG application in transportation construction.

Chapter 12 summarizes key outcomes from this study and describes future development and research opportunities. Several supporting reports and documents are included as appendices.

A list of abbreviations, acronyms, initialisms, and symbols is provided following the references list at the end of the report. Four appendices (A through D), not published herein but available on the Transportation Research Board (TRB) website by searching for *NCHRP Web-Only Document 250* (NCHRP Project 10-77), provide further elaboration on the research.