



## Quantitative Cost-Benefit Analyses of the Use of Automated Machine Guidance in Construction: An Examination of Current Practice

*Requested by*  
Ken Darby, Caltrans Division of Construction

September 15, 2015

*The Caltrans Division of Research, Innovation and System Information (DRISI) receives and evaluates numerous research problem statements for funding every year. DRISI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field. The contents of this document reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the California Department of Transportation, the State of California, or the Federal Highway Administration. This document does not constitute a standard, specification, or regulation. No part of this publication should be construed as an endorsement for a commercial product, manufacturer, contractor, or consultant. Any trade names or photos of commercial products appearing in this publication are for clarity only.*

### Table of Contents

<b>Executive Summary</b> .....	<b>2</b>
Background .....	2
Summary of Findings.....	2
Gaps in Findings.....	4
Next Steps .....	4
<b>Detailed Findings</b> .....	<b>5</b>
National Research .....	5
State Research .....	8
Related Publications .....	13
<b>Contacts</b> .....	<b>15</b>
<b>Appendix A: White Presentation on Automated Machine Guidance</b> .....	<b>16</b>

# Executive Summary

## **Background**

Caltrans' Division of Construction recently initiated implementation of automated machine guidance (AMG) technology in construction projects in accordance with Construction Procedure Directive CPD 13-10 (see <http://www.dot.ca.gov/hq/construc/CPDirectives/cpd13-10.pdf>). The directive describes AMG in this way:

AMG uses positioning devices, singly or in combination, such as global positioning systems (GPS), global navigation satellite systems (GNSS), total stations, and rotating laser levels to display the three-dimensional (3D) location of the working surface onboard the operated equipment. The equipment operator observes both the real-time 3D position of the equipment and a 3D DDM [digital design model], stored by the onboard computer, representing the planned design surface. The operator controls the equipment to perform grading or paving operations using multiple perspectives and comparison graphics to shape the constructed surface to match the planned design surface.

Under the directive, a contractor's use of AMG is optional. Use of AMG is considered most appropriate for projects with major earthmoving or paving operations.

While Caltrans recognizes that there are benefits to using AMG technology, the limited availability of quantified cost and benefit data can hamper the agency's ability to make the most cost-effective use of the new technology. Caltrans is interested in learning more about quantitative analysis tools or other efforts employed by state departments of transportation (DOTs) to examine the costs and benefits of the use of AMG.

To support this effort, CTC & Associates reviewed published and in-progress research to identify publications or projects that address cost-benefit analyses of AMG from the perspective of the state DOT. To supplement the literature review, CTC contacted representatives from a select group of state DOTs, national transportation organizations and universities considered likely to have information relevant to this topic.

## **Summary of Findings**

We sought information about cost-benefit analyses of the use of AMG in the construction of transportation projects using a literature search and contacts made to representatives from within the transportation community. As the findings below indicate, we did not identify a comprehensive, quantitative method or tool that can be used by state DOTs to measure the costs and benefits of the use of AMG. We did locate publications that describe, in general terms, savings reported by state DOTs using AMG, and publications that present savings associated with contractors' use of AMG. The latter set of publications may be helpful when developing a protocol to assess the costs and benefits of AMG from the perspective of a state DOT.

## **National Research**

### **Research in Progress**

The most significant finding in our examination of national research is a National Cooperative Highway Research Program (NCHRP) project in process—NCHRP Project 10-77, Use of Automated Machine Guidance (AMG) within the Transportation Industry. The draft final report

for this project was under review at the time of publication of this Preliminary Investigation. Publications produced in advance of the final report offer preliminary information about what will be addressed in the final report, including potential productivity gains and cost savings from the perspective of the vendor or contractor. The final report is also expected to address how the use of AMG for earthwork operations can aid in determining a more predictable amount of material needed on construction projects. The NCHRP Senior Program Officer overseeing the project has indicated that the final report will not include a comprehensive cost-benefit analysis from the perspective of a state DOT.

### Completed Projects

A 2007 NCHRP report offers estimated resource savings associated with the use of global positioning systems (GPS) for layout, machine guidance and quantity tracking. These savings are associated with the contractor's use of AMG, not savings realized by the state transportation agency.

### **State Research**

The publications highlighted in this section describe state DOT-sponsored investigations into the use of AMG for construction projects. Included are documents produced for DOTs in Florida, Indiana, Kansas, Minnesota, Mississippi, New York and Oregon. While many of these documents cite other studies or projects that describe AMG-related savings reported by the contractor or vendor, a few publications describe savings realized by the state transportation agency owner of the construction project. Examples include:

- Quantified savings in the overbuild pavement required for a Florida DOT lane widening project (a reduction of more than two-thirds in tons of asphalt needed, which translated to savings of more than \$350,000).
- Productivity gains identified in connection with eight New York State DOT projects completed during the summer of 2007.
- A savings of 20 to 30 percent on earthwork costs and time reported by Mississippi DOT.

Publications produced for Kansas and Minnesota DOTs identify the challenges associated with quantifying the benefits of AMG.

- A 2012 TRB annual meeting paper describing Kansas DOT's evaluation of GPS construction processes noted that "it was difficult to evaluate for the STA [state transportation agency] if the additional time necessary during the design process was offset by the benefits of GPS machine controlled grading."
- A 2007 MnDOT report that described efforts to develop a benefit/cost ratio for the use of AMG concluded that such an analysis was not possible at the time given the lack of data, project differences, and difficulties in associating benefits and costs with the appropriate stakeholder group.

Finally, a research project proposed by Oregon DOT's Geometronics Unit sought to develop a productivity model to assess the impact of AMG in construction. While this proposal has not been selected for funding by ODOT, the researcher proposing the project is interested in further developing the idea for other interested agencies.

## **Related Publications**

This section of the report includes two somewhat dated case studies that are cited in other, more recent publications addressing the costs and benefits of the use of AMG. Like most of what we found in our investigation, these case studies examine costs and benefits from the perspective of a contractor or vendor. This section also includes a presentation often cited in the literature that describes estimated savings, from a contractor's perspective, associated with the use of GPS technologies for machine control in construction projects.

## **Gaps in Findings**

Most of the analyses of productivity gains, reduced costs and other benefits of the use of AMG for the construction of transportation projects have been conducted by or from the perspective of the contractor or vendor. We found no evidence of quantitative cost-benefit analyses conducted from the perspective of the state DOT overseeing a construction project, and no formal processes reported by state DOTs to conduct these analyses as part of a broader effort to identify the projects most likely to produce savings from the application of AMG in the construction effort.

The final report for NCHRP Project 10-77, now in a draft version and under review, will not include a comprehensive cost-benefit analysis from the perspective of a state DOT. As the NCHRP Senior Program Officer overseeing the project indicated, more projects that use AMG must be conducted to permit generation of the data needed to identify a return on investment for state DOTs.

We were unable to connect with representatives of NYSDOT to gather additional information about documents or experiences referenced in this Preliminary Investigation. These include a December 2006 conference presentation that provided estimated savings associated with earthwork when using machine guidance systems, and an analysis of the impact of the use of AMG for a limited set of NYSDOT projects constructed during the summer of 2007.

## **Next Steps**

Moving forward, Caltrans could consider:

- Reviewing the final report for NCHRP Project 10-77 when it becomes available. While the final report will not include a comprehensive cost-benefit analysis that focuses on state DOT impacts, it is expected to address how the use of AMG for earthwork operations can aid in determining a more predictable amount of material needed on construction projects.
- Consulting with the Oregon State University researcher proposing development of a productivity model for the use of AMG to learn more about the proposed research.
- Following up with NYSDOT to determine if the agency has conducted recent analyses of the use of AMG.
- Following up with Mississippi DOT to learn more about an analysis that identified the AMG-related cost savings noted in a 2012 AASHTO publication.

## Detailed Findings

### National Research

We highlight below a National Cooperative Highway Research Program (NCHRP) project in process for which the draft final report is under review, and a 2007 NCHRP report that addresses resource savings associated with the use of AMG from the contractor's perspective.

#### Research in Progress

**“Use of Automated Machine Guidance (AMG) within the Transportation Industry,”** NCHRP Project 10-77. Expected completion date February 20, 2015; contractor's draft final report is currently under review.

<http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2504>

Excerpt from the project description:

The objective of this research is to develop guidelines for use of AMG technology for state transportation agency construction projects. The guidelines should (1) include technical procurement specifications for AMG technology; (2) provide guidance on the use of such technology in construction projects; and (3) address the implementation of AMG technology into construction techniques (including the provision of electronic files and models to support the AMG process).

---

#### Supplementary Information

We spoke with David Reynaud, the NCHRP Senior Program Officer overseeing NCHRP Project 10-77, about the scope of the project. Reynaud indicated that the project's final report, now in draft form and under review by the project panel, will not include a comprehensive cost-benefit analysis from the perspective of the state DOT. Reynaud expects such analyses will not be available for some time, perhaps five years or more. More agencies must utilize the technology, and for a longer period of time, to develop the data from which a transportation agency can calculate a return on its investment. The final report is expected to address how the use of AMG for earthwork operations can decrease the amount of material overage identified using traditional methods.

Contact: David Reynaud, Senior Program Officer, NCHRP, 202-334-1695,  
[dreynaud@nas.edu](mailto:dreynaud@nas.edu).

---

Related Resources:

**“Impacts of Automated Machine Guidance (AMG) on Earthwork Operations,”** David J. White and Pavana Vennapusa, *2013 Mid-Continent Transportation Research Symposium*, August 2013.

[http://www.intrans.iastate.edu/events/midcon2013/abstracts/uploads/Impacts-of-Automated-Machine-Guidance-\(AMG\)-on-Earthwork-Operations\\_03152013.pdf](http://www.intrans.iastate.edu/events/midcon2013/abstracts/uploads/Impacts-of-Automated-Machine-Guidance-(AMG)-on-Earthwork-Operations_03152013.pdf)

From the abstract:

The equipment vendors indicated potential productivity gains of around 40% and potential cost savings of about 25 to 40% using AMG. On the other hand, a majority of the contractors indicated potential productivity gains of about 10 to 25% and cost savings of about 10 to 25% using AMG. The literature suggests productivity gains range from about 5 to 265% and cost savings range 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 presentation that relates productivity gain from AMG to cost savings.

**“Impacts of Automated Machine Guidance (AMG) on Earthwork Operations,”** David J. White and Pavana Vennapusa, Center for Earthworks Engineering Research, Iowa State University, *2013 Mid-Continent Transportation Research Symposium*, August 15, 2013. See [Appendix A](#).

This is the presentation described in the abstract above. The presentation provides highlights of eight surveys conducted in connection with NCHRP Project 10-77. Survey results show productivity gains (see slide 22) and cost savings (see slide 23) associated with the use of AMG. Both slides reflect savings from the perspective of contractors and vendors.

## **Completed Projects**

**NCHRP Synthesis 372: Emerging Technologies for Construction Delivery**, John J. Hannon, 2007.

[http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp\\_syn\\_372.pdf](http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_372.pdf)

One of the five emerging technologies examined in this synthesis is the use of global positioning systems (GPS) for layout, machine guidance and quantity tracking. Table 3 on page 17 of the report (page 26 of the PDF) quantifies resource savings associated with the use of GPS; this table is reproduced below.

<b>Quantified GPS Resource Savings</b>		
<b>GPS Technology</b>	<b>Compared With</b>	<b>Estimated Savings</b>
<b>Grade checking</b>	Manual method	Up to 66% time savings
<b>Reduction or elimination of stakes</b>	Conventional staking	Up to 85% time savings
<b>Improved material yields/select fills/undercutting</b>	Overruns using manual methods	3% to 6% by volume
<b>Uninterrupted earthmoving production—all weather continuous shifts (including night work)</b>	Day shifts, nonprecipitous weather	30% to 50% time savings
<b>RTK (robotics stakeout)</b>	Traditional survey stakeout	More than 100% in speed and 66% in staffing (labor count)

RTK = real-time kinetic.

The source of the information contained in this table does not appear to be correctly identified in the body of the NCHRP report. We have, however, noted that the data in this table appears in other publications cited in this Preliminary Investigation, including a 2005 presentation by Alsobrooks and Townes at the Southeastern Asphalt User/Producer Group (SEAUPG) Annual Meeting (see page 13 of this Preliminary Investigation for the citation). It appears that the SEAUPG presentation, or similar versions of this presentation presented at AASHTO meetings, is the source of the data in the table above.

While the 2005 SEAUPG presentation does not indicate where this data originated, another publication cited in this Preliminary Investigation indicates that this data represents “gains presented from experience of one Tennessee contractor over numerous projects.” (See page 41 of the Indiana DOT report *Practices for Seamless Transmission of Design Data from Design Phase to Construction Equipment Operation – A Synthesis Study*. A citation for this report appears on page 9 of this Preliminary Investigation.)

## State Research

The publications highlighted below describe state DOT-sponsored investigations into the use of AMG in construction projects. They were produced for DOTs in Florida, Indiana, Kansas, Minnesota, Mississippi, New York and Oregon.

