TECH**BRIEF**

Determination of Improved Pavement Smoothness When Using 3D Modeling and Automatic Machine Guidance

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This document is a technical summary of the forthcoming Federal Highway Administration report *Determination of Improved Pavement Smoothness When Using 3D Modeling and Automatic Machine Guidance*.

SUMMARY

This TechBrief provides a summary of a study the Federal Highway Administration (FHWA) conducted to evaluate how using three-dimensional (3D) engineered models in conjunction with Automated Machine Guidance (AMG) technology affects initial pavement smoothness. The assessment approach included a comprehensive literature review, engagement with State highway agencies (SHAs) that are using 3D engineered models and AMG technology to understand the current state of the practice regarding smoothness benefits, and a comparison of documentation from five case studies. Researchers also compared the initial pavement-smoothness measurements from these case studies with those from companion projects that were performed without AMG technology to test the null hypothesis that the use of this technology improves initial pavement smoothness. This work led to an enhanced understanding of how 3D engineered models and AMG technology, also referred to as stringless paving, can be used as contractor tools for quality control (QC) and help SHAs mitigate risks and optimize initial pavement smoothness.

INTRODUCTION

In recent years, the use of AMG technology in constructing pavement structures has increased with growing market-led adoption by construction contractors. Efficient construction is a key benefit of using this technology and has led to its rapid adoption in paving; this efficiency results in cost savings, safety improvement, consistent paving-layer thicknesses, and higher material yields. As SHAs deploy specifications, guidance, and manuals to manage and support the use of AMG technology and related construction-inspection automation for grade control, more questions are being asked about how else construction outcomes might benefit from this technology. Improved initial pavement smoothness has been touted as a potential positive construction outcome resulting from the use of AMG technology–equipped machineries (i.e., pavers and graders) because of their superior vertical-grade control and accuracy. However, proof of this benefit is not documented.

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In the context of this study, AMG technology is defined as using positioning devices, specifically Global Navigation Satellite Systems (GNSS), laser-augmented GNSS, and/or robotic total stations, on construction equipment (e.g., scrapers and paving machines) for machine guidance and to establish machine control to grade either all layers of a pavement structure for concrete-pavement projects or to subgrade layers for asphalt-pavement projects. Non-AMG technology, then, is defined as using traditional construction equipment to control the grade of pavement layers (e.g., all layers of a pavement structure for concrete-pavement projects and subgrade layers for asphalt-pavement projects).

Initial pavement smoothness is an important aspect of a pavement structure's functional service life. As a proven paving adage goes, "If you build the pavement smoother, it will stay smooth longer." Capitalizing on the long-term benefits of achieving better initial pavement smoothness has been a goal of both the concrete- and asphalt-paving industries for decades.

RESEARCH OBJECTIVES

FHWA's researchers attempted to test the hypothesis that using AMG technology for grade control can improve initial pavement smoothness by comparing projects that used AMG technology in constructing successive pavement layers to projects that did not use AMG technology for grade control; all other factors influencing pavement smoothness for a given project were considered equal. Researchers also documented the survey equipment used by contractors to control the positioning of systems using AMG technology and various attempts to gather data in real time during paving to improve pavement smoothness. The documented results were used to develop general guidance for leveraging AMG technology to optimize initial pavement smoothness.

OVERVIEW OF STATE OF THE PRACTICE

Preconstruction Surveys and 3D Modeling

Documentation from a 2013 study shows that most SHAs continue to use aerial photogrammetry as the standard operating procedure for preconstruction data collection because of its cost effectiveness, although terrestrial static lidar is also used to obtain preconstruction data.(1) 3D photogrammetry surveys can be augmented with lidar surveys to produce more accurate measurements during pavement-surface analysis.

According to FHWA, 29 SHAs are making or planning to make the use of 3D engineered models standard practice for designing pavement structures.(2) However, using data from 3D engineered models within AMG technology continues to be a challenge for many reasons (i.e., data incompatibility between design and construction systems, lack of standard formats to enable interoperability of data across construction phases, and the geometric complexity and size of the model produced in design). Iowa, Michigan, Missouri, New York, Oregon, Utah, and Wisconsin are some States with mature practices for sharing 3D engineered models as reference information or contractual documents with contractors for AMG-technology use.

