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

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FOREWORD

This report documents case studies and data analysis undertaken to assess the impact of using three-dimensional (3D) models and automated machine guidance (AMG) on achievement of pavement smoothness during construction. The studies evaluated how the use of design models combined with construction equipment automation affected initial pavement smoothness and ride quality. Smoothness acceptance data from companion projects with and without the use of AMG were compared in five documented case studies. The results provide an enhanced understanding of how the technology can be used as a contractor tool for quality control and how State agencies can work with contractors to mitigate risks and optimize pavement smoothness. Leveraging AMG technology can result in faster construction, more consistent pavement depths and materials yields, and optimized smoothness.

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Research and Development

Notice

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16. Abstract

Benefits such as faster construction, more consistent material depths, and savings by better control of material yields have already been noted when automatic machine guidance (AMG) is used in successive pavement-construction activities. Now, the question is whether projects using AMG result in improved smoothness compared with those using conventional construction, with all other factors that affect smoothness being equal. This research attempted to test the null hypothesis that AMG for grade control can also improve smoothness outcomes by comparing projects constructed using AMG on successive pavement layers to projects that did not make use of AMG for grade control, with all other factors influencing smoothness for a given project being equal. The research also documented the survey equipment used by contractors to control the positioning of the AMG systems and attempted to gather data in real time during paving to improve smoothness. The results of the documentation were used to develop general guidance for leveraging AMG technology to optimize smoothness outcomes.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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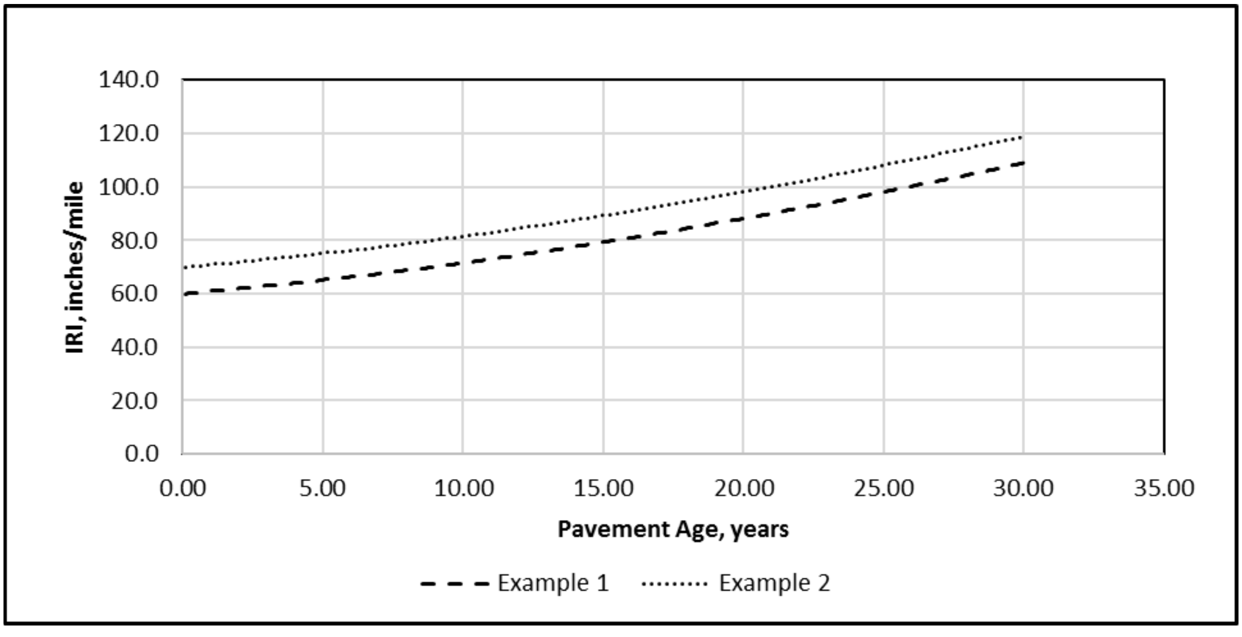
LIST OF ABBREVIATIONS

3D	three-dimensional
AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona Department of Transportation
AHD	extension for proprietary profile data file format from SSI
AMG	automatic machine guidance
CADD	computer-aided design and drafting
CDOT	Colorado Department of Transportation
DMI	distance measurement instrumentation
DOT	Department of Transportation
DTM	digital terrain models
ERD	Engineering Research Division
FAST	Fixing America’s Surface Transportation
FHWA	Federal Highway Administration
GNSS	global navigation satellite system
GPS	global positioning system
GSI	GOMACO smoothness indicator
HMA	hot mix asphalt concrete
HOV	high-occupancy vehicle
IC	intelligent compaction
IRI	International Roughness Index
LiDAR	light detection and ranging
MAP-21	Moving Ahead with Progress in the 21st Century Transportation Act
mmGPS	millimeter global positioning system
MoDOT	Missouri Department of Transportation
MRI	mean roughness index
NCHRP	National Cooperative Highway Research Program
ODOT	Oregon Department of Transportation
PCCP	portland cement concrete pavement
PPF	Filename extension for ASTM E2560 standard file format for pavement profiles
PrI	profilograph index
ProVAL	FHWA profile viewing and analysis software
PSD	power spectral density
QA	quality assurance
QC	quality control
QMP	quality management plan
RTP	real-time profiler
RTS	real-time smoothness
SHA	State highway agency
SSI	Profiling equipment company: Surface Systems and Instruments LLC
TSL	terrestrial static LiDAR

CHAPTER 1. INTRODUCTION

Motorists associate the condition of the road based on their ride experience. Pavement smoothness or ride quality is the number one factor the traveling public associates with road conditions and is the number one criterion for satisfaction.(1,2) To address the needs of the traveling public, State highway agencies (SHAs) started implementing smoothness specifications for construction acceptance of pavements. These specifications indicate the acceptable level of smoothness that contractors must achieve to receive full pavement and incentives and avoid disincentives.(3) Pavement smoothness is defined as the lack of roughness or lack of significant bumps and dips from the pavement surface that cause discomfort to motorists.(4) Smoothness is measured using a variety of methods, which are discussed in chapter 3. National studies show that there is a correlation between initial pavement smoothness and long-term smoothness.(3,5)

Figure 1 is a hypothetical illustration of how pavement smoothness measured in terms of the International Roughness Index (IRI) changes (deteriorates) over time. This illustration shows two example pavements constructed with different initial smoothness, while other factors (i.e., material durability, traffic, design factors) are assumed to remain the same. The figure shows that a pavement that is constructed smoothly initially will remain smooth over its service life—a fact that is backed up by many studies, including National Cooperative Highway Research Program (NCHRP) Project 1-31.(5)



Source: FHWA.

Figure 1. Graph. Correlation between initial pavement and long-term smoothness loss.

Pavement smoothness is one of the national performance measurements with which agencies must comply, in accordance with the final rulemaking put forth by the Federal Highway Administration (FHWA), which was in response to the emphasis placed in the *Moving Ahead with Progress in the 21st Century Transportation Act* (MAP-21), and the *Fixing America's Surface Transportation (FAST) Act*.(6,7) The rule went into effect May 20, 2017. Agencies will continue to focus on managing initial pavement smoothness outcomes using IRI to establish long-term and programmatic targets for performance management measures.

Construction contractors are increasingly using three-dimensional (3D) engineered (or data) models and automated machine guidance (AMG) in construction activities as a tool to control quantities, improve safety, and accelerate schedules, often to meet various contractual incentives. As transportation agencies start to support the use of AMG technology on their projects, they have significantly changed the way they collect preconstruction surveys, design using 3D data models, and perform construction inspection and administration. AMG has been evaluated on various aspects of construction; however, study is lacking on its capability to influence pavement smoothness outcomes.

This report summarizes the literature search that established the framework for the study, presents the methods and technology used for selecting paving projects, and describes the comprehensive case studies of five specific projects in five States: Arizona, Illinois, Iowa, Oregon, and Missouri. The information collected during the case studies was then analyzed to understand the impacts of AMG and to develop recommendations for performing quality control (QC) functions.

BACKGROUND AND SIGNIFICANCE OF WORK

In recent years, the use of AMG has increased with growing market-led adoption by paving contractors. Technology deployment efforts from SHAs, FHWA, and other industry partners have seen an increase in the use of AMG and automation of inspection tasks using the 3D survey technologies that are used for the machine control. As SHAs deploy specifications, guidance, and manuals to manage and support the use of AMG and related inspection technologies for grade control, questions are increasingly being asked about how else construction outcomes might benefit from these new technologies. Improved smoothness has been touted as a potential benefit of AMG-equipped machinery (pavers and graders) because of their superior vertical grade control and accuracy. However, there is no documented proof of this benefit.

Initial pavement smoothness is an important aspect of a pavement’s functional service life. As a proven paving adage goes: if you build the pavement smoother, they will stay smooth longer. Seizing on this reality, achieving better pavement initial smoothness has been a goal of both the asphalt and concrete paving industries for decades. Currently, pavement smoothness is normally assessed after paving operations for a given measurement lot have been completed. For concrete paving, cure times limit access to the pavement to capture smoothness data with a light-weight profiler. Often contractors may not measure smoothness until after the pavement has been ground to improve smoothness. It is common for designers to calculate pavement plan quantities without considering any grinding operation. Therefore, an analysis of bid quantities cannot determine whether AMG operations result in a reduced need to grind to augment smoothness, although contractors have provided anecdotal evidence that it does. More often, construction-related problems that are not corrected in real time can lead to expensive postconstruction fixes to correct irregularities on the pavement surface.

Supplemented by the digital terrain models (DTM) from the 3D environment, AMG provides more accurate real-time horizontal and vertical positioning capabilities, resulting in enhanced precision and control of grading, milling, and paving operations. The use of AMG coupled with real-time smoothness (RTS) measuring tools may become a technology used for better grade control over conventional construction and measurement methods to further enhance construction of smoother pavements; however, this potential outcome needs to be proven using field-validation projects.

RESEARCH OBJECTIVES

Benefits such as faster construction, more consistent material depths, and savings by better control of material yields have already been noted when AMG is used in successive pavement-construction activities. Now, the question is whether projects using AMG result in improved smoothness compared with those using conventional construction, with all other factors that affect smoothness being equal.

This research tested the hypothesis that AMG for grade control can improve smoothness outcomes by comparing projects constructed using AMG on successive pavement layers with projects that did not use AMG for grade control, with all other factors influencing smoothness for a given project being equal. The research documented the survey equipment used by contractors to control the positioning of the AMG systems and any attempts to gather data in real time during paving to improve smoothness. The results of the documentation were used to develop general guidance for leveraging AMG technology to optimize smoothness outcomes. Figure 2 shows AMG grade control for an asphalt paving operation, and figure 3 shows an example of the setup of survey equipment to monitor grade control in AMG operations.

Source: FHWA.

Figure 2. Photo. AMG grade control for subsequent asphalt paving often stops at the top of the granular subbase.[(8)]

Source: FHWA.

Figure 3. Photo. The most efficient tool to capture RTS data may be the equipment used for AMG.(8)

ORGANIZATION OF THE REPORT

Immediately after the introduction presented in chapter 1, chapter 2 begins with a review of the literature on initial pavement smoothness for different types of pavement, including an overview of the factors that have traditionally been considered to significantly impact initial smoothness. A review of the state of the practice in 3D technology used for surveying and design modeling is included next. This chapter concludes with a summary of the best practices in AMG for paving operations.

The approach used to help answer the research question of this report is summarized in chapter 3. This includes an introduction into how case studies were selected, a summary of the case studies, and the data collection approach.

Chapter 4 presents a detailed discussion of the approach used for conducting the statistical analysis for evaluating the improvements offered by the AMG technology over conventional paving methods.

Chapter 5 provides general guidance for mitigating risks and leveraging AMG technology to optimize pavement smoothness results when contractors choose to use the technology on paving projects.

Lastly, chapter 6 concludes with a summary of the study and the findings along with recommendations for future work.