### Florida

**Automated Machine Guidance with Use of 3D Models: Case Study—The Use of Automated Machine Guidance on the Florida SR 417 Lane Widening Project**, Federal Highway Administration (FHWA) TechBrief, Spring 2014.

<http://www.fhwa.dot.gov/construction/3d/amg/pubs/hif13055.pdf>

This case study describes a Florida DOT lane widening project that involved a large number of milling control points and problematic transitions that were expected to present challenges for the contractor. FDOT's design-build contract was altered to allow for the use of AMG when it was determined that overbuild could be reduced by nearly half with the use of AMG. Page 5 of the case study describes the "measured benefits" that arose from using AMG to complete the lane widening project, including:

- Most asphalt was placed in uniform lifts, and the overbuild pavement required was significantly reduced from an anticipated 8,200 tons to 2,500 tons, translating to a savings of more than \$350,000.
- Where overbuild was needed, it was installed as a separate operation and the paver was equipped with AMG, which allowed the structural course to be placed with consistent lift thicknesses.
- The use of models allowed the paving operations to work the length of the project in a circuit, saving time and reducing the number of lane closures required.
- Paving operations were completed in fewer overall shifts, decreasing overhead and inspection costs. It is possible that expenses for the contractor were incurred due to increased survey support and reduced production. The costs may have been mitigated somewhat by the near elimination of correction work.

Related Resource:

**"Integrating 3D Design into Construction for Automated Machine Guidance,"** Ben Brown, *FDOT Design Training Expo*, June 2013.

<http://www.dot.state.fl.us/officeofdesign/training/DesignExpo/2013/Presentations/BrownBen-Integrating%203D%20Design%20Into%20Construction%20for%20Automated%20Machine%20Guidance.pdf>

This presentation provides the contractor's assessment of the FDOT project addressed in the case study above. Benefits of the use of AMG for the project are summarized on slide 34.

## Indiana

**Practices for Seamless Transmission of Design Data from Design Phase to Construction Equipment Operation – A Synthesis Study**, Phillip Dunston and James Monty, Indiana Department of Transportation, May 2009.

<http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2672&context=jtrp>

Researchers considered costs and savings as part of their examination of the state of the technology and the experiences of other state DOTs with using 3D machine control systems for construction projects. See page 39 of the report (page 46 of the PDF) for Section 5.3.2.4, “Savings and Costs of Utilizing 3D-MC and Providing EDFs,” which addresses both contractor and DOT costs and savings.

Also included in this report (see page 79 of the report; page 86 of the PDF) is a discussion of cost savings associated with the use of AMG reported by NYSDOT in connection with eight projects completed during the summer of 2007. In a 2008 interview with NYSDOT that addressed those eight projects, the interviewee identified “[m]ajor increases in productivity by as much as 40-50% noted primarily for the placement, grading and removal of granular materials.”

## Kansas

**“KDOT’s Evaluation of Sharing Electronic Data with Contractors and GPS Construction Processes,”** Kelly Hovey and Howard Lubliner, *TRB 91st Annual Meeting Compendium of Papers DVD*, Paper #12-4323, 2012.

<http://www.efl.fhwa.dot.gov/files/technology/dv/kansas-research-final-paper.pdf>

The authors examined existing state practices and a Kansas DOT pilot project to recommend development of new electronic processes. An examination of the benefits of machine controlled grading begins on page 5 of the paper. An excerpt:

Quantifying the benefits of GPS machine controlled grading was harder to pinpoint. The majority of the benefits were a result of the reduced time required to complete earthwork and reduction in survey support. [According to Dillingham et al. 2007], “Claims of increased efficiency by as much as 50 percent and increase in equipment utilization by as much as 30 percent [had] recently been made.” Another study found a 43 percent fuel savings with the use of GPS. This study compared the speed of construction for GPS machine controlled grading and conventional grading methods by constructing two identical test roadways. The roadway was completed in one-and-a-half days with GPS machine controlled grading and three-and-a-half days with conventional grading methods. It was unclear what portions of the benefits of GPS machine controlled grading were passed on to the STA [state transportation agency], even though the benefits of the technology theoretically included lower bids and higher quality products.

The authors also noted:

Also, it was difficult to evaluate for the STA if the additional time necessary during the design process was offset by the benefits of GPS machine controlled grading.

## **Minnesota**

**Best Practices – Machine Control Evaluation**, John Dillingham, Thomas Jensen and Nick Schulist, Minnesota Department of Transportation, May 15, 2007.

[http://aii.transportation.org/Documents/BestPractices-MachineControlEvaluation\\_FinalReport\(MnDOT\).pdf](http://aii.transportation.org/Documents/BestPractices-MachineControlEvaluation_FinalReport(MnDOT).pdf)

This project sought to evaluate MnDOT's machine control program and develop recommendations for advancing the use of the technology throughout Minnesota. Researchers' evaluation of the existing program began with an assessment of the benefits of implementing machine control technology. Discussion of a benefit/cost ratio begins on page 9 of the report (page 21 of the PDF). The authors note that this analysis could not be completed for the following reasons:

- Existing data was not available for performing a benefit/cost ratio calculation. Internal data was not readily available, and the authors note that while grading contractors could also provide such information, "contractors are unwilling to share this information in public forums for fear of disclosing sensitive information to their competitors."
- The factors involved in a benefit/cost ratio are difficult to assign to one particular stakeholder group. In some instances, MnDOT incurs a larger share of the additional labor costs, while the contractor realizes a bigger share of the benefits. Due to the inequities in sharing the benefits and burdens, the ratio would not be relevant to each individual stakeholder group. A more useful benefit/cost quotient is one that includes only the benefits and costs associated with each stakeholder group.
- No two projects are the same. The best comparison of the technology would be to complete two nearly identical projects, one with machine control technology and one without.

While quantitative data was not available to calculate a benefit/cost ratio, the authors did provide a qualitative assessment, noting that subjective data indicates that most of the benefits of machine control technology can be attributed to the reduction in time required to complete earthmoving tasks on a project. The authors highlight claims made by others of increases in efficiency of as much as 50 percent and increases in equipment utilization of as much as 30 percent. The authors also include the savings data that appears in Table 3 of *NCHRP Synthesis 372* and in other publications cited in this Preliminary Investigation.

---

### **Supplementary Information**

We corresponded with Rebecca Embacher, Advanced Materials and Technology Engineer at MnDOT, to inquire about further efforts within the agency to quantify the impact of the use of AMG. Embacher indicated that MnDOT has not conducted a quantitative analysis to assess the costs and benefits of the use of AMG in construction projects.

Contact: Rebecca Embacher, Advanced Materials and Technology Engineer, Office of Materials & Road Research, Minnesota Department of Transportation, 651-366-5525, [rebecca.embacher@state.mn.us](mailto:rebecca.embacher@state.mn.us).

---

## **Mississippi**

**MDOT Implementation Plan for GPS Technology in Planning, Design, and Construction Delivery**, FHWA and Mississippi Department of Transportation, September 13, 2010.

<http://mdot.ms.gov/documents/research/Reports/Interim%20and%20Final%20Reports/State%20Study%20214%20->

[MDOT%20Implementation%20Plan%20for%20Global%20Positioning%20Systems%20\(GPS\)%20Technology%20in%20Planning,%20Design,%20and%20Construc.pdf](http://mdot.ms.gov/documents/research/Reports/Interim%20and%20Final%20Reports/State%20Study%20214%20-MDOT%20Implementation%20Plan%20for%20Global%20Positioning%20Systems%20(GPS)%20Technology%20in%20Planning,%20Design,%20and%20Construc.pdf)

This report suggests a plan for implementation of GPS technology within Mississippi DOT. The report identifies the broad benefits of using GPS technology as compared to conventional survey methods.

Related Resource:

**Research Impacts: Better—Faster—Cheaper**, AASHTO Standing Committee on Research, July 2012.

<http://research.transportation.org/Documents/Task%20Forces/Value%20of%20Research%20Task%20Force/000high-value-research-final.pdf>

The project described in the Mississippi DOT report cited above is included in this AASHTO report as one of AASHTO's "Sweet Sixteen" projects for 2012. Quantified impacts of the Mississippi DOT project are summarized on page 147 of the report:

AMG is being implemented at MsDOT on certain projects. A recent presentation at MsDOT's Construction Conference by Project Engineer Jordan Whittington revealed that AMG saved approximately 20-30 percent on earthwork costs and time and achieved greater accuracy and efficiency. MSDOT is moving toward 3D design model delivery.

## **New York**

**"Business Advantages of Using Electronic Engineering Data,"** Dan Streett, New York State Department of Transportation, *AGC/DOT Technical Conference*, December 5, 2006.

<http://aii.transportation.org/Documents/AMG/AGC120506ElectronicEngineeringData.pdf>

Slide 10 of this presentation highlights the estimated savings associated with earthwork when using machine guidance systems:

- 50 percent savings on equipment—less use and field adjustments.
- 80 percent savings on survey—little or no roadway stakeout.
- 75 percent savings on labor—less hand work and field adjustments.
- 4 to 6 percent savings on material overruns.
- Potential 5 to 10 percent savings on dirt items.

## **Oregon**

**"Productivity Model for Automated Machine Guidance in Road Construction,"** Hyun Woo "Chris" Lee and Ron Singh, FY 2015 Research Problem Statement, Oregon Department of Transportation.

[http://www.oregon.gov/ODOT/TD/TP\\_RES/docs/stage1/2015stageone/15-019\\_AutomatedMachineGuidanceRoadConstruction.pdf](http://www.oregon.gov/ODOT/TD/TP_RES/docs/stage1/2015stageone/15-019_AutomatedMachineGuidanceRoadConstruction.pdf)

From the research proposal:

This research proposes a comprehensive productivity study comparing road construction operations that use AMG to those that don't. The comparison will be based on bid items selected from ODOT's Bid Item List. The research would identify, evaluate, and determine a list of governing factors ("productivity drivers") that lead to productivity differences between AMG-implemented projects versus conventional projects. The main tasks in the proposed research will be:

1. Identify and review the literature that investigated the impact of AMG on productivity.
2. Identify an ODOT project(s) where AMG is (or was) implemented for a number of bid items.
3. Perform a comprehensive productivity study of the selected bid items.
4. Identify productivity drivers (for each bid item, or for combined bid items).
5. Perform a statistical analysis to compare the findings to the same bid items of projects that were delivered without AMG.
6. Develop a productivity model based on the productivity drivers and statistical analysis.
7. Document the findings and prepare a guideline for the model.

---

### **Supplementary Information**

To learn more about this research proposal's status, we contacted Ron Singh of Oregon DOT, the project's champion, and Dr. Chris Lee, the researcher submitting the proposal.

Singh indicated that while ODOT has used AMG for some time, to date the agency has not conducted a cost analysis. Contractor cost savings have been identified anecdotally, with lower bids coming in from contractors using AMG. Singh noted that, in addition to identifying cost savings, ODOT is also interested in quantifying the impact of the use of AMG on the quality of construction projects.

The ODOT research proposal originated with Lee, who confirmed that the proposal has not been selected for funding by ODOT. Lee is interested in submitting the proposal to other state DOTs or further developing the idea for any interested agencies, but has not yet done so. Lee is unaware of any other agencies undertaking a productivity analysis similar to the one he has proposed.

Contacts:

- Ron Singh, Chief of Surveys/Geometronics Manager, Geometronics Unit, Oregon Department of Transportation, 503-986-3033, [ranvir.singh@odot.state.or.us](mailto:ranvir.singh@odot.state.or.us).
- Dr. H.W. Chris Lee, Assistant Professor, School of Civil & Construction Engineering, Oregon State University, 541-737-8539, [HW.Chris.Lee@oregonstate.edu](mailto:HW.Chris.Lee@oregonstate.edu).

## Related Publications

Below we highlight two somewhat dated case studies that are cited in many more recent publications that address the costs and benefits of AMG use. The last entry in this section is a presentation often cited in the literature that describes estimated savings, from a contractor's perspective, associated with the use of GPS technologies for machine control in construction projects.

**Road Construction Production Study**, Caterpillar, December 2006.

[http://construction.trimble.com/sites/construction.trimble.com/files/marketing\\_material/white%20paper%20-%20CAT%20Road%20Construction%202006.pdf](http://construction.trimble.com/sites/construction.trimble.com/files/marketing_material/white%20paper%20-%20CAT%20Road%20Construction%202006.pdf)

This productivity study was conducted at the Malaga Demonstration and Learning Center in Spain using AccuGrade machine control systems in a comparison of traditional road building with building practices that use AMG.

Researchers built two identical roads. One road was built using manual staking, while the other was built using AMG. The roads were built in the same area using the same materials and machine operators under the same weather conditions. To conduct the comparison, researchers measured the time needed for each operation, the number of passes, buckets or truckloads, and fuel consumption. Results indicate that AMG:

- Lessened construction time (3.5 days for manual staking versus 1.5 days using machine control).
- Increased overall job site productivity by 101 percent.
- Resulted in higher and more consistent accuracy.
- Provided fuel savings of 43 percent.