AMG for Paving Operations

Two types of AMG-technology systems are commercially available for paving operations. Both systems have two main components: an onboard computer system and high vertical accuracy surveying equipment that relies on line of sight for communicating with the positioning sensors mounted on the paving equipment. One system is guided by robotic total stations and the other system by GNSS-augmented laser technology.(3,4)

Many contractors use AMG technology for concrete-pavement projects, but few use them for asphalt-pavement projects. When contractors were interviewed about the benefits they experienced due to the use of AMG technology in concrete paving, increased safety, better material yields, and reduced schedules were among the top responses. Contractors expressed optimism regarding improved initial pavement smoothness in concrete-pavement projects. However, the consensus is that, to date, AMG-technology systems have not proven beneficial for asphalt-pavement projects. Contractors stated that traditional construction methods are sufficient to achieve current SHA smoothness requirements for both asphalt- and concrete-pavement projects, although AMG technology can be beneficial on variable-depth and correction-reconstruction asphalt projects.

DETAILS OF RESEARCH APPROACH

Case Studies to Investigate Benefits of AMG Technology on Smoothness

To test the null hypothesis that AMG technology improves initial pavement smoothness, researchers conducted five case studies. For each case study, the research team collected smoothness data from a pair of carefully selected companion projects—one project in which AMG technology was not used (representing the baseline or control) and another in which AMG technology was used (representing the variable being studied). The data collected for each project included documentation of construction methods and technology used and smoothness-acceptance measures (i.e., International Roughness Index (IRI) or Profile Index (PI)). In choosing companion projects, care was taken to select projects of similar size and paving scope to each other to ensure comparability. Companion projects were selected from Arizona, Illinois, Iowa, Missouri, and Oregon (table 1). The researchers worked with each SHA to collect the data necessary for the analysis. Due to scheduling conflicts and some projects being already concluded, site visits could only be conducted in Iowa and Oregon. These visits were made to study onsite factors and conduct in-person interviews.

Table 2 summarizes the means and standard deviations of smoothness measurements as well as the number of smoothness observations (i.e., number of 0.1-mi segments over which smoothness was measured) for each case study. The descriptive statistics presented in this table do not provide categorical evidence to support the idea that AMG technology offers superior initial pavement smoothness to traditional construction methods.

Data-Analysis Approach

A specific statistical-analysis method, meta-analysis, was conducted to test the null hypothesis. Meta-analysis was chosen because it facilitates the evaluation of the consistency of empirical evidence derived from small sample sizes that have different attributes that could influence results otherwise. This method uses the effect size (i.e., standardized mean difference) to evaluate the difference in pavement smoothness between the AMG- and non-AMG-technology case studies.(5) Four measures were used to describe information on the magnitude, direction, and strength of the difference in smoothness between AMG and non-AMG groups, which are detailed as follows:

1. Cohen's *d*—This measure, otherwise referred as effect size, is the standardized mean difference in smoothness outcomes between AMG and non-AMG groups.
2. Cohen's U_3—This measure returns the normal distribution for effect sizes, which describes the percent of smoothness measurements in the non-AMG group that is exceeded by the average smoothness in the AMG group.

Table 1. Summary of projects used as case studies.

Agency Name	Case Study Name	Description
Arizona DOT	AZ Loop 101	PCCP, new construction to add an HOV lane and median barrier for an urban freeway.
Illinois Toll Highway Authority	IL Tollway I-90	PCCP, full-depth reconstruction and widening of an urban freeway.
Iowa DOT	IA U.S. 20	PCCP, new roadway construction to expand a rural highway from two to four lanes.
Missouri DOT	MO U.S. 40	PCCP, new roadway construction to expand a rural highway from two to four lanes.
Oregon DOT	OR SH 140	Hot-mix asphalt concrete, new construction to realign a rural section of SR 140.

DOT = Department of Transportation; PCCP = portland cement–concrete pavement; HOV = high-occupancy vehicle.

Table 2. Summary of smoothness measures by case study.