CHAPTER 2. LITERATURE REVIEW

AMG FACTORS AFFECTING INITIAL PAVEMENT SMOOTHNESS

A focused literature search was conducted before selecting case studies to identify the factors affecting initial pavement smoothness and gain insight into the most current and best practices employed for utilizing AMG construction equipment in transportation projects. The literature search concluded that the factors influencing both initial and long-term smoothness outcomes can be categorized into four major groups: pavement design and roadway elements, site conditions, materials type and quality, and construction methods.(3,9,10) The objective of this research is to test the hypothesis that the use of 3D modeling and AMG technology improves the quality of initial pavement smoothness. Also, because extensive studies have been conducted about factors that affect pavement smoothness, this report focuses only on the factors that affect initial pavement smoothness, which were then narrowed down to those that may be better controlled through AMG technology. An example of an application of the technology is shown in figure 4.

Source: FHWA.

Figure 4. Photo. Crushed stone base for asphalt pavement placed with AMG equipment.

Base preparation and paver speeds are among some of the main factors that influence the smoothness of both asphalt and concrete roads. The ride quality of asphalt roads is also affected by the lack of proper compaction and pavement layer thickness, whereas geometric characteristics and reinforcement design are factors that impact the smoothness of concrete pavements. The following factors were identified during this study as those that may be controlled by AMG technology:

- Pavement layer thickness (asphalt pavements only).
- Horizontal alignment (concrete pavement only).
- Surface preparation.
- Paver speed (starts/stops).
- Grade control.
- String-line setup and maintenance (concrete pavement only).

Pavement Design

In asphalt pavements, the thickness of the pavement layers as well as the base type are two factors that can affect the initial pavement smoothness. The preparation of the base surface is a critical process in achieving a smooth road because it provides the foundation for the pavement equipment and each subsequent layer.(5) AMG equipment offers a more regulated and consistent way to control the roadway grade during the placement of the base material, which minimizes bumps and irregularities that may result in poor smoothness. QC procedures should include checking the grade of the base surface before starting paving operations to ensure the best foundation possible for the pavement structure.

The pavement design and roadway elements affecting the smoothness in concrete are base type, joint spacing, dowel bar size and alignment, and steel reinforcement.(3,9,11) The base type is the foundation of the pavement structure that is used for initial grade control. If the grade is properly set during the base placement, the concrete layer starts with a smoother foundation, minimizing bumps and irregularities. Setting the proper foundation is particularly important because, once the material is placed, it is more difficult to adjust. Dowel bars and other steel reinforcement can create roughness on the concrete surface if the material being poured does not consolidate properly or is restrained over the steel. Improper placement of dowel baskets also can make a negative impact in initial pavement smoothness.(3,11)

Roadway Elements

Also, certain roadway elements can affect pavement smoothness in asphalt, specifically length of project and whether it is a rural or urban location. A study showed that urban asphalt projects typically have lower ride quality mainly due to challenges with grade control in areas with many utilities, drainage structures, and other geometric considerations for intersecting roads.(12)

Geometric design (i.e., horizontal alignment and superelevation transitions) introduce potential smoothness problems for concrete roadways due to curvature of the alignment and the variation in cross slope within a short distance.(3,13) The paving pan must adjust to meet the varied cross slope in the alignment, which may negatively affect the smoothness of the pavement. It is particularly important to pay close attention to the operations in curves exceeding 6 degrees of curvature. Similarly, vertical alignments with steep grades can cause issues with the equipment grade control and the setup of string lines.(13) The interval selected for placing a string line should be based on the Winkler foundation modulus[1] on tangent sections.

Designers can use 3D models to optimize the geometrics of the project through powerful visualization during the design process. It is important to note that this type of optimization is limited to new construction and variable-depth reconstruction projects. For both cases, the 3D alignment and profile are controlled by the tie-in location and elevation, but adjustments can be made to optimize smoothness for any other location. Profile optimization for reconstruction projects, where the profile is controlled by a fixed location and cross slope of an existing pavement, may not be possible. Furthermore, grade control and elimination of string lines for concrete paving can also be better regulated with AMG equipment because the horizontal and vertical positioning is controlled by high-precision positioning instruments set up on local survey control. This setup allows the operator and grade checkers to see immediate feedback related to elevation and cross slopes.

3D ENGINEERED MODELS AND AMG STATE OF THE PRACTICE

Preconstruction Surveys

The 3D design model starts with the collection of preconstruction 3D surveys. These data can be captured with a variety of modern surveying technology. According to a 2013 study, most SHAs continue to use aerial photogrammetry as the standard operating procedure for preconstruction data collection, although many use terrestrial static light detection and ranging (LiDAR) (TSL).(14) Photogrammetry surveys continue to be popular because they are cost effective and provide 3D data of the existing conditions, which designers can use for information modeling. However, photogrammetry surveys lack the accuracy required for pavement surface analysis and grade control. Photogrammetry surveys can be augmented with LiDAR surveys for better accuracy. Often the best 3D survey datasets for roadway modeling include a fusion of preconstruction data collected using a variety of methods. While LiDAR surveys improve the accuracy of preconstruction data significantly over that of aerial photogrammetry, only TSL data collection methods can provide the accuracy needed for evaluating pavement surfaces. Figure 5 shows a top view of a topographic file derived from helicopter LiDAR flying at a higher altitude.

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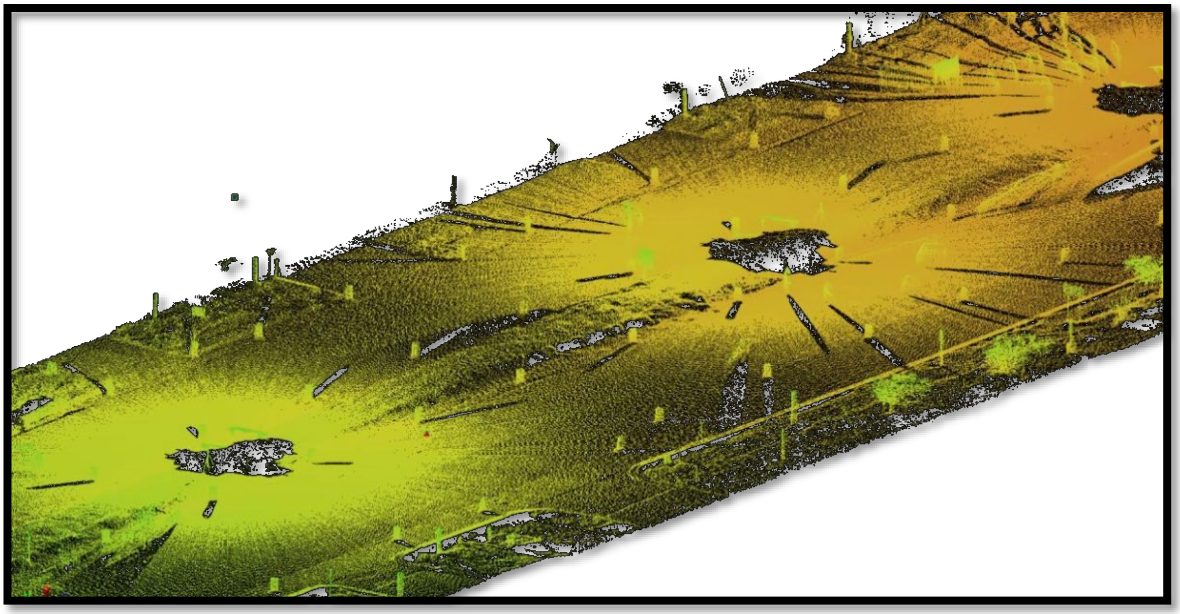
[1] This is also known as the geometric change in grades over the length of a vertical curve (K-value). The term K-value is a critical geometric design parameter used in roadway 3D modeling.

Figure 5. Screen capture. Typical topographic file created from LiDAR data.

It is important to note that for designers to create an accurate pavement surface model to be used in AMG paving operations, they need reliable and accurate survey data that is based on consistent control. These TSL-derived models (figure 6) can provide pavement surfaces that designers can feel confident in using for the pavement analysis and profile grade design.(8) In practice, contractors frequently must enhance the vertical accuracy of control before initiating AMG operations and normally collect new topographic data after doing so, if the original survey data are insufficiently accurate to control grade.

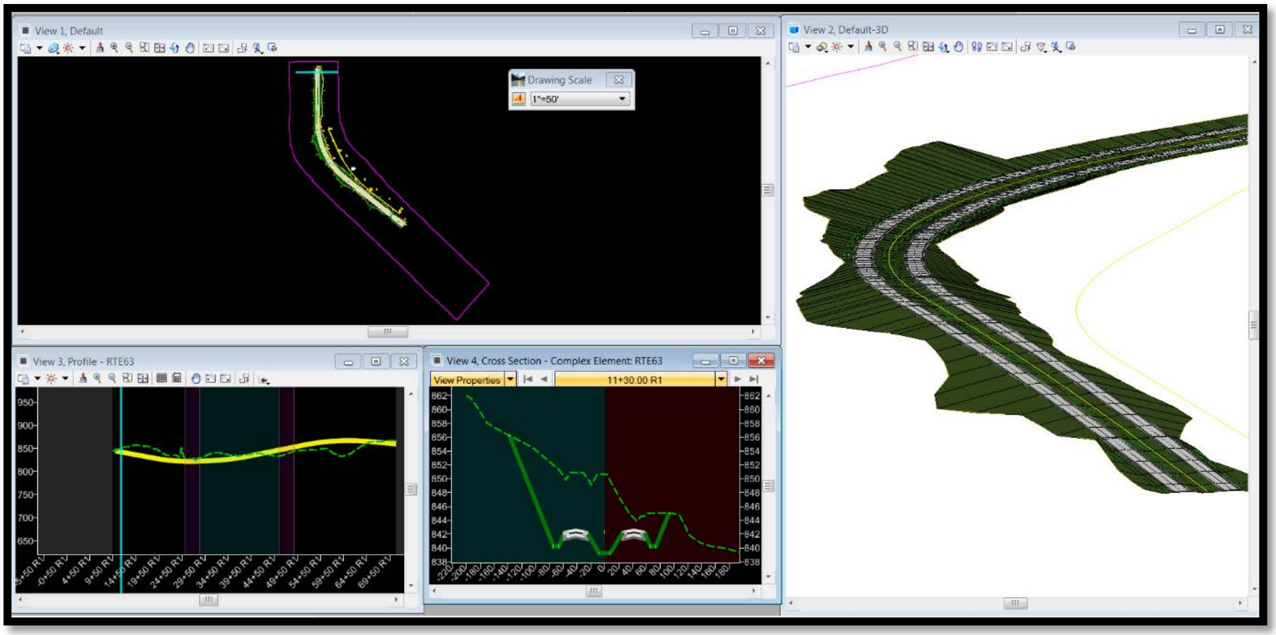


Source: FHWA.

Figure 6. Screen capture. Registered point cloud of preconstruction 3D survey.[8]

3D Design Modeling

Modern design tools that roadway designers use to produce 3D data are becoming more efficient for providing surfaces that can be used in AMG paving operations. Per FHWA, 29 SHAs are either implementing or planning to make 3D engineered models a standard practice, yet the use of 3D design data for AMG operations continues to be a challenge for many reasons (e.g., 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).(15) Iowa, Michigan, Missouri, New York, Oregon, and Wisconsin are some of the States that have mature practices of sharing 3D engineered models as reference information documents or as contractual documents with contractors for AMG operations (figure 7).



© 2015 MoDOT.

Figure 7. Screen capture. Example of 3D corridor design used for highway construction.

Even when a 3D design model is produced and shared with the contractor, there are still several challenges when using these data in the field for AMG construction.(8) For instance, the contractor may use a different software to create a model that can be used with the AMG equipment. In many cases, the contractor may not be able to use the agency-provided 3D model due to the proprietary nature or complexity of the data, thus requiring the development of a new 3D design model based on the paper contract plans using a more familiar software package.