**“Factors in Productivity and Unit Cost for Advanced Machine Guidance,”** Snaebjorn Jonasson, Phillip S. Dunston, Kamal Ahmed and Jeff Hamilton, *Journal of Construction Engineering and Management*, Vol. 128, Issue 5, pages 367-374, October 2002.

Citation at <http://ascelibrary.org/doi/abs/10.1061/%28ASCE%290733-9364%282002%29128%3A5%28367%29?journalCode=jcemd4>

From the Abstract:

This paper presents an initial step in seeking to understand just how the adoption of advanced machine guidance technology, especially global positioning systems, leads to improvements in performance by the earthwork contractor. Two grading scenarios and one dozing scenario are examined based upon site observations and interviews with field personnel. Analysis demonstrated that productivity and unit cost improvements result from a reduction in surveying support, grade checking, an increase in operational efficiency, and a decrease in the number of passes. These results are in agreement with published results of benefits of 3D guidance over 2D guidance.

**“GPS in Construction,”** Bret Alsobrooks and Douglas Townes, Southeastern Asphalt User/Producer Group (SEAUPG) Annual Conference, December 2005.

[http://www.seaupg.org/PDF/2005/Thursday/GPS\\_dtownes\\_fhwa.pdf](http://www.seaupg.org/PDF/2005/Thursday/GPS_dtownes_fhwa.pdf)

This presentation by Bret Alsobrooks of Jones Bros., Inc., a Tennessee construction firm, and Douglas Townes of FHWA provided a summary of cost savings associated with the use of GPS technology. The table appearing on page 4 of the PDF and reproduced below describes

estimated contractor-related savings from the use of GPS for machine control. This data appears in other publications addressing the savings associated with the use of AMG, including *NCHRP Synthesis 372* (see the table on page 7 of this Preliminary Investigation).

<b>Estimated Savings Associated with the Use of GPS Technology</b>		
<b>GPS Technology</b>	<b>Compared With</b>	<b>Estimated Savings</b>
<b>Grade checking</b>	Manual method	Up to 66%
<b>Reduction or elimination of stakes</b>	Using stakes	Up to 85%
<b>Improved material yields/ select fills/undercutting</b>	Overruns using manual methods	3% to 6% in volume
<b>Uninterrupted earthmoving production under any weather conditions (24/7)</b>	Daytime/fine weather operation only/night work	30% to 50%
<b>RTK, robotics stakeout</b>	Traditional survey stakeout	More than 100% in speed and 66% in staffing

## Contacts

CTC contacted the individuals below to gather information for this investigation.

### **National Transportation Organizations**

David Reynaud  
Senior Program Officer  
NCHRP  
202-334-1695, [dreynaud@nas.edu](mailto:dreynaud@nas.edu)

Douglas Townes  
Construction and Contract Administration Engineer  
FHWA  
404-562-3914, [douglas.townes@dot.gov](mailto:douglas.townes@dot.gov)

### **State Agencies**

#### **Minnesota**

Rebecca Embacher  
Advanced Materials and Technology Engineer  
Office of Materials & Road Research  
Minnesota Department of Transportation  
651-366-5525, [rebecca.embacher@state.mn.us](mailto:rebecca.embacher@state.mn.us)

#### **Oregon**

Ron Singh  
Chief of Surveys/Geometronics Manager  
Geometronics Unit  
Oregon Department of Transportation  
503-986-3033, [ranvir.singh@odot.state.or.us](mailto:ranvir.singh@odot.state.or.us)

### **Researchers**

Dr. H.W. Chris Lee  
Assistant Professor, School of Civil & Construction Engineering  
Oregon State University  
541-737-8539, [HW.Chris.Lee@oregonstate.edu](mailto:HW.Chris.Lee@oregonstate.edu)

David J. White  
Richard L. Handy Professor, Civil, Construction and Environmental Engineering  
Iowa State University  
515-294-1463, [djwhite@iastate.edu](mailto:djwhite@iastate.edu)

# Impacts of Automated Machine Guidance (AMG) on Earthwork Operations

August 15, 2013

*David J. White, Ph.D., P.E.*  
*Pavana Vennapusa, Ph.D.*



# Acknowledgements

- NCHRP 1077
- Iowa DOT
- Wyoming DOT
- Caltrans
- Contractors: McAninch, Peterson Contractors, Kewit, Guntert & Zimmerman, Reilly Construction, Fox Contractors, Corell Contracting, H.B. Rowe & Co, ICPA, Hexagon Measurement Tech, Starr Equipment
- Manufacturers: Caterpillar, Ziegler Inc., GOMACO, Leica Machine Control , Trimble, 3D Surface Solutions, AMW Machine Control, Carlson
- Software: Bentley, Autodesk
- National CP Tech Center
- Iowa State University
- University of Southern Mississippi
- 500+ Survey Participants

# Earthworks









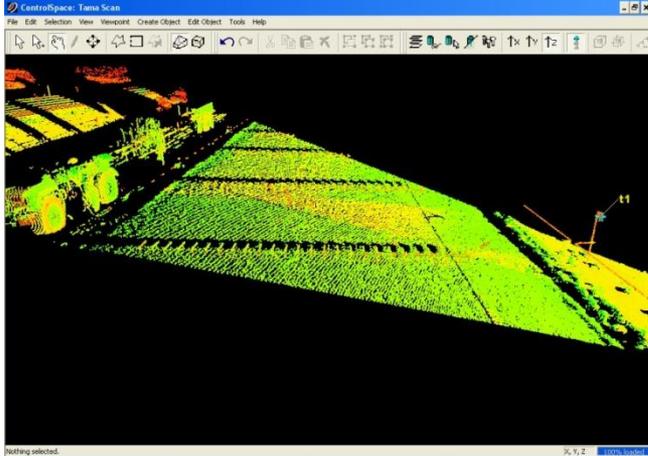
RX-50B

ROADTEC

A859

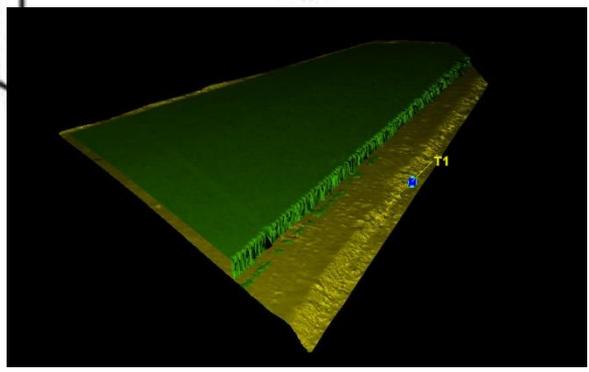
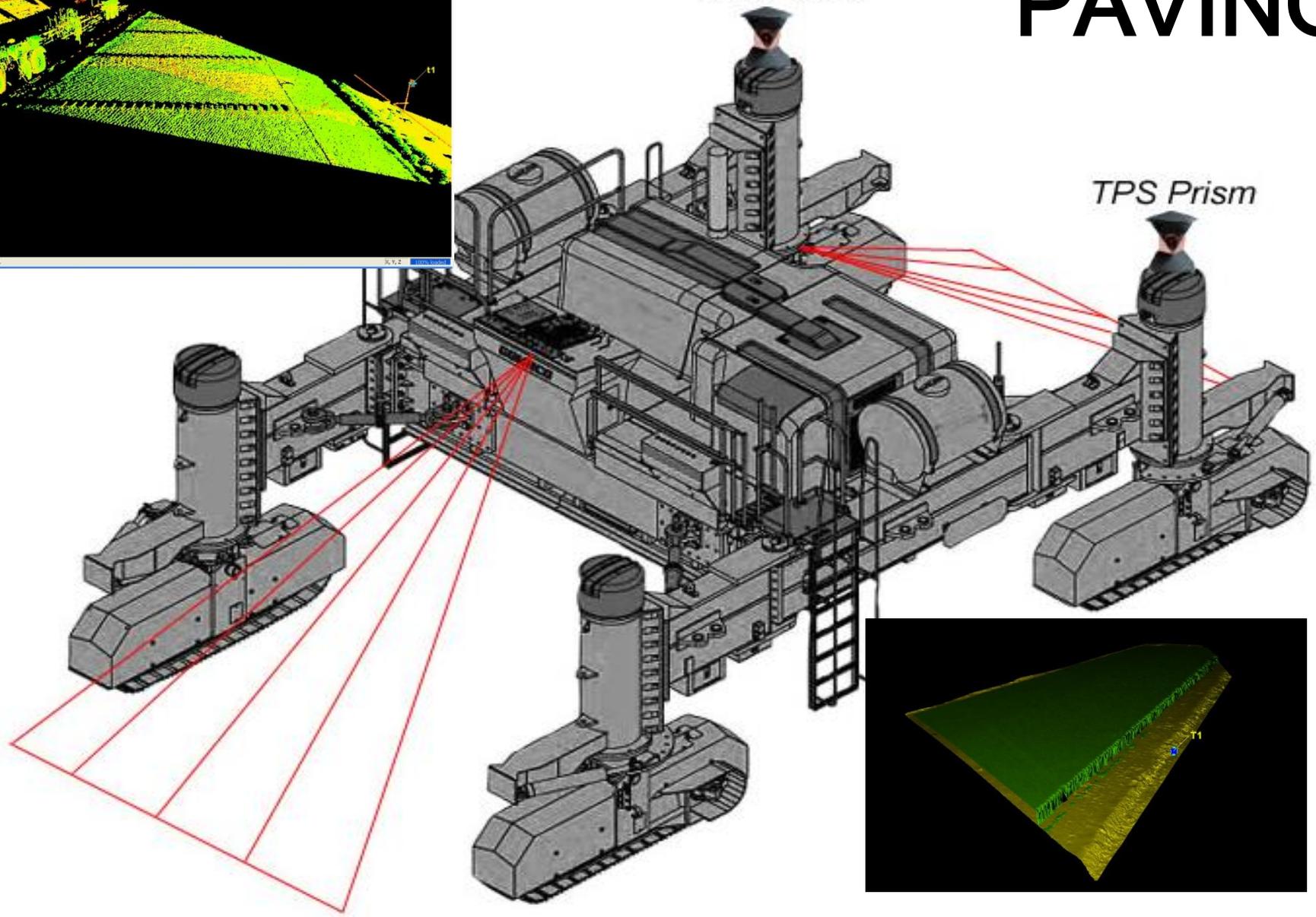
HENNINGSEN