Case Study Name	AMG: No. of 0.1-mi Segments	AMG: Mean IRI (Inch/mi)	AMG: Standard Deviation (Inch/mi)	Non AMG: No. of 0.1-mi Segments	Non AMG: Mean (Inch/mi)	Non AMG: Standard Deviation (Inch/mi)
AZ Loop 101	223	34.3	5.8	310	35.6	7.9
IL Tollway I-90	6	56.2	10.1	26	60.3	10.1
IA U.S. 20	170	58.2	9.9	1028	52.3	8.6
MO U.S. 40*	183	12.3	6.6	137	13.8	3.1
OR SH 140	132	54.5	11.7	27	54.4	23.8

*PI is reported for Missouri U.S. 40, while IRI is reported for other sites.
No. = number.

3. Common Language Effect Size (CLES)—This measure indicates the likelihood that the smoothness metric of a randomly selected segment from the AMG group will be greater than the smoothness metric of a randomly selected segment from the non-AMG group.
4. Summary effect—This measure is the weighted mean of individual effect sizes to indicate the combined effect observed across all case studies.

Effect Sizes Based on Occurrence of Disincentives

Another statistical measure, the odds ratio (OR), was used to evaluate the relative performance of AMG and non-AMG groups in achieving desired quality levels and percent within tolerance limits. The OR is the probability of success over the probability of failure. Using preset acceptance measures for ride smoothness in existing specifications as the benchmark, the percentage of 0.1-mi segments not receiving disincentives was counted toward the probability of success, while the percentage of segments receiving disincentives was counted toward the probability of failure. This measure evaluates the hypothesis that the use of AMG technology would result in a smaller number of pavement segments that receive smoothness-related disincentives in comparison to those paved using non-AMG technology. The OR was computed based on the number of 0.1-mi segments where the measured smoothness exceeded a specific threshold for both AMG and non-AMG groups. OR was interpreted as follows:

- OR = 1—Paving with AMG technology and traditional, non-AMG technology equally influence the odds of meeting smoothness-acceptance measures.
- OR > 1—Paving with AMG technology has greater odds of influencing the process toward meeting smoothness-acceptance measures than paving with non-AMG technology.
- OR < 1—Paving with non-AMG technology (e.g., string line) has the higher odds of influencing the process toward meeting smoothness-acceptance measures than paving with AMG technology.

Evaluation of Random Effects and Heterogeneity

A random-effect meta-analysis was conducted to account for possible confounding effects in smoothness outcomes due to unexplained variations in paving operations. Random-effect models indicate how much of the observed effect (i.e., grand mean of smoothness change) is the true effect (i.e., change resulting from AMG-technology use) and random effect (i.e., change caused by other influencing factors). Both true effects and random effects are analogous to the treatment effects and experimental error terms, respectively, used in conventional analysis of variance. Furthermore, each case study is expected to produce an effects estimate (i.e., mean change in smoothness outcomes) of varying magnitudes (i.e., percent changes) and directions (i.e., positive or negative change). Observed variations across case studies could be attributed to random effects or inconsistency in true effects (i.e., heterogeneity) from the use of AMG technology.

RESULTS

Summary of Effect Sizes Based on Standard Mean Difference

The effect-size estimates indicate that the use of AMG technology utilizing 3D engineered models for paving resulted in slightly better smoothness outcomes than the use of non-AMG technology for three of the five case studies. Table 3 summarizes the effect sizes of the five case studies. The effect sizes in smoothness data from the Arizona and Missouri case studies demonstrate the marginal superiority of paving with AMG technology over paving with non-AMG technology. The CLES values for the Arizona and Missouri case studies show that paving with AMG technology had an average of a 5- and 8-percent advantage over paving with non-AMG technology, respectively.

The smoothness outcomes from the Oregon case study showed negligible or no difference between the paving with and without AMG technology. The Iowa case study produced a robust trend in which the segments that were paved using AMG technology had consistently better initial pavement smoothness than segments that were paved using non-AMG technology. The use of AMG technology on the Illinois Tollway I-90 site produced moderate improvements in measured initial pavement smoothness, however, the prediction intervals show high levels of uncertainty with the estimated effect size.

In summary, effect-size estimates of individual case studies at both 50- and 95-percent confidence intervals indicate an absence conclusive evidence of whether the use of AMG technology in conjunction with 3D engineered models for paving resulted in better overall smoothness outcomes than the use of non-AMG technology. This inconclusive trend was reflected in the Cohen's U_3 and CLES estimates. In other words, given the evidence available from the five case studies, the probability that one technology is superior to the other is roughly equivalent to a coin toss.