Regardless of the origin of the 3D design model, the accuracy depends on the preconstruction survey data, which are sufficiently accurate for AMG earthwork operations but not for operations requiring higher level positioning, such as paving. Consequently, if the survey was not completed with the accuracies needed for AMG paving operations, the designer may not feel comfortable in providing the data. Other challenges that designers face today are a lack of familiarity with creating 3D models with the detail needed for construction, the lack of universally supported data schema, and a lack of standards by which to create and review 3D models for constructability. The types of files used in AMG paving operations include subgrade and/or pavement surfaces, surveying control points, alignments and profiles, break lines of the pavement structure, and side-slope conditions.(8)

Once a DTM is developed with sufficient accuracy for pavement surface analysis, designers can use tools within their design software package to view the surface and cut profiles along any linear element that represents a path on the model. Similarly, the designer can review the existing surface model and cut cross sections at questionable areas to measure cross slopes. These data can then be exported in ASCII[2] format to be imported into a pavement software to calculate profiler indexes.(16)

Topographic surveys collected with accuracies to support pavement profiling can be used not only to measure multiple profiles along the pavement but also to optimize overlay vertical alignments using 3D design software and profile optimization tools. While profile optimization tools are available in various software packages, anecdotally this type of 3D design analysis is not the current state of the practice in roadway design.[3]

When 3D design models are used for AMG construction operations, the need for roles and responsibilities for reviewing the data must be established and specified in the contract. In addition, specifications or guidelines to address problems as they arise are necessary to avoid claims and major project delays.(17)

The availability of 3D engineered models from designers for contractors to use for AMG technology is a growing practice. A total of 6 States have institutionalized practices for delivering 3D models to the contractors on a for-information-only basis, and 29 are implementing it or planning to make it a standard practice.(15) Nevertheless, contractors continue to create or recreate the model for their own use in AMG construction. Some of the reasons contractors continue to take it upon themselves to create the 3D engineered models include the following:(8)

- SHA does not create 3D models for certain types of projects (i.e., reconstruction and overlays).
- SHA created the 3D model, but the data were not compatible with the contractor's software.
- Contractor needed 3D data models for construction activities typically not reflected in the plans or design model, such as interim surfaces and excavation surfaces for bridge foundations.
- Original survey model was not correct, and project had to be resurveyed and remodeled.

The use of 3D and AMG technologies in milling and resurfacing projects requires significant investments (cost and time) for survey data collection and design modeling. In addition, the uncertainty of the means and methods to be used by the prospective bidders is a real concern for many SHAs.(8) The solution to overcome these challenges is to add a pay item to the contract for surveying the pavement surface. However, this can create some issues, as some contractors may not have the knowledge to understand the data requirements for 3D milling operations. This was the case for a project in Colorado to correct pavement undulations on I-70.(18) The Colorado Department of Transportation (CDOT) required the contractor to collect the pavement surface as part of the contract. The subcontractor used global navigation satellite system (GNSS) technology to collect the pavement surface information, which was not accurate for a milling

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[2] American Standard Code for Information Interchange.

[3] Bartlett, J. 2016. "Determining Theoretical Ride Quality on Projects Performed by Surveying Solutions Inc." Personal Communication. April 4, 2016.

operation, resulting in significant quantity overruns. Although the technology is available to support 3D milling and resurfacing projects, the investments up front to collect survey data continue to be the roadblock. However, new data collection methods are also advancing quickly to provide more cost-effective solutions, such as vehicle-mounted road resurfacing scanner technology.(19) In the meantime, a more cost-effective approach for milling and resurfacing projects is the use of sonic averaging skis on both the mill and the paver.

AMG for Paving Operations

Two types of AMG systems are commercially available for concrete paving operations. The distinct difference in the systems is the type of surveying equipment used to control grade. The system can either rely on a robotic total station or a GNSS-augmented laser setup (known commercially as millimeter global positioning system [mmGPS]). Both systems have two main components: an on-board 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. The computer system interfaces with the paving machine controller (control box) through a control area network and communicates with the surveying equipment to control the grade instead of using string lines. Digital 3D design files are loaded via the computer 3D control software to run the machine guidance system. The operator can monitor values through the controller box display, and measurements may be verified in real time as a QC measure.(20,21)

Robotic total station systems rely on locating the position of two prisms through radio communication that are mounted on the paver, and mmGPS relies on a laser transmitter to communicate with the two laser receivers on board.(22)

For slip-form concrete paving operations, the robotic total station system (figure 8) uses surveying instruments, which are sight control points, and determines their location with resection.(17)[4] The survey instruments then scan the positions of the prisms through radio frequencies and determine the paver location. One survey instrument tracks a single prism on the paver. The computer can calculate the *x*, *y*, and *z* coordinates as well as attitude (yaw, pitch, and roll) of the paver through scanning the position of the prisms. The terms yaw, pitch, and roll are attributes of the paver’s rotation about its vertical, transversal, and longitudinal axis, respectively. All data communication between the robotic total station and the control system are conducted via a radio modem. The minimum number of instruments is two, although, in practice, nine robotic stations are commonly used to provide a third survey instrument for independent grade checking and two additional setups so that the paving operation is not interrupted when it reaches the limit of the robotic total station range (300–500 ft).

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[4] Amann, Jacob. (2016). “AMG Equipment and Paving Operations Used by Ajax Paving Industries.” Personal Communication. May 18, 2016.

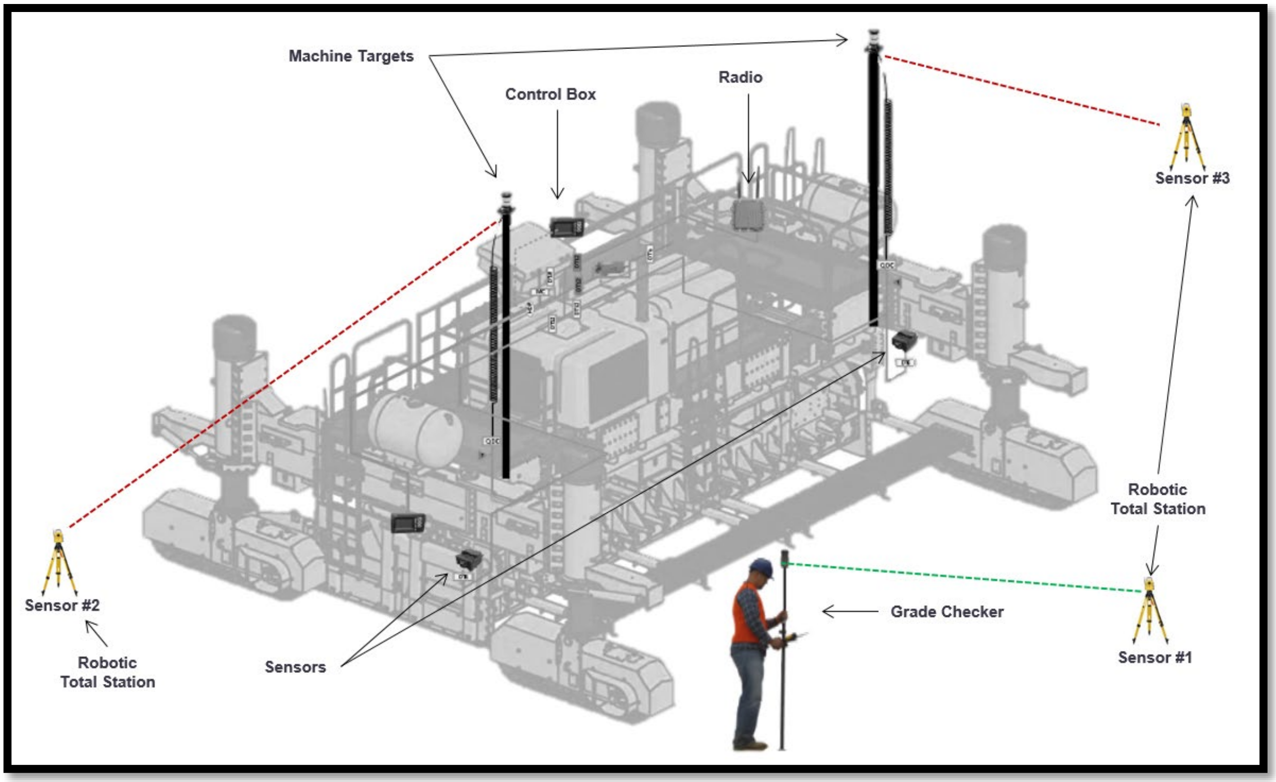

Figure 8. Illustration. Robotic total station-controlled AMG system for concrete paving.(23)

By contrast, the mmGPS system (figure 9) uses real-time kinematics GNSS triangulation for calculating horizontal positioning while the laser transmitter fine-tunes the vertical positioning of the machine.(22) Multiple laser transmitters are needed to support continuous paving operations.

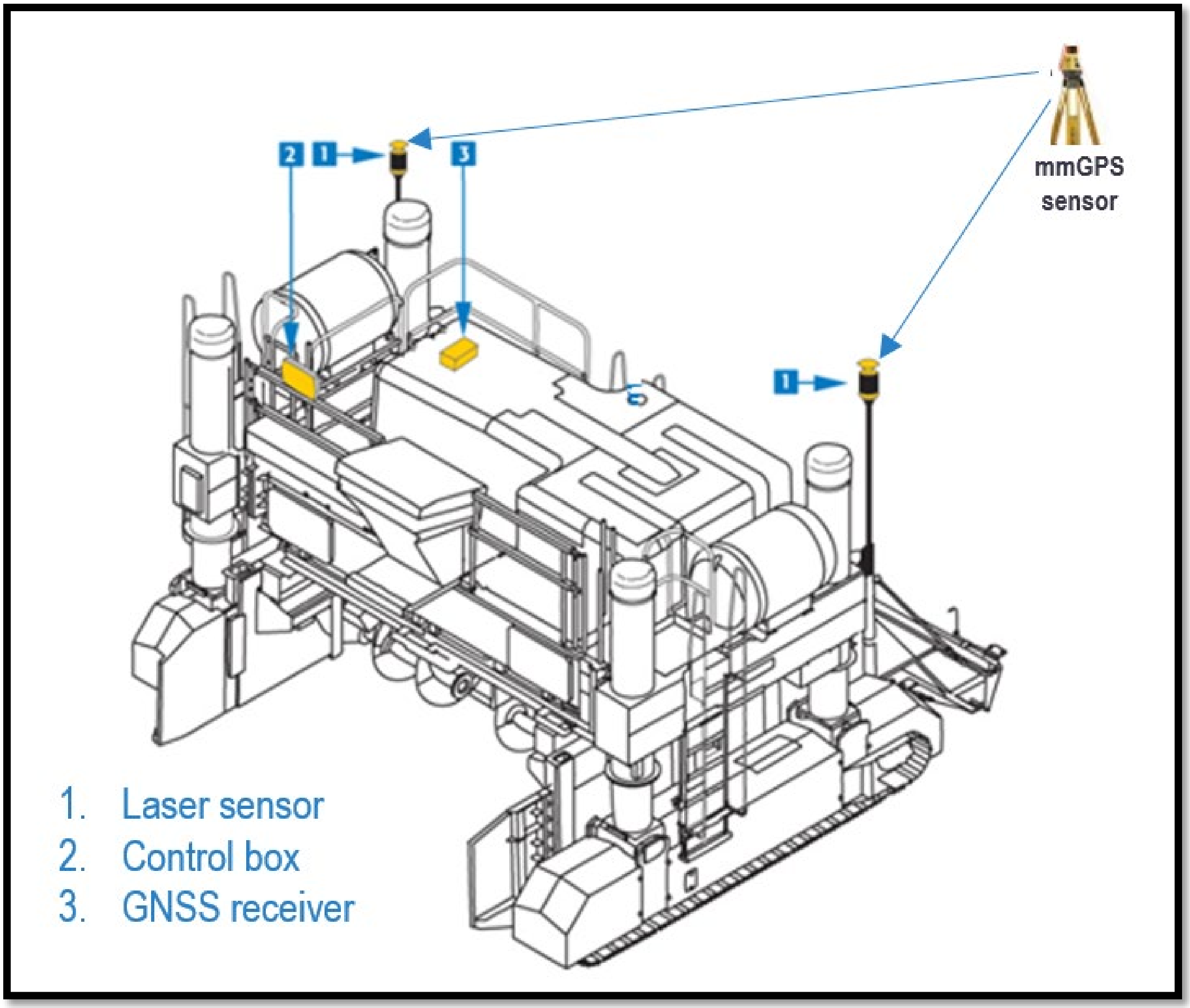

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Figure 9. Illustration. AMG system for concrete paving controlled by GPS laser augmented technology.(22)

AMG systems for asphalt paving operations use similar technology as in concrete paving. In addition to the positioning sensors on board (robotic total stations or mmGPS), asphalt paving AMG systems include additional on-board sensors to control cross slopes by using advanced ultrasound technology. These cross-slope control sensors may be able to detect irregularities in the surface that contribute to problems with achieving the desired smoothness of the pavement.