TPS Prism

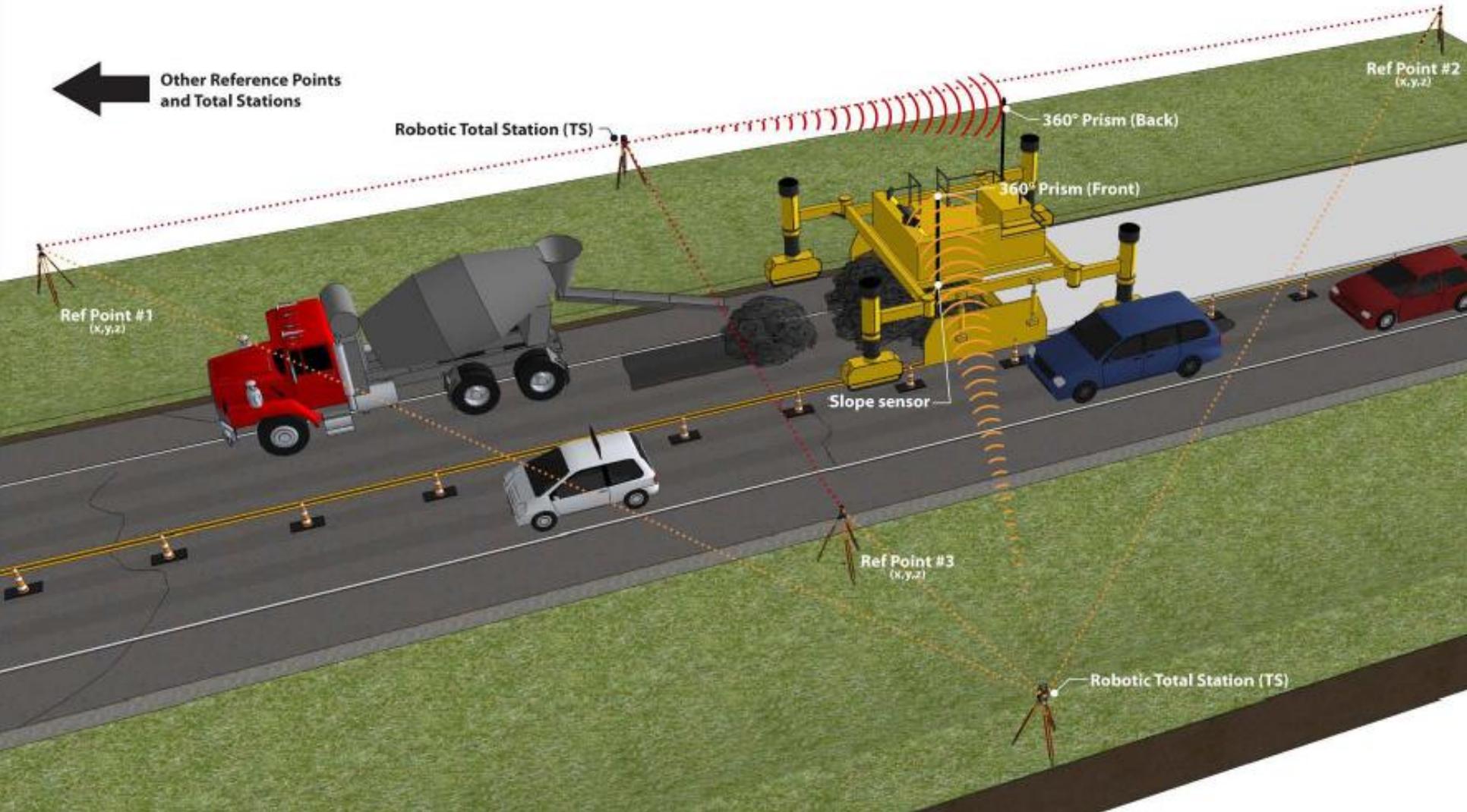
# PAVING



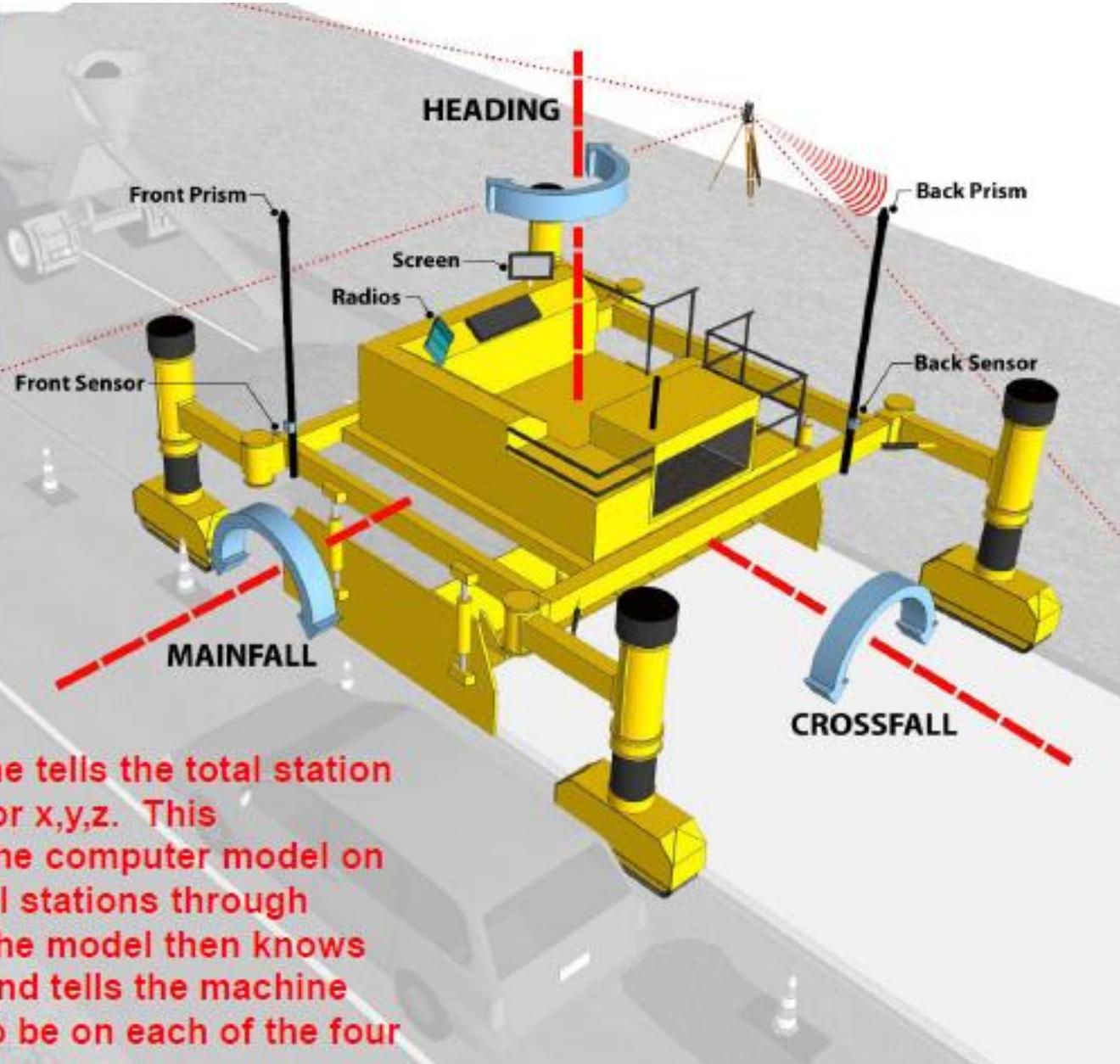
Courtesy of Ed Jaselskis



# Stringless Paving



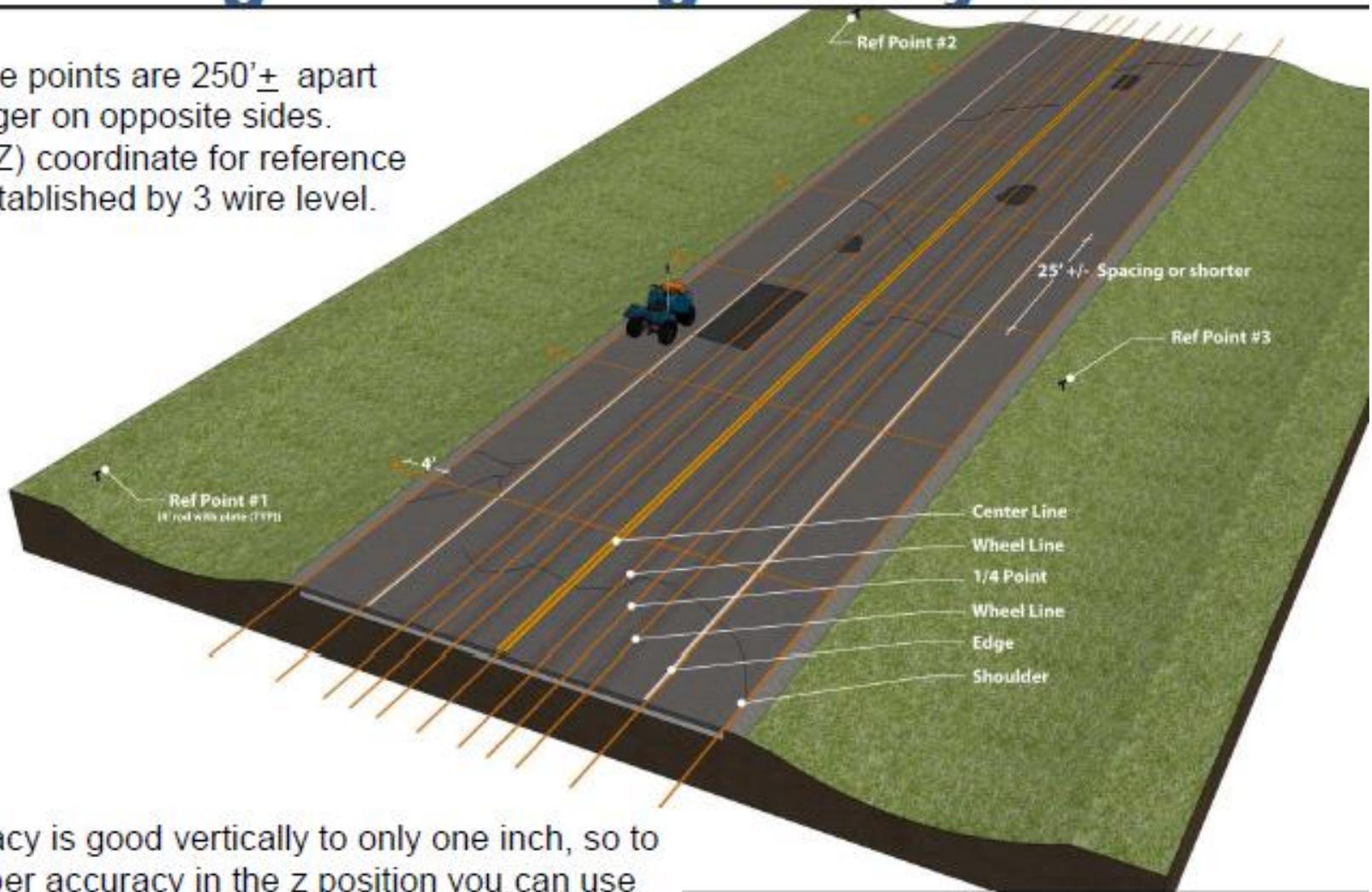




The prisms on the machine tells the total station where the machine is at for x,y,z. This information is related to the computer model on the machine from the total stations through radios on the machine. The model then knows where the machine is at and tells the machine what elevation in needs to be on each of the four corners of the pan.

# Stringless Paving Survey Grid

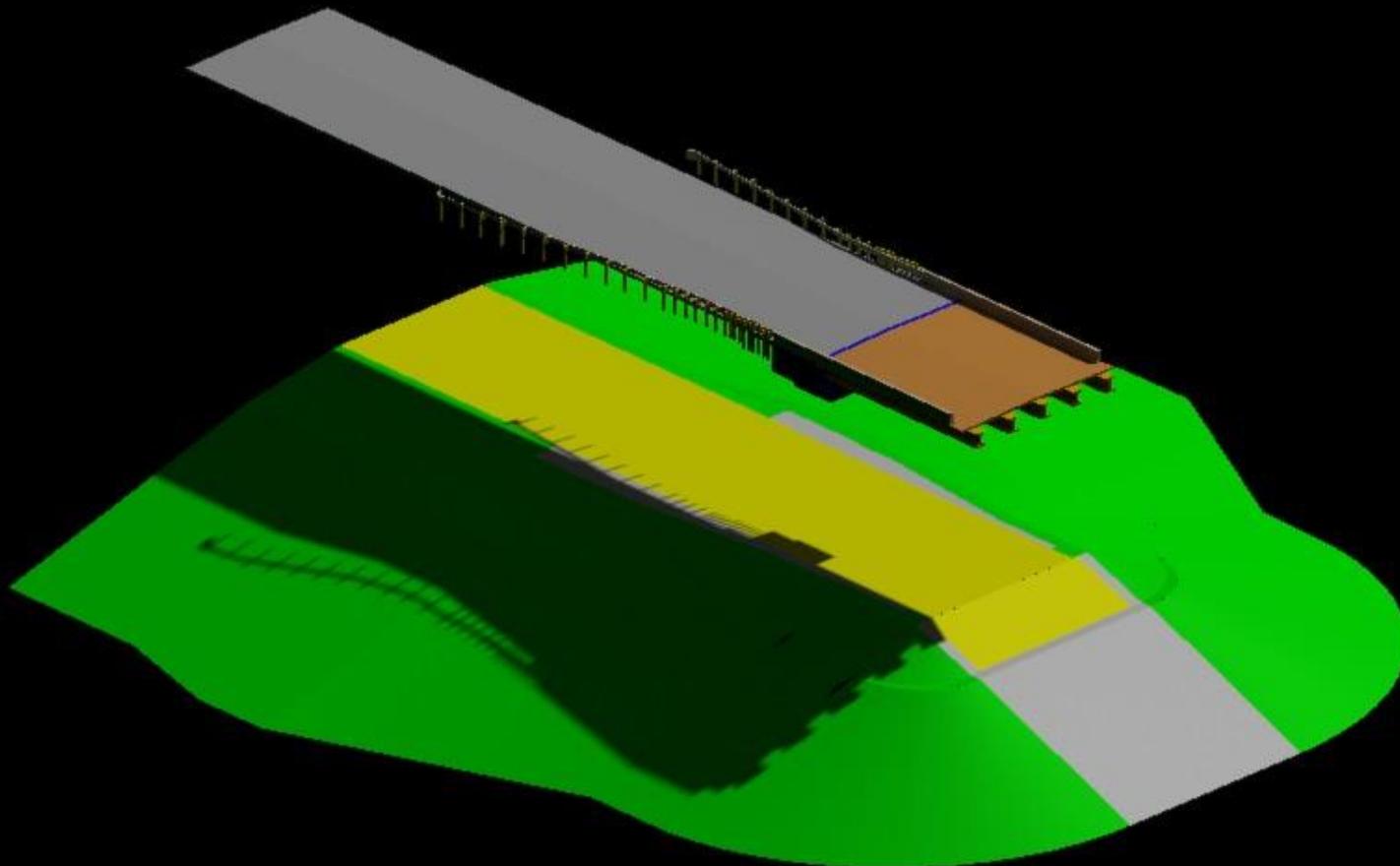
Reference points are 250'± apart and stagger on opposite sides.  
Vertical (Z) coordinate for reference points established by 3 wire level.