Effect Sizes Based on the Occurrence of Disincentives

The ORs indicated the differences in risks related to the specification compliance between paving methods using AMG technology and non-AMG technology. Table 4 presents a summary of the OR analysis, which indicates that paving with AMG technology generally resulted in higher odds of meeting smoothness-acceptance measures than paving with non-AMG technology. However, the degree of consistency achieved with using AMG technology can be described to range between marginally and moderately better odds. Based on this range and on the fact that the range of ORs estimated at 95-percent confidence interval was much wider for all case studies, it cannot be concluded with a high degree of certainty that the use of AMG technology improves the number of segments exceeding smoothness-acceptance measure.

Table 3. Summary of effect sizes based on the standard mean difference.

Case Study Name	Effect Size (LL, UL)*	Cohen's U_3 (%)	CLES (%)
AZ Loop 101	0.18 (0.008, 0.353)	57.1	55
IL Tollway I-90	0.40 (−0.489, 1.297)	65.7	61
IA U.S. 20	−0.67 (−0.839, −0.510)	25.0	32
MO U.S. 40	0.274 (0.052, 0.497)	60.8	58
OR SH 140	0.00 (−0.419, 0.409)	49.8	50

*Values estimated with 95-percent confidence.
LL = lower limit; UL = upper limit.

Table 4. Summary of the OR analyses.

Case Study Name	Paving Technology	Percent of 0.1-mi Segments With Acceptable Smoothness	Percent of 0.1-mi Segments With Unacceptable Smoothness	OR (LL, UL)*
AZ Loop 101	AMG	0.91	0.09	1.46 (1.71E-04, 1.25E+04)
AZ Loop 101	String line	0.87	0.13	1.46 (1.71E-04, 1.25E+04)
IL Tollway I-90	AMG	0.67	0.33	1.71 (5.61E-03, 5.24E+02)
IL Tollway I-90	String line	0.54	0.46	1.71 (5.61E-03, 5.24E+02)
IA U.S. 20	AMG	1.00	0.00	N/A
IA U.S. 20	String line	0.99	0.01	N/A
MO U.S. 40	AMG	0.99	0.01	0.63 (5.39E-14, 7.46E+12)
MO U.S. 40	String line	0.99	0.01	0.63 (5.39E-14, 7.46E+12)
OR SH 140	AMG	0.95	0.05	2.63 (3.28E-05, 2.10E+05)
OR SH 140	String line	0.89	0.11	2.63 (3.28E-05, 2.10E+05)

*Values estimated with 95-percent confidence.
LL = lower limit; UL = upper limit; N/A = not applicable.

Evaluation of Random Effects and Heterogeneity

Table 5 presents the descriptive statistics of summary effect, which indicates the combined effect observed across all case studies. The mean value of summary effect indicates that the positive difference in smoothness that paving with AMG technology produces when compared to paving with non-AMG technology is statistically negligible. The estimates at a 95-percent confidence interval indicate that the summary effect could plausibly go in either direction, thus, reaffirming the lack of conclusive evidence between the two technologies.

Figure 1 shows a plot that presents the effect sizes of each case study as well as the summary effect with their corresponding prediction intervals. A positive difference indicates AMG technology yielded a pavement that is smoother at construction than non-AMG technology is and vice versa. The closer the positive effect size is to 0, the weaker the advantage of AMG technology over non AMG technology in producing better smoothness outcomes. All horizontal lines show the lower and upper limits of the effect-size estimates.

Table 5. Descriptive statistics of summary effect.

Statistic	Estimated Value
Mean	−0.001
Variance	0.058
Standard error	0.240
Lower limit (95%)	−0.472
Upper limit (95%)	0.470
p-value (1-tailed)	0.498