In practice, AMG systems for asphalt paving are rarely used in highway construction, although there may be some applications in complex geometric corrections, such as superelevation improvements and variable depth paving. However, asphalt pavers are less sensitive to grade-control systems. A common practice for asphalt paving is to prepare the top of the stone base using AMG systems and pave consistent depths with sonic averaging skis on the paver.(1)

Additional Automation Systems Used in Paving Operations

Contractors are starting to use two other systems in paving operations: intelligent compaction (IC) and RTS sensors.

IC technology (figure 10) is used for the compaction of road materials (i.e., soils, aggregates, and asphalt pavement materials), using modern vibratory rollers equipped with an integrated measurement system. As with other machine guidance technologies, IC uses GNSS positioning and on-board computer systems to facilitate real-time compaction monitoring and to enable the operator to make timely adjustments to rolling patterns during the process. IC can also maintain records of the compaction operation that can be used for contractor QC.(24) No studies were found that indicated that the use of IC improves asphalt pavement smoothness.

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Figure 10. Photo. Intelligent compaction equipment.

AMG concrete systems may soon be combined with a new emerging technology to measure pavement smoothness in real time. A recent case study funded through the Strategic Highway Research Program evaluated two devices capable of measuring pavement smoothness in real time: the GOMACO Smoothness Indicator (GSI) and the Ames Engineering real-time profiler (RTP) systems.(25) These two systems can be mounted directly on the paver to conduct profile measurements during the paving operation without making direct contact with the pavement surface. Both systems can be used when they are not mounted on the paver, and they provide data files that can be used to calculate profile smoothness indexes (IRI, profilograph index [PrI], and so on). However, only the GSI nonintegrated system can collect data without contacting the surface.

The GSI device (figure 11) uses three separate sensors: two sonic and one slope. These sensors read the smoothness data from the wheel tracks or anywhere else on the surface of the slab “on up to eight traces or four lanes in one pass.”(26) This system can provide immediate data, so the operator can make adjustments in real time, if required. In addition, this device can detect localized roughness in the slab that may need to be fixed, while also recording the location using a distance tracking encoder. This information can be used to repair the concrete surface while it is still in a plastic state.


[redacted]

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Figure 11. Photo. GSI device attached to a paver with AMG system.

The RTP (figure 12) is a “[l]aser enabled smoothness measurement system [that] monitors profile and calculates smoothness indices directly behind the paver.”(27) This system is also capable of locating localized roughness areas and uses alerts to inform the operator so that necessary adjustments can be made.

Source: FHWA.

Figure 12. Photo. Contractor using profiler equipment.

These two emerging technologies are recommended for use as part of a quality management plan (QMP) for monitoring and making improvements in real time. However, neither technology is capable of measuring suitable quality assurance (QA) at this time, nor it is an American Association of State Highway and Transportation Officials (AASHTO) proven and accepted technology for measuring smoothness specifications, because the fresh concrete smoothness is different from harden concrete. Nevertheless, a draft model was developed for the use in a QMP.(25)

Smoothness Measuring Systems

Smoothness measuring devices for construction acceptance include inertial profilers, which can be lightweight or high-speed devices (figure 13-A through figure 13-D) and profilographs (figure 14).(28) The selection of the measuring system depends on the requirements in smoothness specifications. The inertial profilers collect data for smoothness specification that use IRI, the half-car roughness index, or the mean roughness index (MRI). Profilographs are used for calculating smoothness measurements for smoothness specification based on the PrI.

Source: FHWA.

A. Photo. Hung-from-a-rack inertial profiler.(38)

Source: FHWA.

B. Photo. Bumper-mounted inertial profiler.(38)

Source: FHWA.

C. Photo. Bumper-mounted and hung-from-a-rack inertial profiler.(38)

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D. Photo. Lightweight inertial profiler.

Figure 13. Photos. Inertial profilers.

Figure 14 illustrates the components of an inertial profiler, which consists of a pair of accelerometers and laser height sensors (on both wheel tracks), and a distance measurement instrumentation (DMI) mounted on a host vehicle, either a truck or a golf cart. The accelerometer collects vertical acceleration signals that can be double integrated into inertial references of the device. The inertial references are used to remove the influence of bouncing of the host vehicle. The laser measures the distance from the device to the surface of the pavements. Combining the inertial references, height sensor measurements, and DMI produce true profile data that can be, in turn, used to compute IRI. Most SHAs require inertial profilers and operators to be certified on a yearly basis.

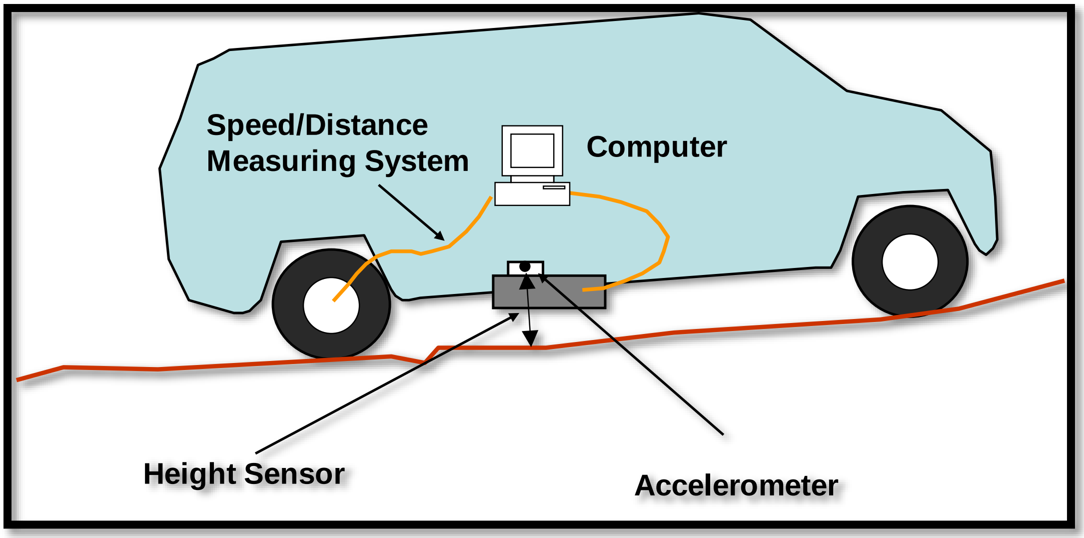

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Figure 14. Illustration. Inertial profiler and its components.

Profilographs are composed of a rigid metal frame with a system of supporting wheels at each end of the device and a center wheel that measures the profile of the pavement. The data acquired are used to calculate the PrI of the pavement but do not measure ride quality. The California profilograph (figure 15) is being phased out because its measurements are distorted at various wavelengths. Inclinometer-based profilers measure the slope in the direction of the pavement measurement using tilt-sensing technology, whereas inertial profilers use height-sensing lasers, accelerometers, and distance-measuring devices to measure true pavement profiles and distance traveled on the pavement. Only inertial profilers can measure true profiles for pavement smoothness index computation, such as IRI.(28)

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Figure 15. Photo. California profilograph.

CHAPTER 3. CASE STUDY PROJECTS

The second phase of the study focused on documenting five case studies, which was a central component of this research. The objective was to compare the smoothness results of each case study using AMG construction methods to those of a traditional string-line paving project (the baseline) of similar scope and size. Another goal was to select case studies that would represent various types of pavements, construction projects, and geographic locations.

SELECTION CRITERIA

Selection criteria were developed in the first phase of the project to test the hypothesis. The research team solicited several SHAs for potential projects to evaluate for final selection. First, the team developed selection criteria based on the nontraditional literature review the team conducted in the first phase of the project; the focus was identifying key factors that affect initial pavement smoothness. A list based on these factors was created and incorporated into a project element data capture tool as a standard form. The form was then shared with selected agencies for gathering information that could be evaluated for case study project selection.

The hierarchy for prioritizing the selection of case studies was as follows: new construction, reconstruction, major rehabilitation (structural overlays), and possibly widening and perhaps minor rehabilitation (thin overlays, mill and fill) as a low priority.

Upon receiving information from SHA, the characteristics of each project were entered into a spreadsheet to keep track of selection criteria. The criteria were based on the following factors:

- Agency and contractor collaboration and buy-in. This information was used to gauge the willingness to participate. Contact information was collected to conduct phone interviews.

- Project length, scope, location, and schedule. This information was used to segregate projects based on project lengths of less than 1, 1–5, 5–10, and over 10 mi. The scope was used to segregate projects according to new construction, rehabilitation, or reconstruction. The provided location was used to determine whether the project was rural or urban, and the schedule was requested to decide whether data would be available in time to finish the project and write conclusions.

- Pavement design. This information was used to segregate concrete and asphalt pavements for specific smoothness analysis.

- Methods for accepting pavement smoothness. This information was needed to ensure the researchers were comparing datasets with similar statistical parameters.

- Availability of preconstruction survey and design model data. This information was used to decide whether the original data could be used by a contractor to use the technology being researched.

- Type of survey equipment used for QC and QA. This information was used to determine whether the project team had the tools necessary to conduct the data collection for statistical analysis.

- Availability of AMG/non-AMG project pairs. This information was necessary to have a sizeable statistical sample.

The selection criteria were based on the primary concern of obtaining the data needed to test the hypothesis. There were several challenges in finding pairs of projects that could provide the best combination for comparison once the details of each project submitted as a candidate were evaluated.

The challenges encountered during the selection of projects were:

- Lack of a diverse pool of projects to study.
- Comparison data were unavailable or difficult to access.