GPS accuracy is good vertically to only one inch, so to get the proper accuracy in the z position you can use laser augmentation on the 4 wheeler. An alternate to the 4 wheeler is to shoot the existing pavement with total station.







Courtesy of Iowa DOT

# EERC Survey Questionnaire

EARTHWORKS ENGINEERING RESEARCH CENTRE

## NCHRP 10-77, Use of Automated Machine Guidance (AMG) within the Transportation Industry

The eight questionnaires to the right are a component of NCHRP 10-77, *Use of Automated Machine Guidance (AMG) within the Transportation Industry*. They are designed to gather information about the software and equipment currently used to implement AMG.

You have been asked to provide input for one or more of these questionnaires because of your professional experience with some aspect of AMG technology.

### Instructions

Please complete the questionnaire by Friday, February 26.

Each questionnaire addresses a different set of practitioners who deal with AMG in their professions. Using the links in the table to the right, choose the questionnaire that you believe best reflects your area of professional experience.

The questionnaire will open in a new browser window. Please respond to the questions to the best of your knowledge. You may choose to complete more than one questionnaire.

After you begin the questionnaire, you may save your progress at any time and complete the questions later at your convenience.

Transportation Agencies	Private Industry	Other
<a href="#">Agency Surveying Functions</a> (30-45 minutes)	<a href="#">Construction Contractors</a> (30-45 minutes)	<a href="#">Legal Aspects</a> (30-45 minutes)
<a href="#">Agency Design Functions</a> (30-45 minutes)	<a href="#">Heavy Equipment Suppliers</a> (20 minutes)	<a href="#">Trainers/Educators</a> (15 minutes)
<a href="#">Agency Construction/ Bid/ Contract Functions</a> (30-45 minutes)	<a href="#">Software/ Hardware Vendors</a> (20 minutes)	

### About NCHRP Project 10-77

The goal of NCHRP 10-77, *Use of Automated Machine Guidance (AMG) within the Transportation Industry*, is to develop guidelines for using AMG technology for state transportation agency construction projects. The principal investigator is [David A. Hulse](#), Associate Professor of Civil, Construction, and Environmental Engineering and Director of the [Earthworks Engineering Research Center](#) (EERC) at Iowa State University.

An important component of the project is to conduct a worldwide survey of state transportation agencies, software and equipment vendors, and contractors to determine the types of software and equipment currently being used to implement AMG processes. The survey is designed to cover current drafting and design software capabilities, types of electronic files submitted to contractors (e.g., dgn, dwg, dmf, tin, and LandXML), the times these files are made available to contractors (e.g., pre-bid or post award), and equipment capabilities and reliability. The survey also documents the perceived benefits and liabilities of AMG processes.

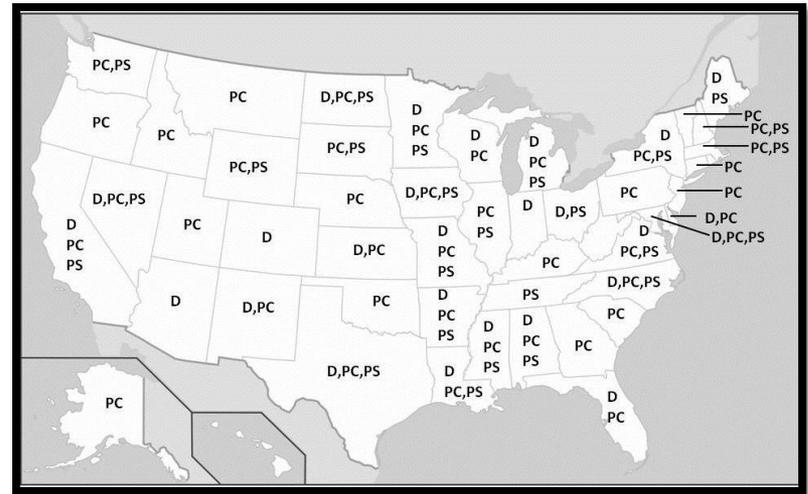
For more information about AMG and NCHRP 10-77, download the 2009 [Report of the Workshop on Automated Machine Guidance \(AMG\) within the Transportation Industry](#) (2.5 mb pdf). The report documents the findings of a 2009 workshop that brought together contractors, equipment and software suppliers, state agencies, and academics to explore issues that must be addressed to facilitate seamless electronic data transfer throughout all phases of a transportation project.



IOWA STATE UNIVERSITY  
Institute for Transportation



# Survey – 500+



D=Design Transportation Agency Survey Questionnaire  
 PS=Planning and Surveying Transportation Agency Survey Questionnaire  
 PC=Procurement and Construction Transportation Agency Survey Questionnaire

## Contractor Survey Respondents by Industry Segment

Answer	Count	Percentage
Prime Contractor-Private Market (A)	18	15%
Prime Contractor-Public Works Market (B)	58	49%
Subcontractor-Private Market (C)	3	3%
Subcontractor-Public Works Market (D)	10	9%
Consultant-Private Market (E)	4	3%
Consultant-Public Works Market (F)	2	2%
Other*	5	4%
No answer	18	15%
Non completed	0	0%

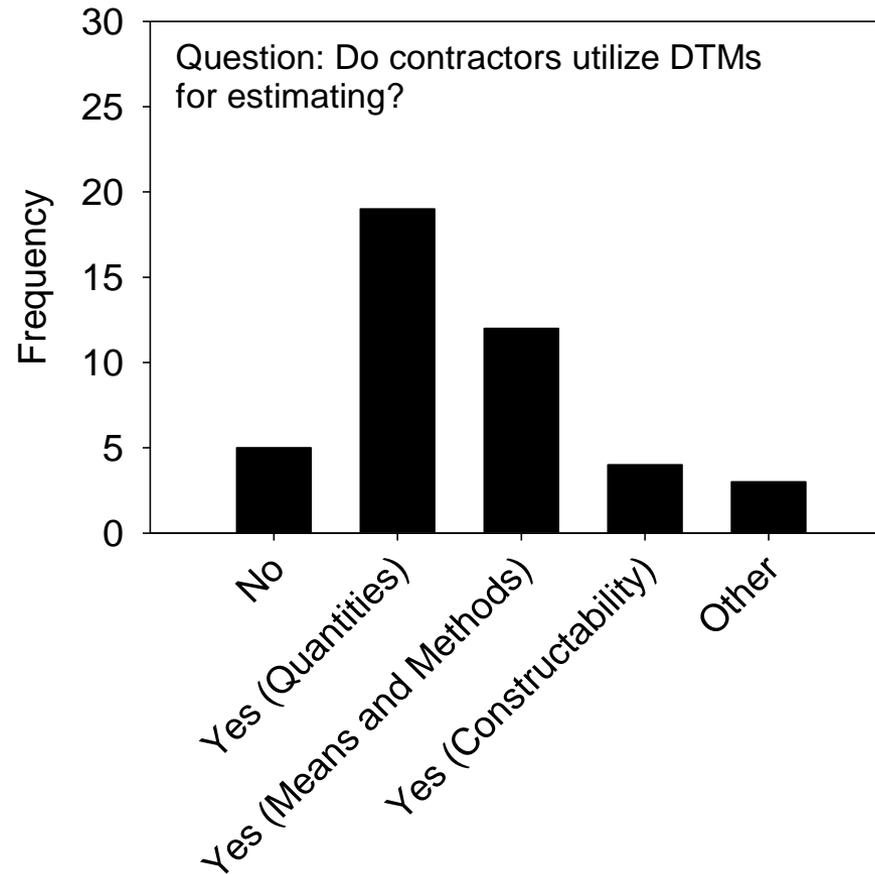
\*Other: Prime - Private & Public, Oil Refinery, General Contractor, Equipment Dealer, DOT.

# A workshop revealed prioritize for research.

Rank	Topic and Synthesis
1	Data
2*	Training and Education
2*	Standardization
4	Quality/Improvements
5	3D Model
6	Benchmark Case Studies
7	Legal Challenges
8	Safety
9	Virtual Real-Time Network to Work for AMG
10	AMG Applications for Subgrades/Paving/Overlays



# Survey responses by contractors indicate broad use of DTMs.



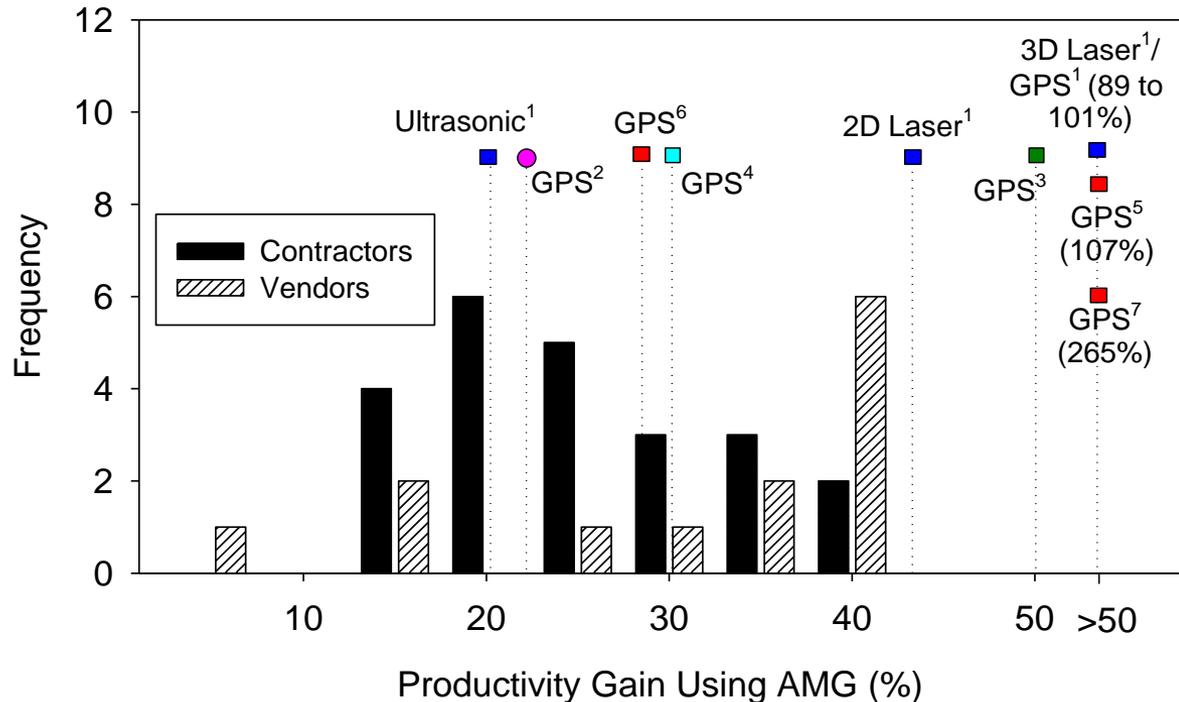
# Survey results identified AMG risk factors.