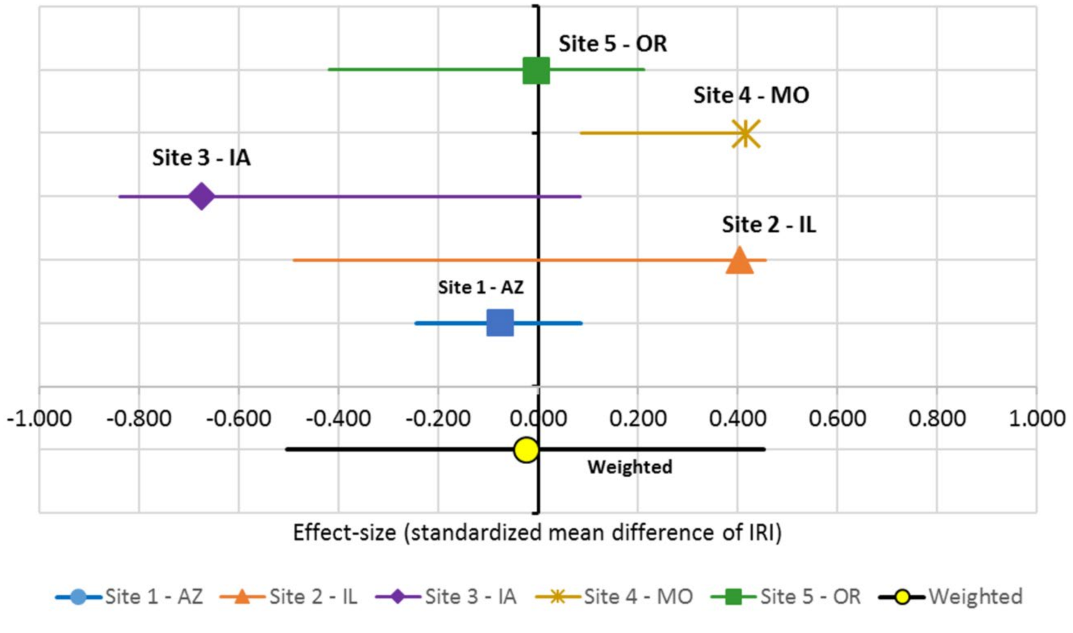
Table 6 presents I^2 estimates, which describe statistical heterogeneity in the smoothness data. An I^2 estimate of 94.2 percent indicates a high level of inconsistency in estimated differences in pavement smoothness between the AMG and non-AMG groups across case studies.

While other factors (i.e., terrain, geometric alignment, pavement-layer types, design features, concrete-mix properties, concrete delivery and finishing, and contractor means and methods) could significantly confound smoothness outcomes after paving, the summary effect and I^2 estimate collectively suggest that

Table 6. Estimate of heterogeneity.

Statistic	Estimated Value (%)
I^2	94.20
Lower limit of I^2 (95%)	89.28
Upper limit of I^2 (95%)	96.86

Figure 1. Forest plot. Standardized mean differences of smoothness of different case studies.



Source: FHWA.
Note: Positive difference indicates that IRI of segments using AMG technology is better (smoother) than those not using this technology.

the smoothness data from the five case studies provide no statistically conclusive evidence to support the null hypothesis that the use of AMG technology alone for paving would reliably produce better smoothness than the use of non-AMG technology. Further, the observed variability in true effects among the case studies is too high to suggest that the use of AMG technology can produce reliably better smoothness outcomes over traditional methods. Deploying AMG technologies during construction, however, is apparently beneficial in preparing a more uniform and stable base as well as guiding paving operations for better elevation and alignment control.

GUIDANCE FOR MITIGATING RISKS IN AMG TECHNOLOGY–PAVING PROJECTS

Regardless of AMG technology's effectiveness in providing better initial pavement smoothness, the primary benefit of using it for guiding pavement equipment is the ability to have better grade control during paving. However, it is important to note that paving operations using AMG technology heavily depend on the survey setup, appropriate QC during and after the placement of each layer of the pavement structure, and the data files used by the onboard system. Thus, guidance for mitigating risks when using AMG technology for paving operations should focus on survey- and data-management specifications through a quality-management plan (QMP). It is important for SHAs to know how a contractor will manage the setup of equipment, files used on the onboard sensors, and any discrepancies in grade and elevations. Further, all construction specifications and training material should be updated to ensure the inspector has the proper knowledge and guidance to successfully inspect projects in which the contractor uses AMG technology. The remainder of this TechBrief describes potential sections to include in a QMP for AMG-technology system operations.

Sources, Management, and Validation of 3D-Design Files

A section on sources, management, and validation of 3D-design files should include a narrative outlining the validation of the 3D engineered model in the base mapping and any changes made to the SHA-provided 3D engineered model to prepare the necessary files for construction equipment. If the SHA does not provide a 3D engineered model, the contractor should describe how the construction model was developed to preserve the original design intent of the contract plans. In addition, the narrative should describe the protocol for managing the versioning of the files being used for daily operations.