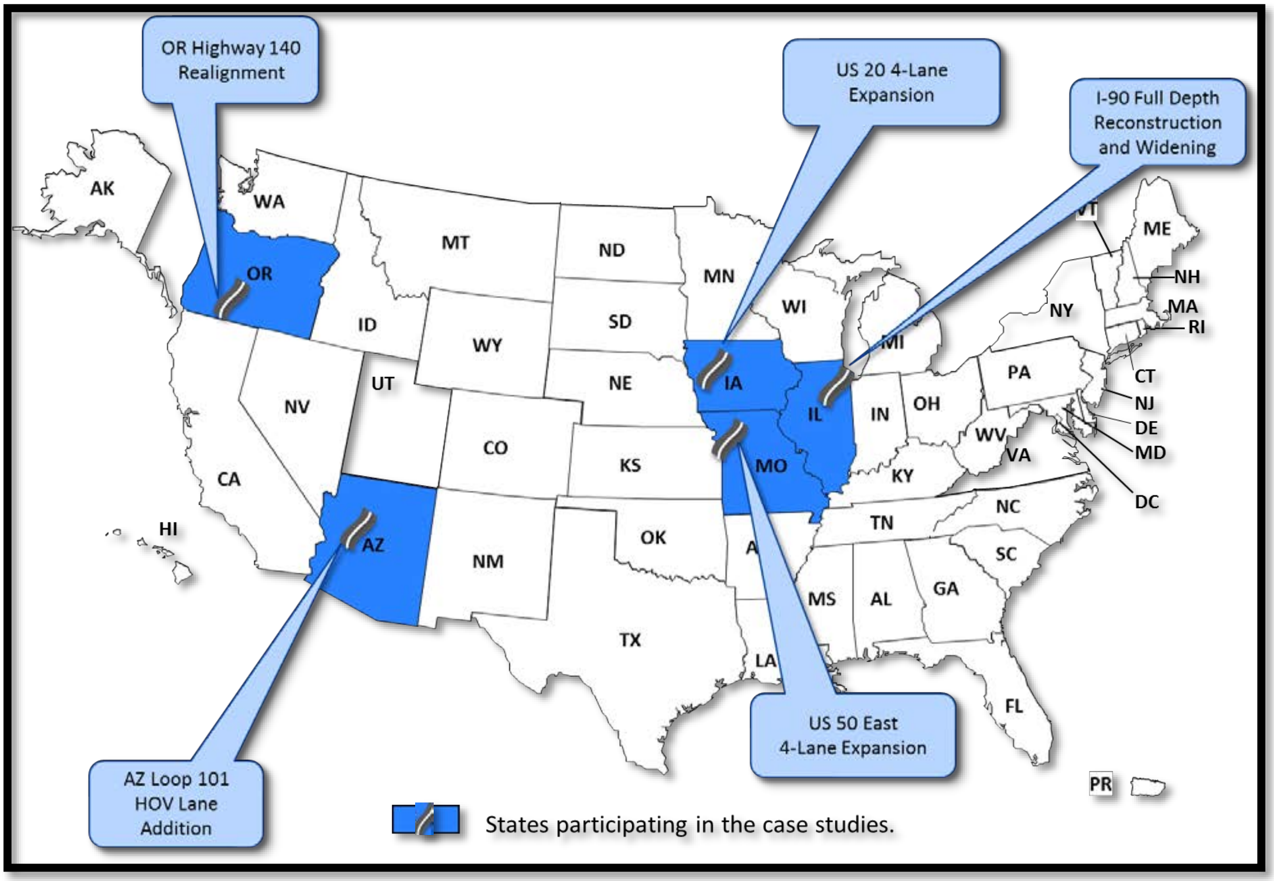
The case study candidates submitted for consideration were mostly concrete paving projects. The team used their professional network to reach out to SHAs, contractors, and pavement equipment vendors to extend the search for case study candidates to include asphalt paving projects. At first glance, the search appeared to be successful, but once more detailed information was acquired from the contractor, it was discovered not to be the case. As the research team began conversations with the contractors, it was quickly discovered that contractors were using AMG technology on asphalt paving for airport runways and racetracks, but not for roadway projects. These contractors explained that the airport minimum requirements for acceptance of pavement smoothness are such that they can only be achieved by placing AMG systems on the asphalt paving equipment or using string lines (not a preferred method). Furthermore, the current requirements for roadway smoothness acceptance, according to contractors, can be met without AMG technology on the pavers. It is important to note that, although asphalt paving contractors may not be using AMG technology on the paving equipment as standard practice, these modern systems are heavily used on excavators and graders. In fact, most of the asphalt paving contractors indicated they have been using AMG for grading for several years. As a result, the criteria were changed to define AMG paving operations as those using these systems for placing the base before the asphalt layer. This criteria selection change helped to identify two asphalt project candidates, but only one of those became a case study.

On the other hand, the use of AMG for concrete paving (also referred to as “stringless concrete paving”) has become a mature practice in the contracting community. For example, States in which the contracting community is using AMG for concrete paving have been doing so for several years. However, this fact created a different challenge for selecting case studies. The research team was able to identify several concrete paving projects in which AMG technology was being used; however, traditional string-line paving projects were not available. Nevertheless, historical smoothness data of similar projects could be used for the comparison, which created a new challenge. On older projects, the type of measurements used for smoothness acceptance may have been different from current practice. For example, some of the project candidates submitted had historical smoothness data accepted using PrI instead of IRI. The main reason that almost all SHAs are moving to IRI for smoothness acceptance is due to the distortion of PrI that does not reflect ride quality. Furthermore, using IRI would make construction smoothness acceptance consistent with all network data required for submission to the FHWA Highway Performance Monitoring System and for the MAP-21 and FAST performance measures.

Even with all the challenges encountered, five projects were selected for case study documentation and data analysis, which are described in the next section.

SUMMARY OF PROJECT SELECTED

This section introduces the five case studies analyzed as part of this research project. Figure 16 illustrates their geographic locations, and table 1 provides the list of projects selected as final case studies for this research.



Source: FHWA.

Figure 16. Map. Location of case study projects.

Table 1. Summary of projects used for case studies.

Agency Name	Case Study Name	Description
ADOT	Arizona Loop 101	PCCP, new roadway construction to add an HOV lane and median barrier for 30-mi of an urban freeway (in each direction). Baseline comparison: Arizona Loop 101. Half of this project was paved using AMG technology and the other half with string-line methods.
The Illinois State Toll Highway Authority (Illinois Tollway)	Illinois I-90	PCCP, full depth reconstruction and widening for 4 mi of an urban section of I-90. Baseline comparison: Illinois Tollway I-90. AMG paving was tested on *a small* portion of the project.
Iowa DOT	Iowa U.S. 20	PCCP, new roadway construction (expansion) for 7.5 mi of a section of rural highway (two lane to four lane). This project was paved using AMG technology. Baseline comparison: Iowa U.S. 20, also a two-lane to four-lane expansion of rural highway (previous section of paving: 14.5 mi). This project was paved using string-line methods.
MoDOT	Missouri U.S. 50 East	PCCP, new roadway construction (expansion) for 6.6 mi for a section of rural highway (two lane to four lane). This project was paved using AMG technology. Baseline comparison: Missouri U.S. 50 West, also a two-lane to four-lane expansion of rural highway (previous section of paving: 10.9 mi). This project was paved using string-line methods.
ODOT	Oregon State Highway 140	HMAC, new roadway construction for realignment of 9.2 mi of a rural section of Highway 140. This project was graded using AMG graders. The paver itself was not machine controlled. Baseline comparison: a 2.2-mi expansion of the Milwaukee Expressway. This project was graded with traditional graders and pavers (not AMG).

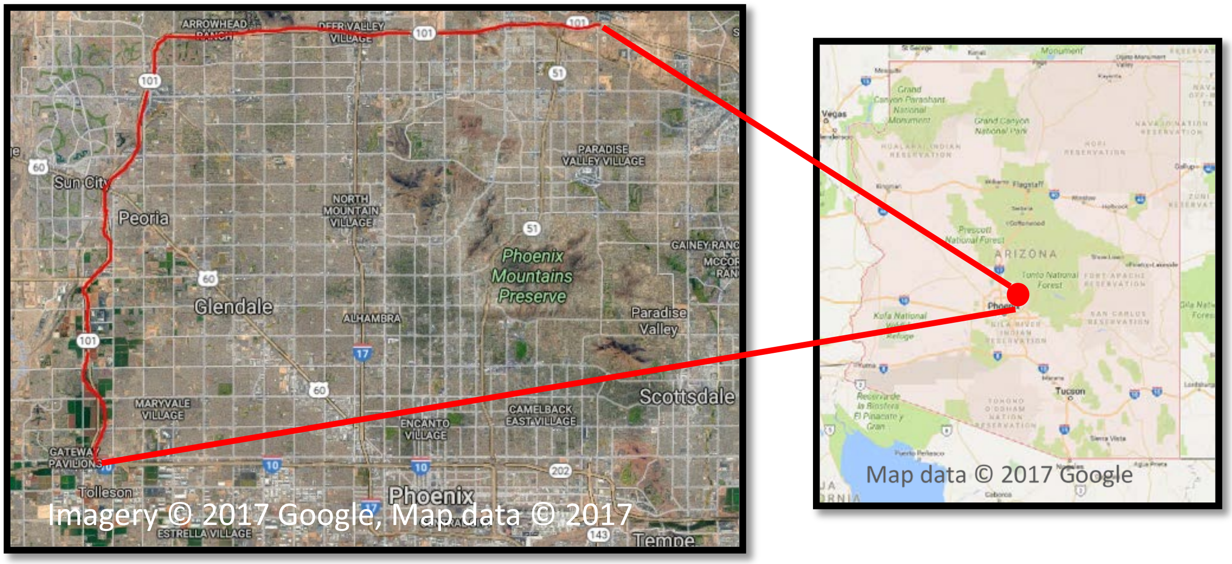
ADOT = Arizona Department of Transportation; DOT = department of transportation; ODOT = Oregon Department of Transportation; MoDOT = Missouri Department of Transportation; ODOT = Oregon Department of Transportation; HOV = high-occupancy vehicle; PCCP = portland cement concrete pavement; HMAC = hot mix asphalt concrete.

CASE STUDY DETAILS

Arizona Loop 101

Project Background

This new roadway construction project consisted of adding a high occupancy vehicle (HOV) lane and median barrier on 30 mi of urban freeway in each direction of the Arizona Loop 101 or Agua Fria and Pima Freeways from I-10 to Tatum Boulevard. in the Phoenix metropolitan area (figure 17). The contract was awarded in December 2010, and the project was completed in November 2011.



Original Map © 2017 Google ®. Annotated by FHWA (see Acknowledgments section).

Figure 17. Map. Location of Arizona Loop 101.

The pavement design used on this project was 12 inches of plain jointed. The elevation of the lane grade was constrained to best fit the existing pavement. The contractor indicated there were two separate setups for this project: one used a traditional non-AMG paving system, whereas the other used an AMG paver. This technology was selected for half of the operation because the contractor in charge of paving that section already owned the equipment, but the other contractor did not own an AMG paving system. This AMG setup would allow the contractor to go faster, which was a priority to meet an aggressive timeline. Additionally, the contractor indicated that an AMG setup would give them the flexibility to move the paver around fixed objects in an urban setting to reduce the time that the construction crew was exposed to traffic; thus, it was a safety consideration. The contractor also specified smoothness was not a major contributor for selecting AMG equipment because it is not necessary to achieve the required smoothness specifications.

3D Modeling and AMG Specifications

Arizona Department of Transportation (ADOT) does not have a standard specification for using AMG construction methods on roadway projects. Because the contractor wanted to use the technology for a significant portion of the project, a special provision to the contract was added to allow the technology. The owner created the preconstruction survey using aerial photogrammetric methods, but the contractor had to resurvey the project to create an existing surface to meet the tolerances for machine-guided equipment. The contractor used a combination of total stations and GNSS equipment to collect the survey, which was then used as a base map to recreate the design from the paper plan sheets using 3D modeling tools. The contractor created a DTM and edge lines and established the alignment and profile grade line in accordance with the plan sheets. These digital files were used to place the base and all pavement layers with AMG equipment (figure 18).

Figure 18. Photo. Concrete AMG paving operation controlled with total stations under live traffic on Arizona Loop 101 (Phoenix metro area).

Equipment and Operations

The contractor set and maintained the survey control for all AMG operations using total stations in accordance with the manufacturer’s guidance at least 500 ft from the paver, but not exceeding 1,000 ft in between setups. The contractor had a checker behind the paver who used GNSS rovers for QC in the AMG section. Also, the checker checked the grade using stakes every 2–3 ft for the string-line setup and every 100 ft for the AMG section. The construction inspector used a straightedge and tape for quality verification.

The contractor indicated there was an equal amount of grinding to achieve the smoothness requirements on both AMG and non-AMG segments of the paving due to multiple starts and stops to move the paver during the operation to avoid light pole foundations.

Source of Smoothness Data

ADOT provided a summary of PrI and IRI reports created by the construction inspector to document the contractor's compliance with the specifications. ADOT pavement smoothness specifications require a surface profile of all sections of pavement to be tested with the profilograph furnished by ADOT.(29) The smoothness results of the pavement are provided to the contractor within 48 h to allow operations to resume as quickly as possible and to locate the areas of the pavement to be ground. Additionally, the agency provided the final smoothness incentive reports that summarize the IRI per 0.1-mi segments. No raw profile data were provided. Thus, the smoothness analysis was limited to the reports provided by ADOT. These reports can be found in the appendix.

Table 2 is an excerpt from Table 401-2 in ADOT's specifications that explains the basis of payment for pavement smoothness of portland cement concrete pavement (PCCP).(29) In terms of IRI, ADOT's target value for newly constructed pavements with asphalt-rubber asphaltic concrete friction course (AR-ACFC) over PCCP is 41 inches/mi. Table 3 presents the basis for incentive/disincentive determination based on the reported IRI values. No pay adjustments are made when the reported IRI at 0.1-mi base length is within two points of the target value of 41 inches/mi, while incentives and disincentives are applied when the reported IRI values are below 39.0 and above 43.0 inches/mi, respectively.

Table 2. Basis of payment for PCCP PrI-based smoothness per ADOT specifications.