<b>AMG Risk Factors*</b>	<b>Contractor</b>	<b>Agency P/C</b>	<b>Equip. Vendors</b>
Lack of cooperation by owner-agency inspectors	57%	33%	80%
High initial investment in equipment-lack of Return-On-Investment data	54%	43%	44%
Lack of competent personnel for implementation (internally)	75%	58%	81%
Lack of training required to implement (internally)	64%	74%	69%
Dependence on 3rd-party consultants for DTM creation	41%	42%	69%
Operators may be distracted by looking at monitors in the machine cockpits	11%	N/A	N/A
* Percentage of respondents choosing the factor at the two highest risk levels			

# Survey results quantified AMG benefits.

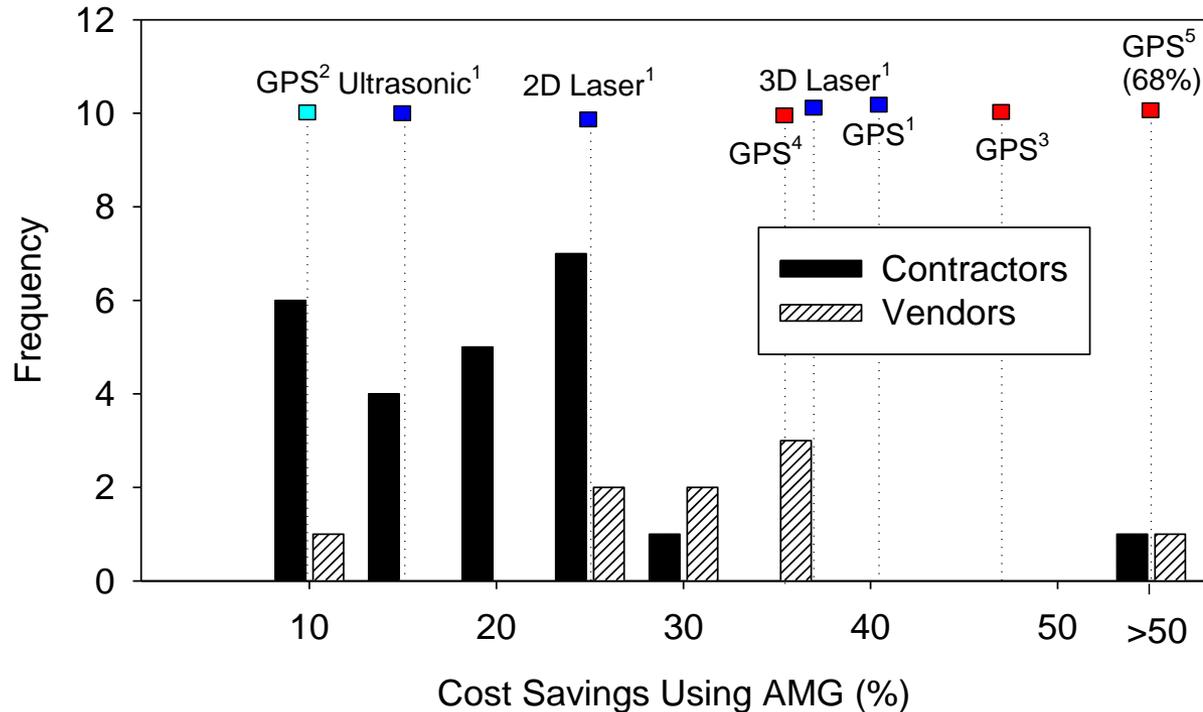
Perceived AMG Benefits*	Contractor	Agency P/C	Equipment Vendors
Labor savings (direct cost on projects)	96%	76%	80%
Environmental-Fuel savings	---	36%	60%
Project schedule compression	86%	57%	93%
Avoidance of re-work (re-grading)	93%	60%	87%
As-built documentation	58%	57%	80%
Ease of constructability review	44%	49%	73%
Jobsite safety	68%	44%	60%
Safety of the traveling public	---	31%	40%
* Percentage of respondents choosing the benefit at the two highest risk levels			

# Survey results show AMG productivity impacts.



- Notes:
- <sup>1</sup>Fine-grading using CAT 140H motor grader (Jonasson et al., 2002)
  - <sup>2</sup>Trench excavation using CAT 330DL hydraulic excavator (Aðalsteinsson, 2008)
  - <sup>3</sup>Earth moving and fine grading (general values; not project specific) (Forrestel, 2007)
  - <sup>4</sup>Earth moving and fine grading project - Port of Brisbane (Higgins, 2009)
  - <sup>5</sup>Bulk earth moving and subgrade fine grading using CAT D6N dozer (gain in the number of passes; Caterpillar, 2006)
  - <sup>6</sup>Bulk earth moving using CAT 330D excavator (Caterpillar, 2006)
  - <sup>7</sup>Base course fine grading using CAT 140H motorgrader (gain the number of passes; Caterpillar, 2006)

# Survey results show cost impacts.



- Notes: <sup>1</sup>Fine-grading using CAT 140H motor grader - Overall unit cost (Jonasson et al., 2002)  
<sup>2</sup>Earth moving and fine grading project - Port of Brisbane (overall cost savings) (Higgins, 2009)  
<sup>3</sup>Bulk earth moving using CAT 330D excavator - fuel cost savings (Caterpillar, 2006)  
<sup>4</sup>Bulk earth moving and fine grading using CAT D6N dozer - fuel cost savings (Caterpillar, 2006)  
<sup>5</sup>Fine grading using 140H motorgrader - fuel cost savings (Caterpillar, 2006)

# Accuracy at several stages is a key issue.

- Initial data collection for surface terrain,
- Constructing DTMs and EEDs,
- AMG processes, procedures, and end-user competencies,
- QA/QC reporting practices,
- Heavy and fine grading equipment operations, and
- Paving equipment operations

# Position measurement technologies cover a range of accuracies and costs.

System	Accuracy	Range	Principle	Cost	Reference
Laser	±2 mm	300 m/line of site radius of laser source	Integrated laser receiver references established elevation	Low to moderate	Retscher, 2002
Ultrasonic	±1 mm	Immediate reference	Reference existing surface using sonic travel time	Low to moderate	Trimble, 2008
Robotic total station	±2 mm	700 m/line of site radius of source	Various electronic distance measurement technologies, angel measurements	High	Retscher, 2002
RTK GPS	cm*	Global	Time of arrival, lateration, differential technique	Moderate to high	Mautz, 2008
Assisted GPS (via mobile phones)	Variable, 10 m	Global	Time of arrival, lateration	Low	Mautz, 2008
Laser- augmented GPS	3 to 6 mm	300 m/line of site radius of laser source	Time of arrival, lateration, differential technique, and integrated laser receivers	Moderate to high	Trimble, 2008
Ultrasonic augmented GPS	±1 mm	Immediate reference	Time of arrival, lateration, differential technique, and sonic sensors	Moderate to high	Trimble, 2008
GPS integrated with INS	Variable	Global	Time of arrival, integrating angular velocity and linear acceleration	Variable	Mautz, 2008
Locata (pseudolites)	6 mm	2 to 3 km	Time of arrival, lateration	High	Barnes et al., 2003
Infrared laser	0.1 to 0.2 mm	2 to 80 m	Time of arrival, angular measurements, spatial forward intersection	High	Kraut- schneider, 2006)

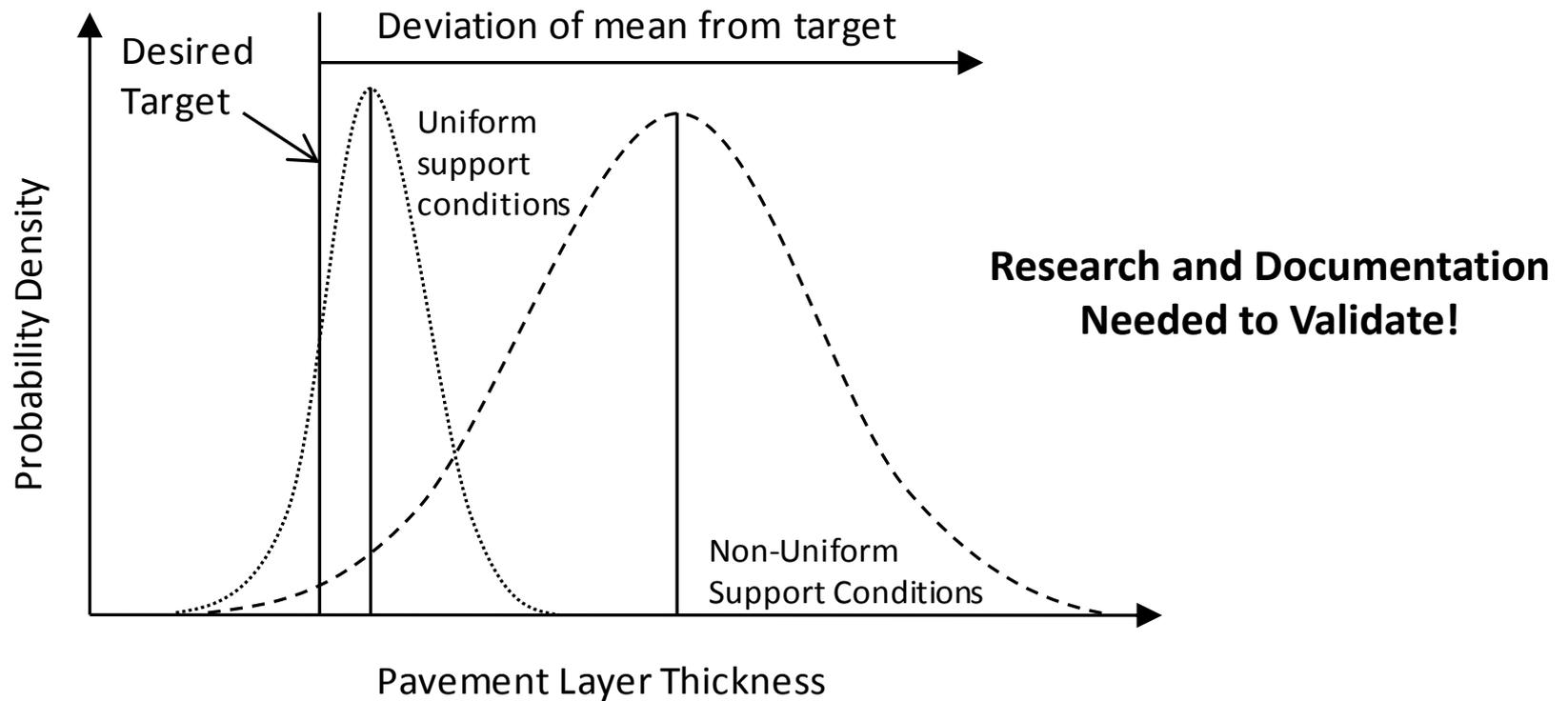
\* About 90% of survey respondents reported horizontal accuracy of 2 cm or less and 45% of respondents reported vertical accuracy of 2 cm or less with GPS (See Chapter 3)

# Requirements are being established for AMG applications.

Equipment	Major Application Field*	Typical Precision Requirements
Dozer	Bulk earthworks and earthmoving	up to $\pm 20$ mm
Grader	Fine grading, side slope work	up to $\pm 5$ mm
Road Paving machine	Asphalt/concrete surfaces for pavements	up to $\pm 5$ mm in plane and $\pm 3$ mm in height
Slipform paving machine	Concrete surface for pavements and high speed railways	up to $\pm 5$ mm in plane and $\pm 2$ mm in height
<p>*Vertical accuracy requirements (Houghton, 2001): finished surface: <math>&lt; \pm 6</math> mm; base course: <math>\pm 6</math> mm; upper road surface: <math>\pm 8</math> mm; road base: <math>\pm 15</math> mm; Subbase: <math>\pm 10</math> to <math>30</math> mm; formation and cap: <math>\pm 20</math> to <math>30</math> mm. Accuracy requirements (Peyert et al. 2000): subbase: <math>\pm 30</math> mm; base: <math>\pm 20</math> mm; binder course: <math>\pm 15</math> mm; wearing course: <math>\pm 5</math> mm</p>		

(after Retscher 2002)

With proper DTM captures, system factors can be better understood.



# There can be several sources of errors that contribute to overall AMG accuracy.

<b>Description (random order)</b>
• Errors in setting up the control network
• Inaccuracy in the preconstruction survey used to develop the digital terrain model
• Errors in the design
• Errors that result from faulty software
• Errors that result from faulty hardware
• Limitations to the accuracy of positioning method (GPS, total station, or laser)
• Errors transmitting control information from the positioning equipment (GPS, total station receiver, or laser) to the machine hydraulic controls for the ground- or pavement-engaging equipment
• Inability of machine hydraulic controls to respond accurately or smoothly to instructions from AMG units (overcorrection, slow response, and other similar problems)
• Human error in operating hardware, software, and equipment
• Failure to identify inaccuracies during the QA/QC process (or false indications of inaccuracy during a QA/QC process)
• Sensor/technology/system limitations (such as pushing beyond the limits of the equipment)

# DTM Accuracy Factors Rating

DTM Accuracy Factors*	Contractor	Agency P/C	SW/HW Vendor
<b>Number of data points in DTM</b>	70%	90%	80%
File types of shared data	52%	56%	67%
Number of data translations	56%	77%	63%
DTM constructability review	77%	70%	73%