Procedures Establishing, Verifying, or Augmenting Survey Control

Whether the contractor plans on using AMG technology for construction or not, a survey QMP should be provided. Survey control establishes a common and consistent network of points that are the foundation for controlling the horizontal and vertical positions for construction projects. AMG technology–based construction methods used for paving operations require a higher density of control points than construction staking. Thus, at a minimum, the contractor should include the following items in their QMP:

- Process for establishing, verifying, and/or augmenting the SHA-provided survey control points that were used for creating the preconstruction survey.
- Approach to densification of the survey-control network for a higher order of vertical accuracy to support paving equipment using AMG technology.
- Protocols for managing interference to GNSS satellite signals from canyons, buildings, trees, etc.

A professional surveyor should create and verify a survey-control report as required by the SHA's survey manual or specifications.

Proposed AMG Technology–Supported Construction Methods, Equipment-Guiding Sensors, and Setup

The contractor should provide an overview of what activities will be performed with AMG-technology systems (i.e., grading, trimming, paving) and name the person overseeing the AMG project or AMG QC manager. The person overseeing typically has a survey background and has been trained by the manufacturer to operate the system, including initial setup and operation of controlling instruments, radios, and machine computer systems. Further, the QMP should describe what positioning-technology method will be used to guide systems, such as GNSS and robotic total stations, and the number of sensors to support each operation.

Providing diagrams showing the setup of the equipment is helpful for the construction staff to understand how positioning of the equipment is being controlled, and it helps the survey crew troubleshoot any issues that may arise during construction. Figure 2 shows a GNSS-guided grader, and figure 3 shows a robotic total station–guided concrete paver.

Figure 2. Photo. GNSS-guided grader.

Source: FHWA.

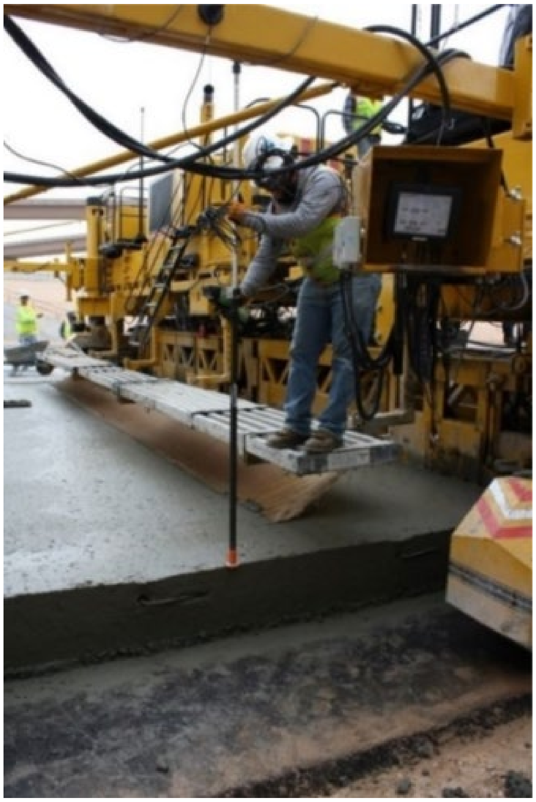
Figure 3. Photo. Total station–guided concrete paver.

Source: FHWA.

Approach for Verifying Grade Elevations of Each Layer of the Pavement Design

The contractor should describe how elevations, depths, and cross slopes will be checked during the project. If a checker will be available to perform real-time verification with high-precision surveying equipment, this circumstance should be stated in the QMP.

Figure 4. Photo. Checking elevations behind a paver.



Source: FHWA.

In addition, the contractor should describe the equipment and approach for performing these real-time verifications. The paving foreman can store information being collected with the data collector used for real-time verifications. Information, such as station, offset, and elevations, can be used to produce a report (in a spreadsheet format) showing pavement depths that can be attached to the inspection's daily reports. Figure 4 depicts a person conducting real-time verification.