Profilograph Index (PI) (Inches per mi per 0.1-mi Section)	Unit Price Adjustment
≤7.0	Plus ($0.20) × [7.0 − (PI)] per square yard ($1.00 maximum)
7.1–8.0	Minus $0.50 per square yard
8.1–9.0	Minus $1.00 per square yard

PI is rounded to the nearest whole number. The "plus" unit price adjustment will not be made for pavement placed within each 0.1-mi section that has grinding in excess of 1.5 percent of the area included in any traffic lane involved.

Table 3. Basis of payment for PCCP IRI-based smoothness per ADOT specifications.

International Roughness Index (Inches per mi per 0.1-mi Section)	Incentive/Disincentive Determination
Reported IRI between 39.0 and 43.0	No pay adjustment
Reported IRI < 39.0	Incentive = $3,750 × (39 − reported IRI)/41
Reported IRI > 43.0	Disincentive = $1,200 × (reported IRI − 43)/41

Table 4 is a comparison of the Loop 101 project smoothness incentives achieved by different methods of paving (AMG versus non-AMG).

Table 4. PCCP smoothness comparison conducted by ADOT on the Loop 101 project based on PrI acceptance.

Parameter	Segment 1 (AMG Paving)	Segment 2 (non-AMG Paving)
Total amount available for smoothness incentives per contract specifications	\$85,878.93	\$100,717.28
Amount paid to the contractor	\$50,251.51	\$74,014.01
Amount of incentives lost due to must-grind areas	\$35,627.42	\$26,676.27
Percent incentive achieved by contractor	58.5%	73.5%
Total number of areas with a PrI greater than 3 (must-grind areas)	447	373
Total number of square yards paved	332,939.9 yd^2	370,065.8 yd^2
Total number of PCCP pour by manual methods	31,569.72 yd^2 (9.5 percent)	31,348.53 yd^2 (8.5 percent)

Smoothness Data Analysis Using ProVAL Software

No raw profile data were provided; thus, a ProVAL analysis was not conducted for this case study.

The smoothness data, as received from ADOT, are summarized in table 5. The table presents the summary of IRI values reported at 0.1-mi base length by segment, direction, and the technology used for construction.

Figure 19 presents the cumulative frequency distribution of reported IRI values. The figure indicates that there is only small difference in the distribution of IRI values between the segments using AMG and non-AMG paving, while about 85 to 90 percent of all reported values were below the threshold value of 43 inches/mi.

Table 5. Arizona Loop 101: summary results based on IRI reports at 0.1-mi base length.

IRI Report File Name	Segment	Paving Technology	Northbound (Inches/mi)		Southbound (Inches/mi)	
H7456_aft.cons_2011-12-23_10.38am.xls*	1	AMG	32.84	4.28	32.47	4.93
H7456_aft.cons_2011-10-21_12.57pm.xls	1	AMG	66.52	5.43	53.49	6.03
H7456_aft.cons_2011-10-4_10.48am.xls	1	AMG	34.61	6.95	35.42	5.29
H7456_aft.cons_2011-11-6_8.36pm.xls	2	Non-AMG	37.11	3.46	34.98	5.49
H7456_aft.cons_2011-8-9_1.03am.xls	2	Non-AMG	37.18	8.07	42.27	11.24
H7456_aft.cons_2011-8-31_12.44pm.xls	2	Non-AMG	30.43	6.31	NA	NA
H7456_aft.cons_2011-12-23_10.38am.xls	2	Non-AMG	32.53	4.73	NA	NA

NA = not applicable.
*The data from (H7456_aft.cons_2011-12-23_10.38am.xls) are excluded due to the fact that the data are located at bridge approach and departure areas.

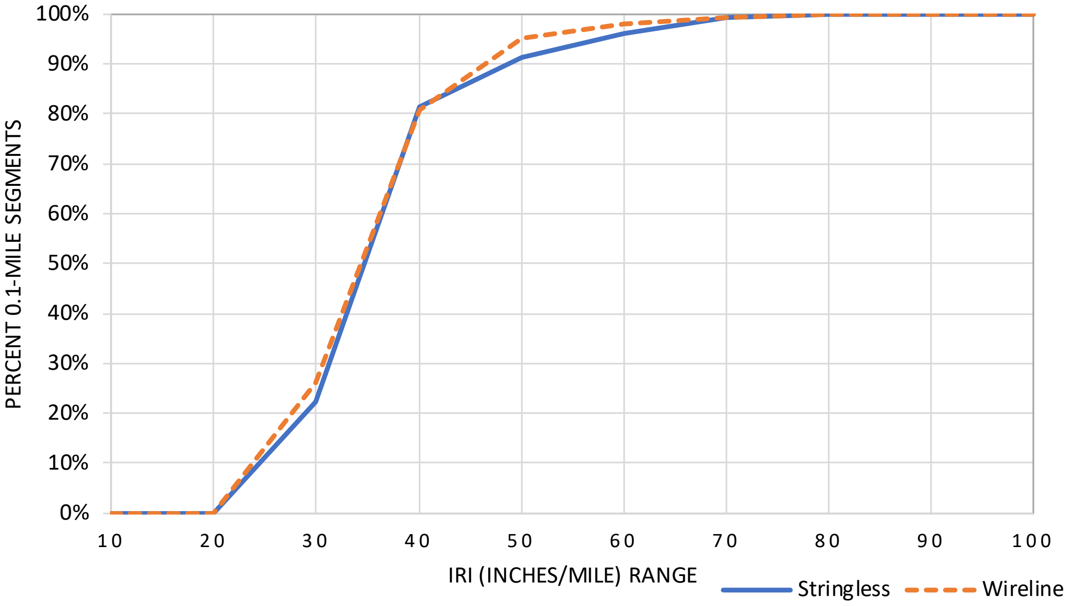


Figure 19. Graph. Arizona Loop 101: cumulative frequency distribution of IRI.

Table 6 presents a comparison of key statistics of IRI for sections using AMG and non-AMG methods. The statistical summary indicates that the segments constructed with AMG paving have slightly better smoothness indicators, in terms of lower average of reported IRI, in comparison with those constructed with non-AMG paving. Lower standard deviation and coefficient of variation indicate the ability of AMG paving to produce relatively more consistent smoothness outcomes than non-AMG paving. In addition, the number of 0.1-mi segments reporting disincentives was fewer for those using AMG than those paved with non-AMG.

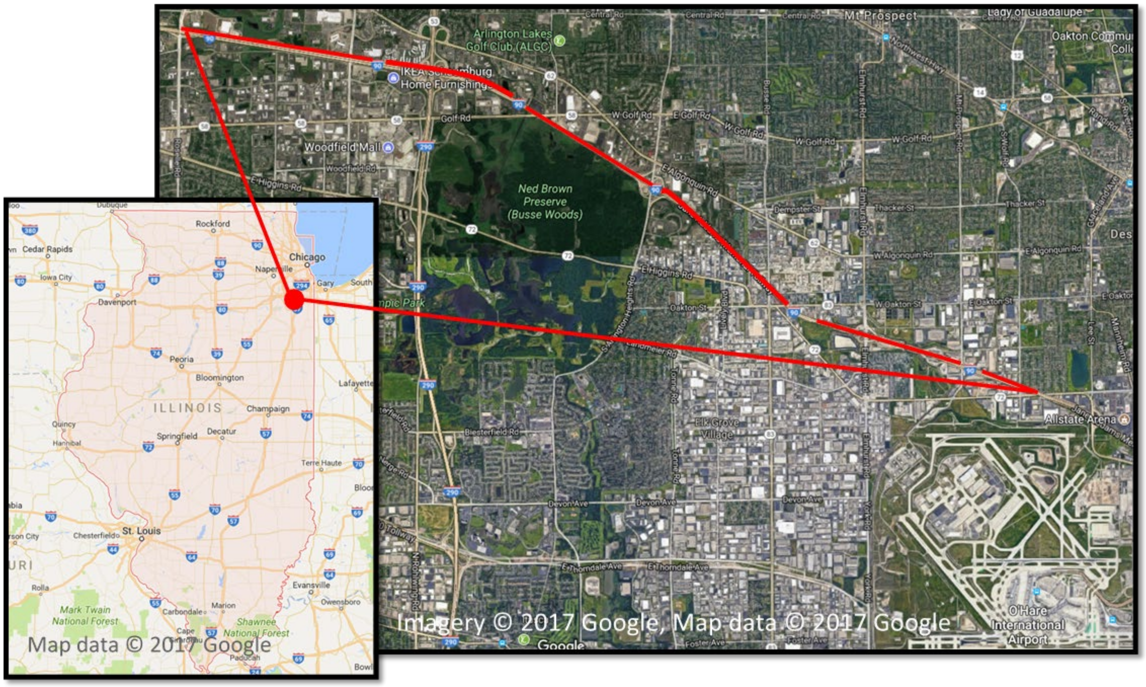
Table 6. Arizona Loop 101: statistical summary of IRI by construction technology.

Statistic	AMG	Non-AMG
Number of segments	223	310
Average IRI (inches/mi)	34.3	35.6
Standard deviation (inches/mi)	5.8	7.9
Maximum IRI (inches/mi)	59.4	78
Coefficient of variation (percentage)	16.9	22.3
Number of 0.1-mi segments with IRI exceeding 43 inches/mi	20	39
Percentage of 0.1-mi segments with IRI exceeding 43 inches/mi	9.0	12.6

Illinois Tollway I-90

Project Background

Contract I-14-4206 scope of work was to complete a full-depth reconstruction for lanes and widening for 4 mi of urban freeway on the Jane Addams Memorial Tollway (I-90) between Higgins Road and Roselle Road in the Chicago metropolitan area (figure 20). The contract was awarded in January 2015, and paving was completed in June 2016.



Original Map © 2017 Google ®. Annotated by FHWA (see Acknowledgments).

Figure 20. Map. Location of Illinois Tollway I-90.

The pavement design used on this project was 13-inches of plain jointed PCCP. The contractor used traditional non-AMG methods to do most of the paving on this project. The contractor had used an AMG paving system for airport projects and wanted to try it on roadway construction. So a small portion of the project was paved with an AMG paving system. The system was subsequently needed on an airport project, and so it became unavailable to pave more test sections on the I-90 corridor.

3D Modeling and AMG Specifications

The Illinois Tollway does not have a standard specification for using AMG construction methods on roadway projects. The owner created the preconstruction survey was created using aerial photogrammetric methods, but the contractor had to resurvey the project to create an existing surface to meet the tolerances for machine-guided equipment. The contractor used GNSS equipment to collect the survey, which was then used as a base map to recreate the design from the paper plan sheets using 3D modeling tools. The contractor created the model directly from the paper plans. The alignments and profiles were established first and then templates were made to run on the horizontal alignment and the vertical profile using the Carlson Civil Suite Software. The templates were then used to guide the paving machine.

Equipment and Operations

The contractor set control points along the centerline 150-ft apart on alternating sides of the pour using traditional surveying methods. Once the control was set, the paver used two total stations to control the machine (one for each side of the paver). Two additional total stations were set up at a maximum distance of 300 ft to leapfrog the equipment to keep up with the paver speed.

Having these additional total stations kept the contractor from stopping the paver. In addition to the total stations on the paver, there was a sonar sensor on the texturing machine and a laser (augmented global positioning system [GPS]) on the belt placer. The contractor had a fifth total station setup for checking line and grade behind the paver. The contractor used a trimmer and concrete paver. Technologies used during this project included a GPS, laser-augmented GPS, and total stations. The only problem encountered during the paving operation was on the first day of paving when the contractor experienced intermittent loss of signal, which forced the paver to stop and restart. Figure 21 shows the paver used on the project.

Figure 21. Photo. Concrete AMG paving operation controlled with total stations under live traffic on I-90 (Chicago metro area).

Source of Smoothness Data

The Illinois Tollway provided raw profile smoothness data (as Engineering Research Division [.ERD] data files) collected with a Surface Systems and Instruments (SSI) high-speed inertial profiler based on the sublots developed for the performance-related PCCP special provision (table 7). These sublots included the sections paved with traditional non-AMG and AMG methods. An IRI map was provided, which included a layout and stationing of the sublots. The researchers used this information to conduct the analysis later discussed in chapter 4. The contractor’s smoothness was likely achieved with a combination of grinding and no grinding.