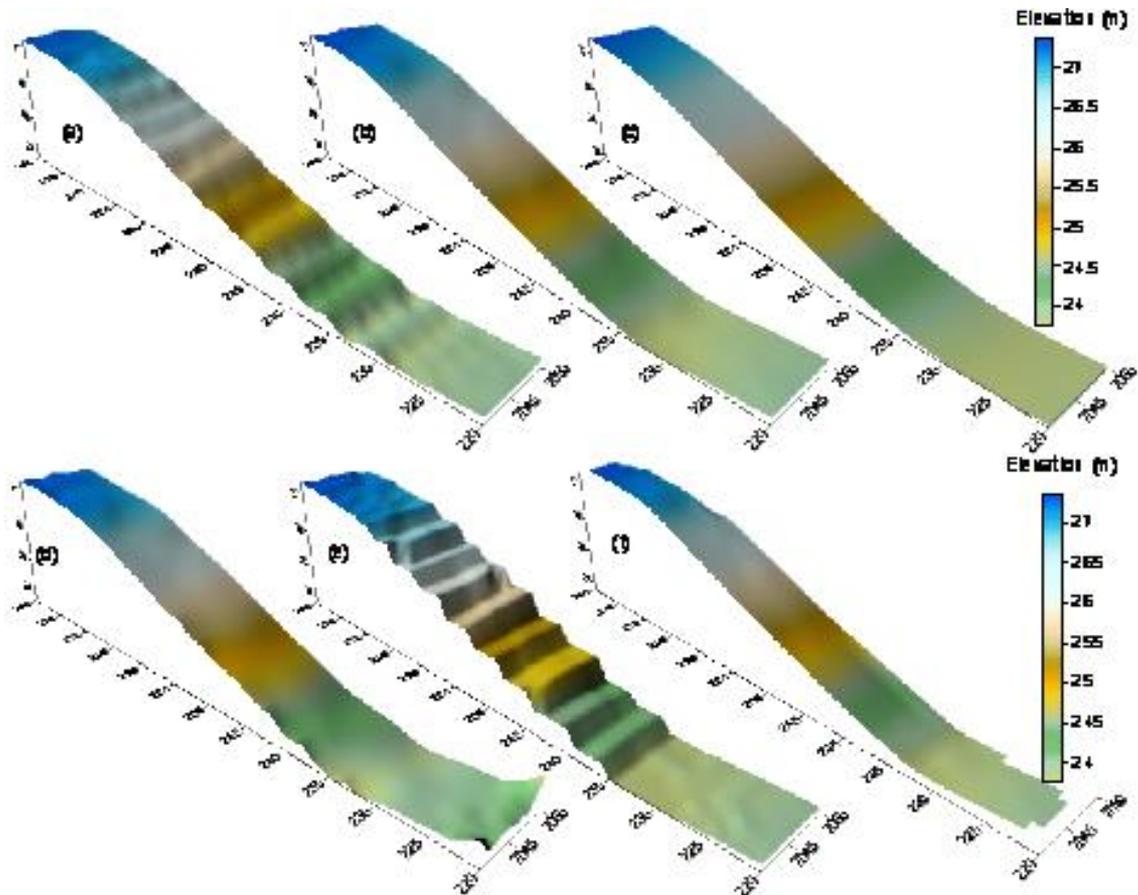
*\* Percentage of respondents choosing DTM Accuracy as Important or Very Important*

## Factors Contributing to EED Accuracy

Factors Contributing to EED Accuracy*	SW/HW Vendor
Elevation point density	94%
Adhering to CAD Standard/Defined work-flow processes	81%
The sequence of when the models are created in the delivery process	88%
<b>Engineer design competencies in design software use</b>	<b>100%</b>

*\* Percentage of respondents choosing EED Accuracy as Important or Very Important*





DTMs of a 540m<sup>2</sup> Area using 78 Elevation Data Points using Different Interpolation Methods: (a) Inverse Distance to a Power; (b) Kriging; (c) Local Polynomial; (d) Minimum Curvature; (e) Nearest Neighbor; (f) Triangulated Irregular Network (TIN)

## Mean error various with the interpolation method (79 points).

---

<b>Data Interpolation Method</b>	<b>Estimated Elevation Absolute Mean Error (cm)</b>
Inverse distance to power	10
Kriging	2
Local polynomial	7
Minimum curvature	5
Nearest neighbor	4
Triangulated irregular network (TIN)	3

---

For a  $\Delta$ Elevation = 3.5 m over a length of 60 m

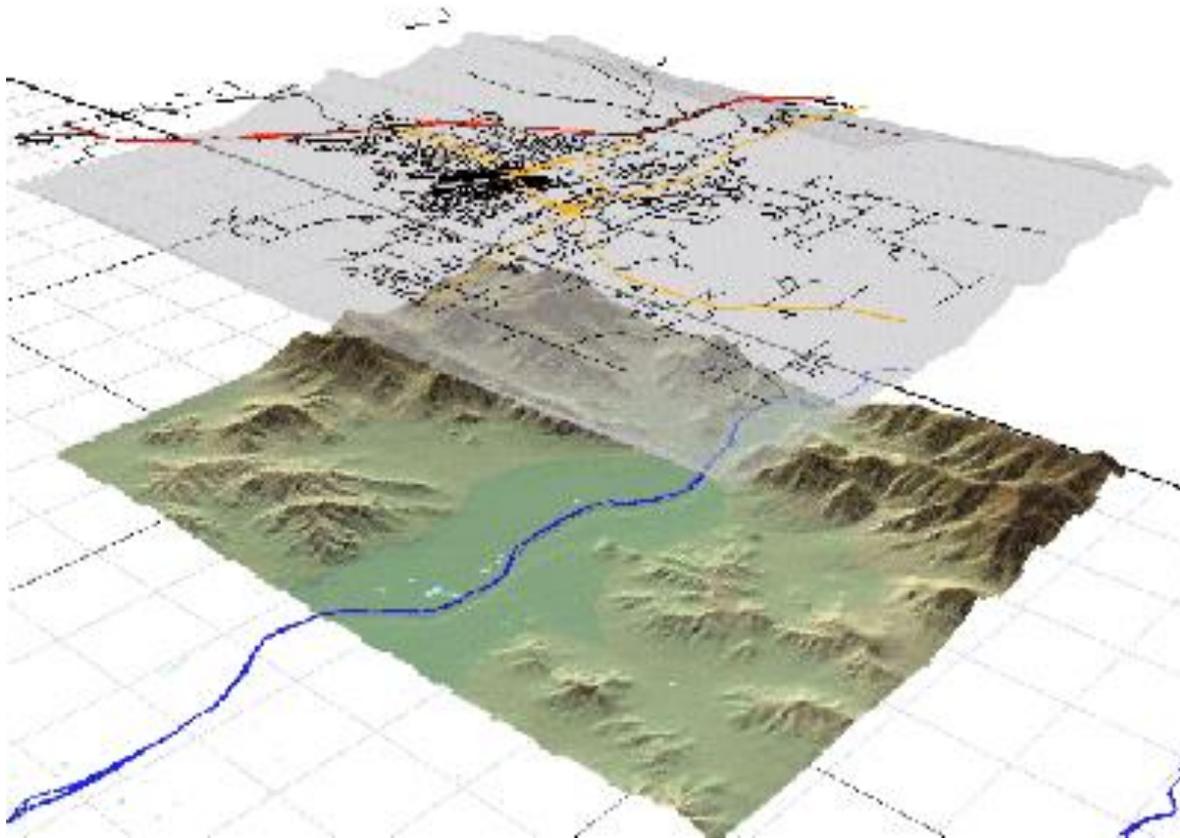
# The Future of AMG

# Heterogeneous collection of players are converging.

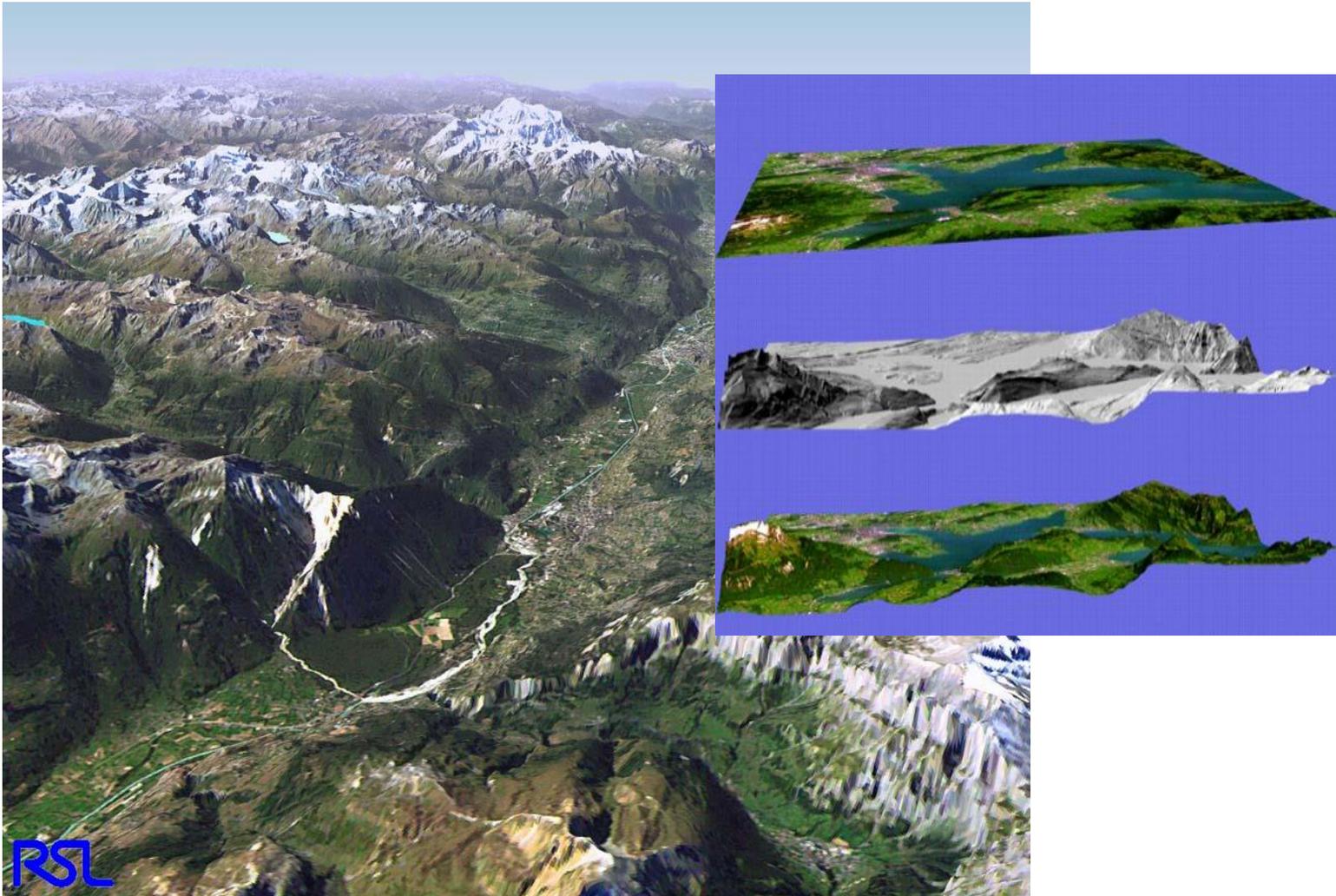
Locations	Tools	Players	Disciplines
<ul style="list-style-type: none"><li>• Workstation</li><li>• Field/Project Site</li><li>• Cloud</li></ul>	<ul style="list-style-type: none"><li>• Software (CAD, GIS, GPS, Google Earth/internet, social media)</li><li>• Hardware (laptops, reference stations, lasers)</li><li>• Heavy Equipment (Graders, Compactors)</li></ul>	<ul style="list-style-type: none"><li>• Clients (public, private)</li><li>• Engineers (Civil, Geotechnical, Construction, etc.)</li><li>• Designers (Civil Engineers, Landscape Architects, Architects)</li><li>• Contractors (Site, Road)</li><li>• Surveyors (pre, during, post construction)</li></ul>	<ul style="list-style-type: none"><li>• Civil Engineering</li><li>• Landscape Architecture</li><li>• Robotics</li><li>• Mechanical Engineering</li><li>• Statistics</li><li>• Hollywood/Computer Graphics/Animators</li><li>• Software Engineering</li><li>• Law</li></ul>

Barriers are no longer technical, rather cultural, vocabulary-based, or legal/proprietary/economic.

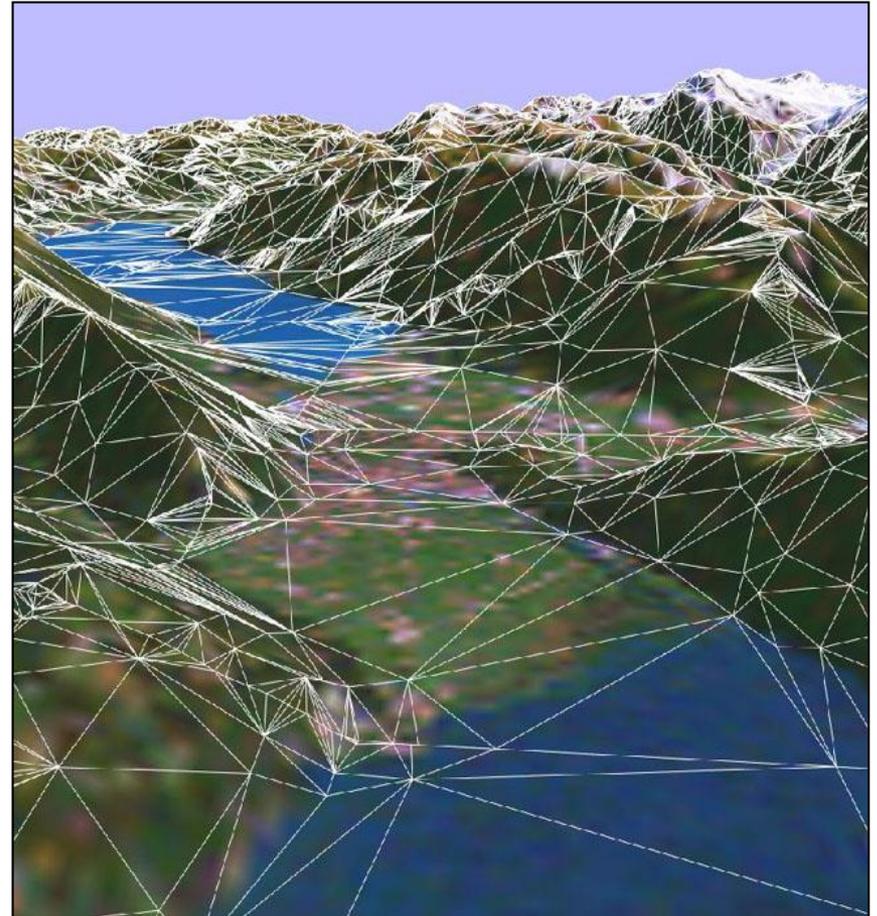
Site mapping capability is expanding (i.e., show ecological and other site natural system information).