While contractors are well versed in using high-precision surveying equipment as tools to perform QC, SHA inspection staff typically do not have access to the same equipment for real-time verification. Closing this gap is a significant step toward being able to leverage the benefits AMG technology–assisted paving operations offer for real-time verification. Some SHAs include the furnishing of surveying equipment as part of the construction contract to ensure the inspector can perform real-time verification for QC purposes. If the contractor is furnishing this equipment, it should be noted in the QMP. Further, there should be a description of the approach for training the inspector to use the field survey equipment.

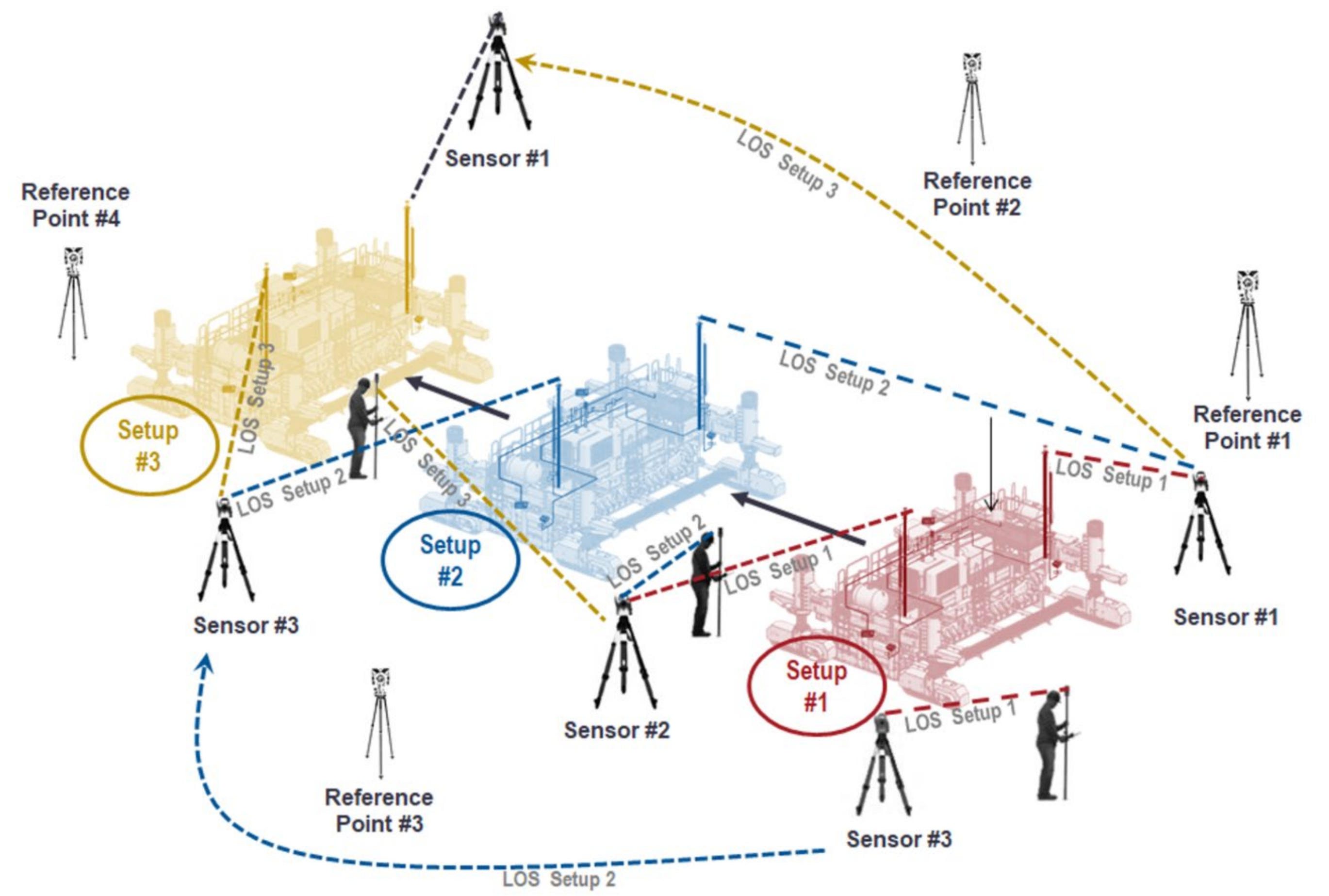
Protocols for Resolving Survey Discrepancies

If the SHA does not have a standard protocol for resolving survey discrepancies in the field, the contractor should include a narrative in their QMP describing the procedure for resolving any survey discrepancies.