The owner does not run smoothness measurement before grinding. However, according to the contractor, the grinding was minimal.

It is important to note that only four segments were paved using the AMG paving system; among which three of them had raw profile smoothness data.

Table 7. Smoothness contract specifications.

Smoothness Acceptance Criteria	Value
Target quality level (standard deviation 10)	60 inches/mi (mean value)
Rejectable quality level	>80 inches/mi
Maximum quality level	50 inches/mi (lot mean)

Smoothness Data Analysis Using ProVAL Software

The data received for the Illinois Tollway I-90 project are shown in table 8.

Table 8. Profile data on eastbound I-90 provided by the Illinois Tollway Authority.

File Name	Segment Number	Segment Using AMG Paving
4206_EB-19.erd	19	19
4206_EB-20-22-24-25-27.erd	20, 22, 24, 25, 27	20, 22
4206_EB-26.erd	26	No
4206_EB-35-37-39-42-61.erd	35, 37, 39, 42, 61	No
4206_EB-36-38-40-43-45.erd	36, 38, 40, 43, 45	No

Only four segments were paved with the AMG system; among which profile data were available for three segments (numbers 19, 20, and 22). In addition, there were reported issues with loss signals during the AMG paving operation. Given limited and questionable quality data, the interpretation of the smoothness analysis results can be challenging. Therefore, a power spectral density (PSD) wavelength analysis was conducted to facilitate more detailed investigations of the road profiles.

PSD Wavelength Analysis

Figure 22 shows segment no. 19 (AMG) in red (solid line) versus segment no. 26 (non-AMG) in blue (dashed line). The wavelength contents are similar. The contents under 1 ft are likely affected by surface textures. The wavelengths within midrange (5–25 ft) for the non-AMG case are lower than those of AMG, which is unexpected. Both profiles have been low-pass filtered.

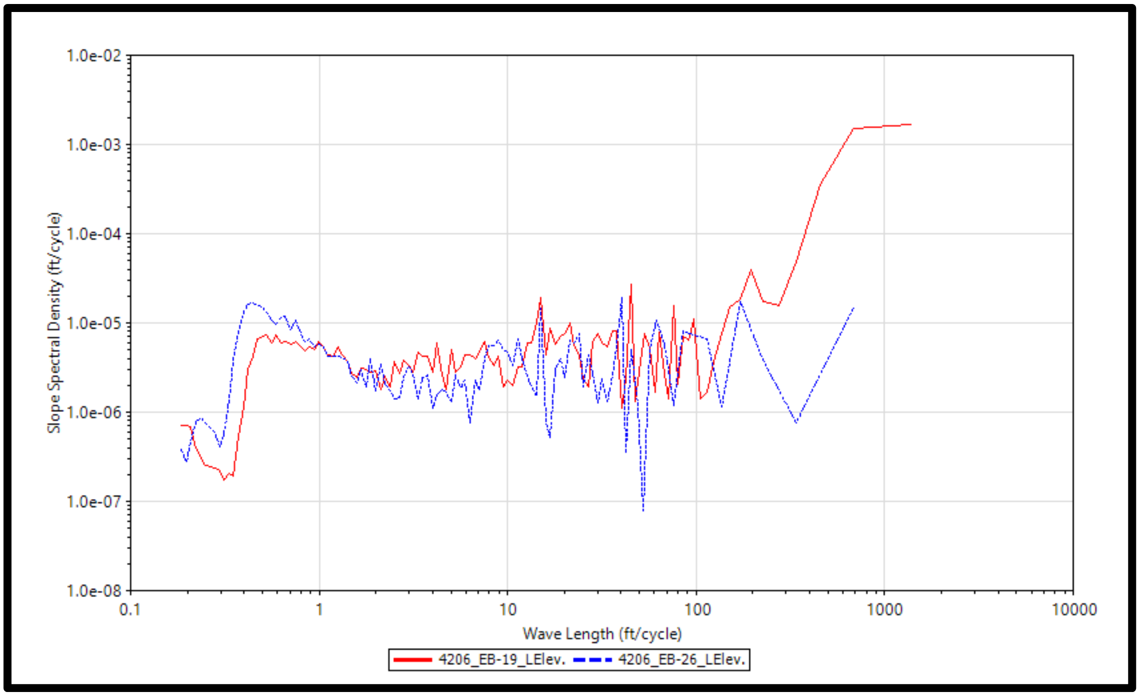


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Figure 22. Graph. PSD wavelength analysis: no. 19 (AMG) versus no. 26 (non-AMG).(39)

Ride Quality Analysis Continuous Reports

Segment no. 19 (AMG) has two localized roughness events, seen in figure 23. One of them exceeds 120 inches/mi.

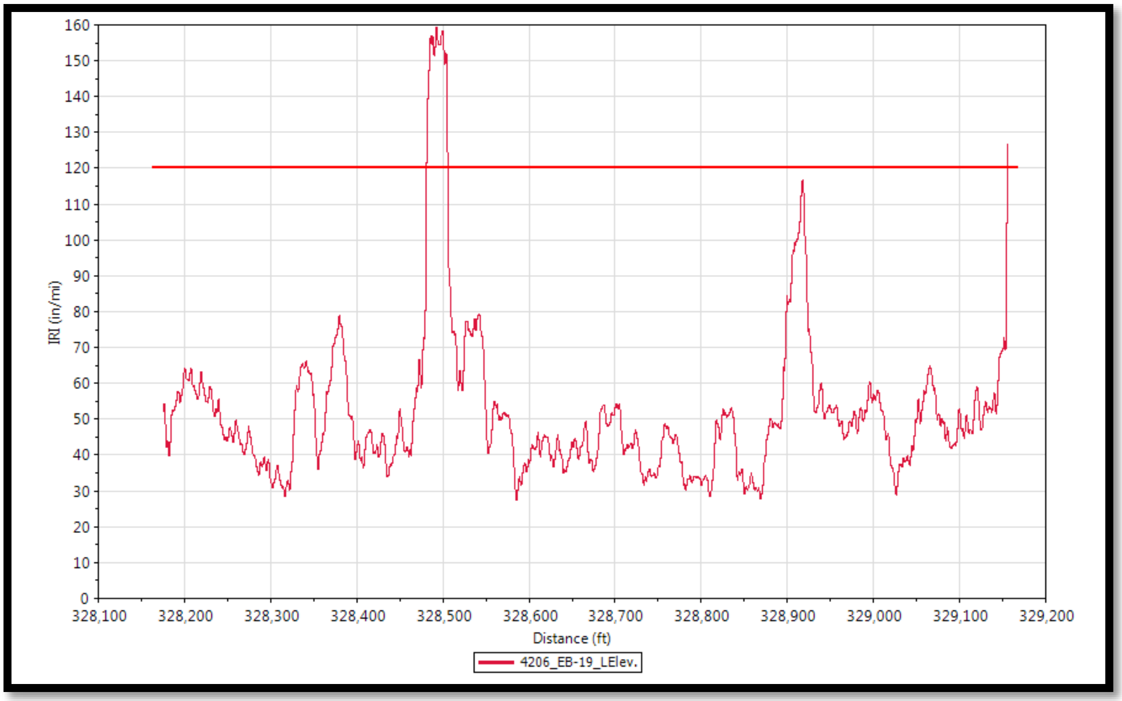

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Figure 23. Graph. Ride quality analysis for segment no. 19 (AMG).(39)

Segment no. 26 (non-AMG) has one localized roughness event that exceeds 120 inches/mi, seen in figure 24. There are no significant differences in other areas.

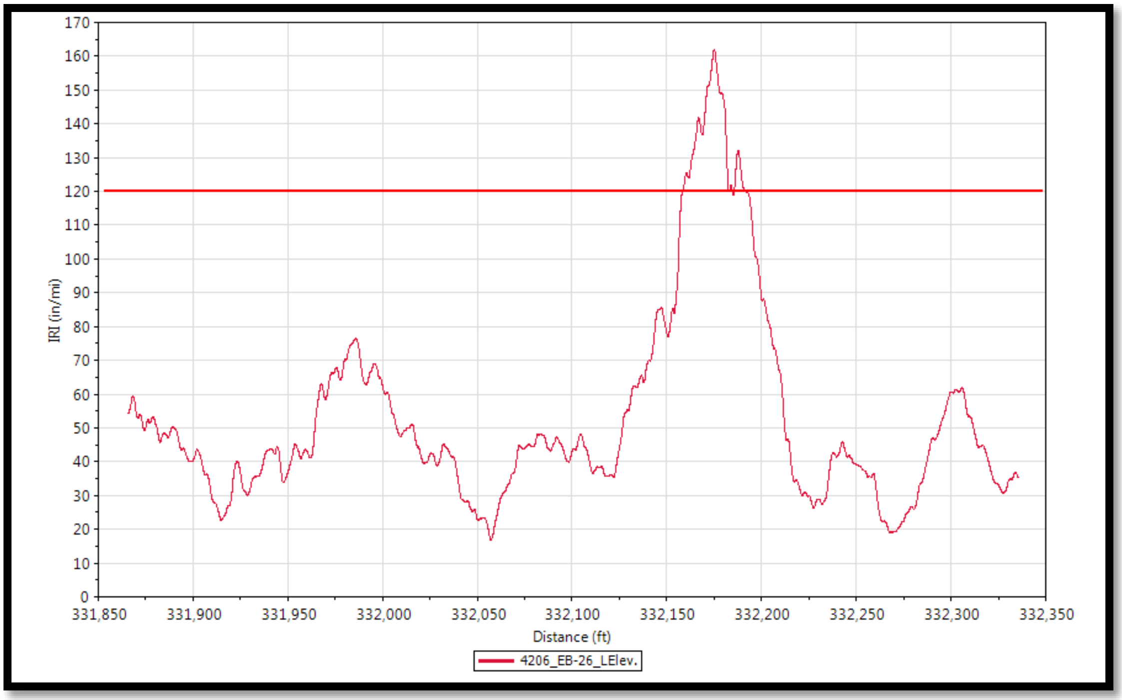

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Figure 24. Graph. Ride quality analysis for segment no. 26 (non-AMG).(39)

Analysis of Mixed Segments

File name 4206_EB-20-22-24-25-27.erd consists of five continuous segments, among which the first two are AMG segments. The profile length is 4,695 ft. Therefore, it is assumed that each segment length is 939 ft. The profile is divided into a 1,878-ft AMG section and 2,817-ft non-AMG section.

The PSD analysis results, in figure 25, do not indicate significant differences between the AMG and non-AMG sections. Both sections are not low-pass filtered, unlike the ride quality analysis shown in figure 22.

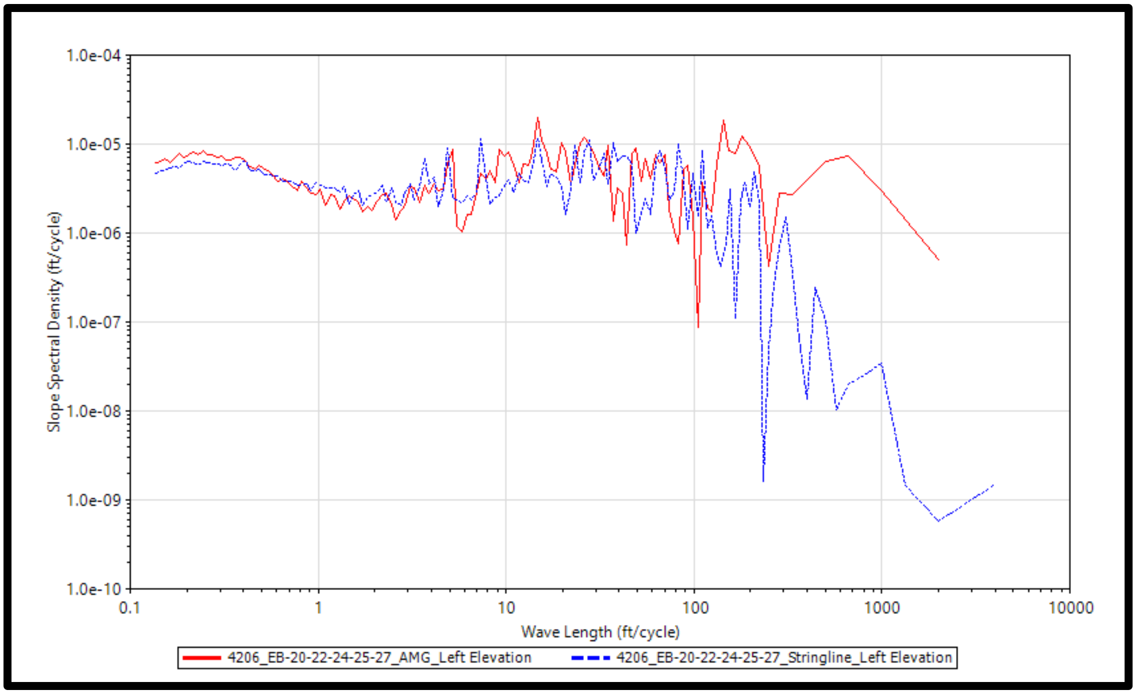

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Figure 25. Graph. PSD wavelength analysis for mixed segments.$^{(39)}$

The continuous roughness analysis is shown in figure 26 (AMG) and figure 27 (non-AMG). The analysis shows that the AMG and the non-AMG have three (three exceed the 120 inches/mi thresholds) and seven localized events (four exceed the 120 inches/mi thresholds), respectively. Although the overall average roughness is the same, the AMG section indicates less localized roughness and more consistent smoothness results.