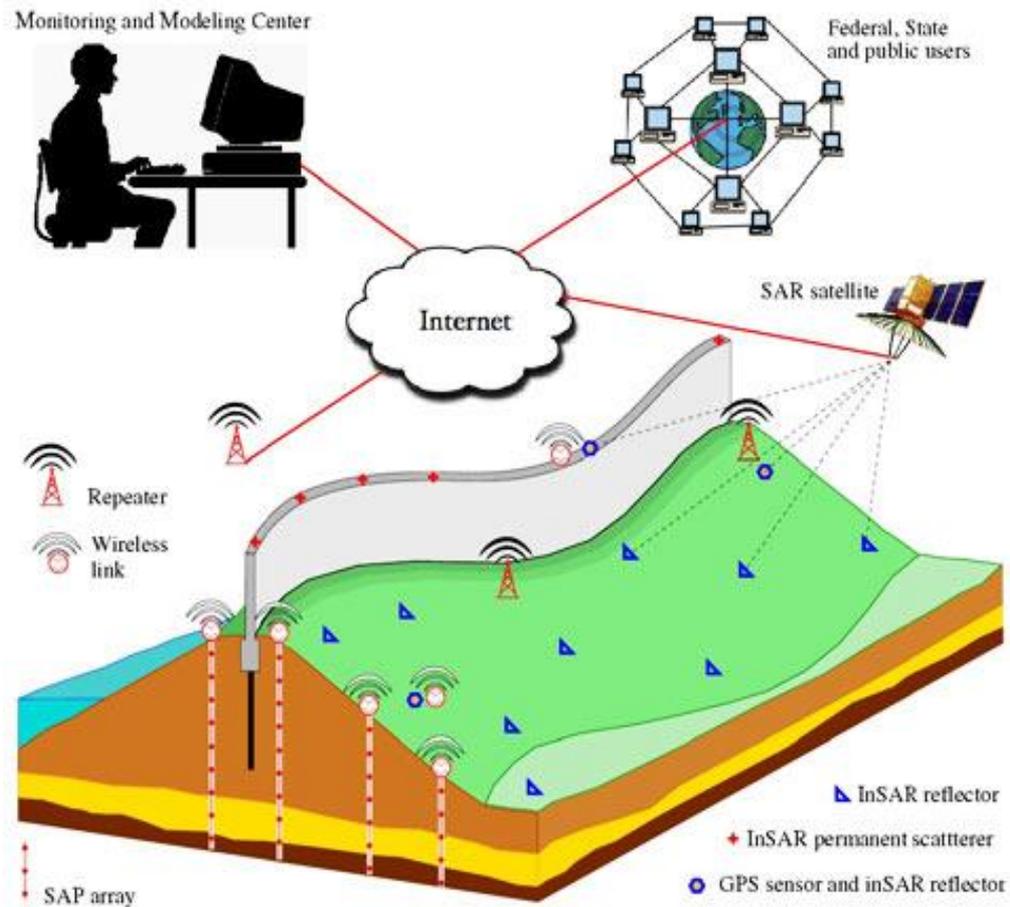
# Rendering/visualization tools are advancing at rapid pace.



Data presented in context as near-medium-far views can including construction data, weather effects, etc.



Design development carries over onto the site itself. i.e., beyond conceptual, design phases, but to the during construction phase.



Christi Wilson's Fleet EquipmentManager (EM)

Event Summary

Event Start Date  Event End Date

Select a Group

Status	Equipment	Incidents
<input checked="" type="checkbox"/> Action	3	3
<input type="checkbox"/> Monitor	6	21
<input checked="" type="checkbox"/> Normal	17	24

SOS Incidents last updated: 13/12/2006 09:44:36 AM

Equipment Search

Equipment Group

Equipment ID \*

Manufacturer

Equipment Type

Product Family

Model \*

Serial Number \*

(Fields marked with a \* support partial-word matching)

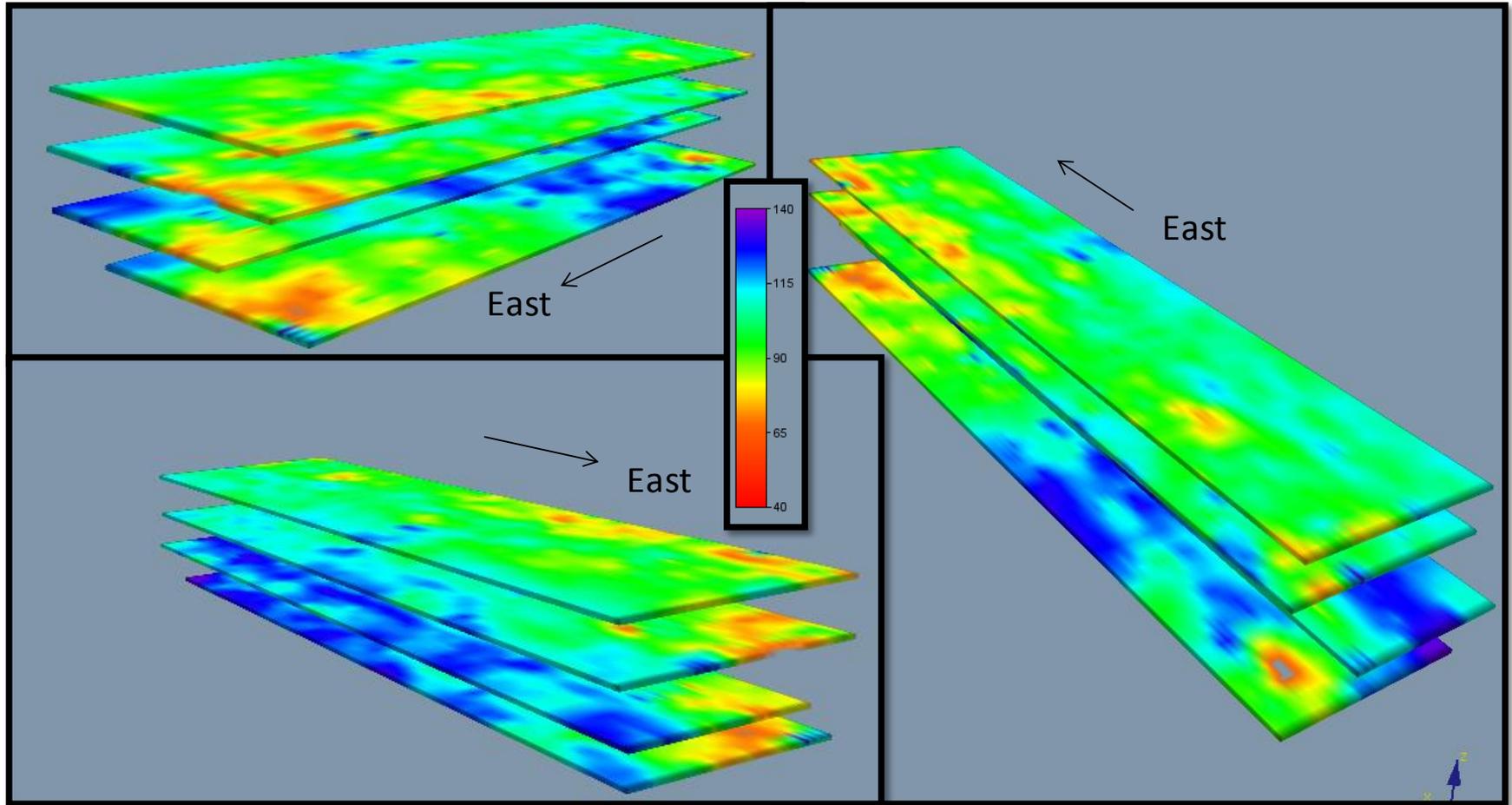
or Perform an [Advanced Search](#)

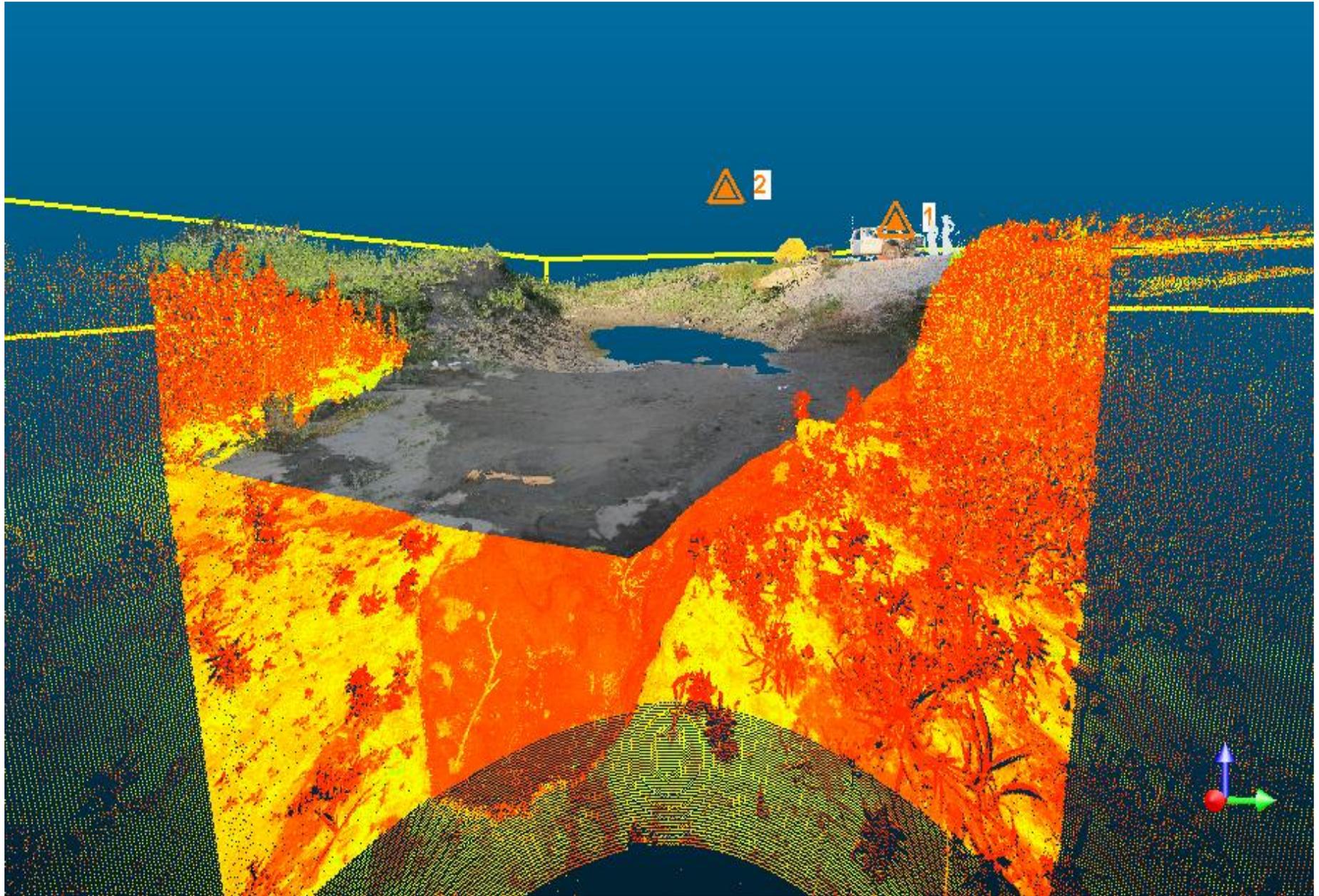
**Equipment Manager** is a web-based application that uses key indicators from your equipment such as hours, location and diagnostic codes and combines it with powerful tools like mapping, maintenance scheduling and troubleshooting instructions.

This application enables quick identification of actions required to maximize your equipment uptime and control owning and operating costs.



QC/QA compaction monitoring results can be linked to geospatial coordinates.





- Please keep our NCHRP 10-77 project in mind – full report late 2013)

Thank You.