Documenting and Managing Site Conditions

AMG technology depends on communication between reference-positioning survey equipment on the ground and receivers on the paver. Thus, the contractor, being

Figure 5. Illustration. Setup of a robotic total station–guided AMG-technology paving operation.



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LOS = line of sight.

the one providing QC, should avoid or minimize conditions that may compromise those communications as any loss of signal will force the paver to stop abruptly, which may lead to unnecessary localized areas of roughness. The person responsible for setting up and maintaining the surveying equipment that guides the paver should become familiar with the site prior to beginning paving. All equipment stops and restarts should be properly documented, and comments should be made if any of the stops were due to issues with the surveying equipment guiding the paver. Over time, both the contractor and SHA will learn how to mitigate certain situations.

Minimum Versus Optimal Requirements

Most manufacturers of AMG technology require a minimum of three robotic total stations to guide mainline pavers. Two robotic total stations control the paver, and the third one is used for real-time verification and storing data to produce electronic reports. The third total station is also used to leapfrog the paver as it moves down the grade. As illustrated in figure 5, the total stations must continue to leapfrog the paver to relinquish control of the machine from one sensor to another. Often, this leapfrogging process cannot keep up with the speed of the paver, forcing unnecessary stops and restarts, which may result in localized areas of roughness on the pavement. Further, setting up the minimum pieces of guiding equipment provides no contingency for malfunctioning equipment. Experienced contractors recommend having as many robotic total stations as possible. Setting up about six total stations is considered good practice. Also, having two surveyors to move the equipment and continuously check the machine computer for proper operation is highly recommended.

CONCLUSIONS AND RECOMMENDATIONS

This study set out to test the null hypothesis that AMG technology supported construction methods used for grade control can improve initial pavement smoothness outcomes by comparing projects constructed using AMG technology on successive pavement layers to projects that did not. To test this null hypothesis, five paving projects, in which AMG technology was used on different roadway classes, were selected as case studies. The smoothness measures from each project were compared to a companion project that was similar in scope and size but on which AMG technology was not used for the paving. The selected projects ranged from reconstruction to new construction. Four of the projects were concrete-pavement projects, and one of the projects was an asphalt-pavement project.

The study had practical challenges in obtaining a large sample size and companion projects with adjacent AMG- and non-AMG-technology applications to control other influencing factors. To overcome these challenges, the research team used meta-analysis to evaluate the improvements offered by AMG technology over conventional methods.

The smoothness data collected from the five case studies provide a lack of statistically conclusive evidence to show that AMG technology results in overall better initial pavement smoothness than non-AMG technology. At present, AMG technology can be viewed as a tool to eliminate or mitigate risks that adversely affect smoothness; however, the realization of such benefits depends on how other factors affecting smoothness are controlled.

The benefits and costs of using AMG technology to obtain better paving smoothness outcomes are yet to be fully understood. Contractors typically expect returns on their investments in AMG-technology systems through accelerated construction timelines and material yields; however, some hypothesize that AMG technology also helps achieve smoothness incentives. Thus, examining the influence of AMG technology on the unit prices of relevant pavement bid items and smoothness-related pay incentives in comparison with non-AMG technology is recommended. Future studies can investigate the following questions:

- Are there statistical differences in bid items of AMG and non-AMG projects?
- How do smoothness incentives received on AMG projects compare with those on non-AMG projects?
- Is there a need to update smoothness specifications with the widespread adoption of AMG-technology systems in paving operations?

One of the key observations of this study is how contractors use AMG technology as a tool in their process control. Pavement smoothness is an outcome of a contractor's workmanship and the quality of paving operations. Field observations show that some contractors effectively use AMG technology for grade control, while other contractors with excellent process control might not benefit from AMG technology. Other contractors might still fail to realize the benefits of AMG technology due to poor control of other important material and construction factors that impact smoothness. These contractors might benefit from additional guidance on incorporating AMG technology into the paving process with a recommended list of best practices and a checklist of unique factors, such as those relating to calibration and vertical-level adjustments. The possibility of incorporating the needs of AMG technology–related processes in method specifications can also be incorporated for design–bid–build contracts.

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