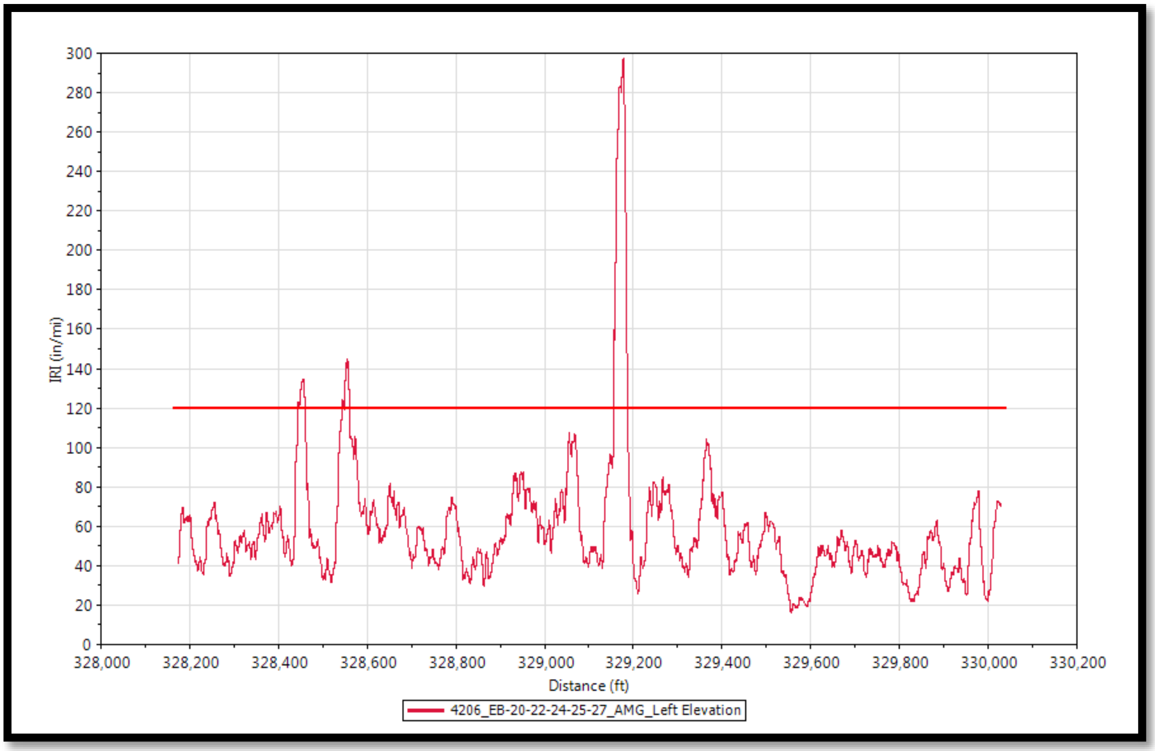

Figure 26. Graph. Continuous roughness analysis for AMG segment.(39)

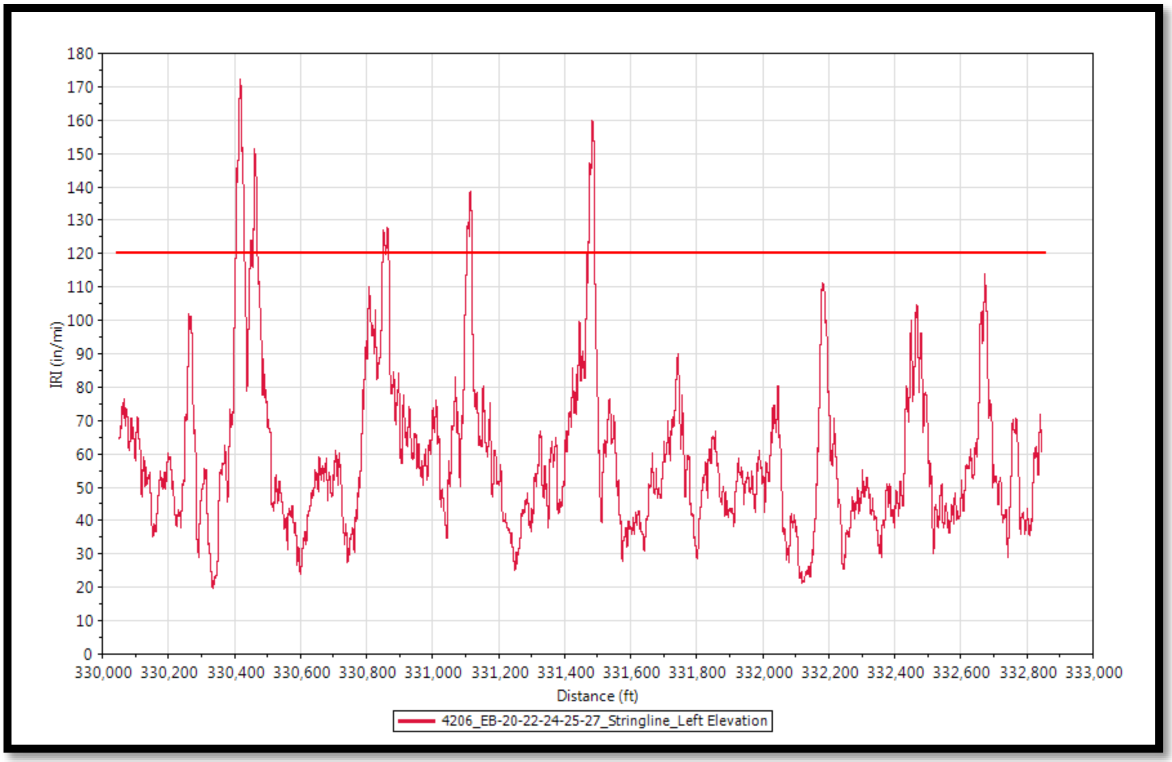

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Figure 27. Graph. Continuous roughness analysis for non-AMG segment.(39)

The following observations were made based on the detailed analysis of road profiles for the Illinois Tollway I-90 project:

- Comparison of segment no. 19 (AMG) and segment no. 26 (non-AMG) does not indicate significant differences in smoothness.
- Analysis was also conducted on a profile that consists of multiple AMG and non-AMG segments. The comparison indicates less localized roughness and more consistent results on the AMG segments, although it was reported that loss of GPS signals causes paver stops.
- It should be stressed that the average roughness results may mask localized issues due to the averaging process.

Statistical Summary

Table 9 presents the statistical summary of IRI for AMG and non-AMG segments. The table indicates that the segments with AMG paving have statistically lower average IRI than those paved with non-AMG. However, because of the loss of signals issues reported during data collected and smaller sample size of AMG segments, the validity of conclusions from the profile data analysis is limited.

Table 9. Illinois Tollway I-90: statistical summary of IRI by construction technology.

Statistic	AMG	Non-AMG
Number of segments	6	26
Average IRI (inches/mi)	56.2	60.3
Standard deviation (inches/mi)	10.1	10.1
Maximum IRI (inches/mi)	69.6	86.8
Coefficient of variation (percent)	18.0	16.8
Number of 0.1-mi segments with IRI exceeding 60 inches/mi	2	12
Percentage of 0.1-mi segments with IRI exceeding 60 inches/mi	33.3	46.2

The inclusion of smoothness data with questionable quality brings in the risk of introducing bias and distortions in statistical measures computed to infer the "overall effect." However, given that the study uses only five case studies, it was decided to retain the Illinois Tollway I-90 data for statistical analysis with a caveat: the I-90 smoothness data will not be simply pooled with data from other sites, rather they will be combined by providing due consideration to heterogeneity. In other words, weights will be assigned to each case study based on how statistical variation is observed within the case study and among five case studies. The case study with higher statistical variation with receive a lower weight, and vice versa, when multiple studies are combined to make inferences about the overall effect. While this approach will help manage the variability issue to some extent, the inferences about "overall effect" have to be managed with and without this study.

Iowa U.S. 20

Project Background

The scope of work for this project was to expand a rural stretch of approximately 7.5 mi of U.S. 20 from two to four lanes east of Sioux City, IA, between Moville and Minnesota Avenue (figure 28). The contract was awarded in October 2015, and work was completed November 2016.

Original Map © 2017 Google ®. Annotated by FHWA (see Acknowledgments).

Figure 28. Map. Location of Iowa U.S. 20.

The pavement design used in this project was 10-inch PCCP with a quality management concrete mix. The contractor used an inertial profiler to produce profile traces of the surface being tested in accordance with Iowa Department of Transportation (DOT) specification 2317.02, which requires the use of PrI for smoothness acceptance.(30) However, the Iowa DOT is in the process of evaluating changing their specifications to use IRI instead, and this project was used as a pilot for that effort. The contractor also used a real-time smoothness sensor to track smoothness of the pavement in real time for QC purposes. A similar project previously constructed was used as the baseline comparison.

3D Modeling and AMG Specifications

The Iowa DOT standard specification 1105.16 provides the requirements for AMG projects, and it is used in conjunction with the construction survey specifications. The agency created the preconstruction survey using aerial photogrammetric methods. Also, original 3D surfaces and string lines were provided by the agency. The contractor hired a subcontractor to build the model needed by the AMG equipment based on the files provided by the agency. The data preparation for the AMG equipment was minimal. The subcontractor made minor edits to complete the original model gaps at intersections and tie-in points using Carlson Civil Suite Software.

Equipment and Operations

The contractor has been using an AMG paving system since 2010 almost exclusively. The survey control is set by the agency every 250 ft. Once the control was set, the paver used two total stations to control the machine (one for each side of the paver) (figure 29). A third total station was used for grade checking. The belt placer and the finisher did not have any machine control.

The project had two different contracts, one for grading and one for paving. The grading and paving contractors were different. Before paving operation started, it was discovered that the grade at the tie-in location was 6 inches higher than those detailed on the plans and the model. The resident construction engineer approved to transition the grade to match the tie-in points instead of trimming the material to keep the project on schedule. The contractor indicated that the amount of grinding on this project was minimal.

Source: FHWA.

Figure 29. Photo. Concrete AMG paving operation controlled with total stations on rural remote site on U.S. Route 20 (east of Sioux City, IA).

Source of Smoothness Data

A total of 20 files containing raw profile data for this project were provided by the contractor. The raw profile data were collected using an SSI profiler. In addition, over 200 files were provided in AHD format for the baseline comparison, which were collected using a profilograph. These AHD format files had to be converted to a PPF profile; however, profilograph data cannot be used to compare inertial data because of distortion of wavelength contents due to the profilograph's inherent mechanical filter and masking effects of using blanking bands. The distortion of wavelength makes profilograph measurements and PrI irrelevant to ride quality. The masking effects may make rough pavements be mistaken for smooth. The reasons are mainly why almost all SHAs are moving to IRI-based smoothness specification.

Smoothness Data Analysis Using ProVAL Software

A pair of the U.S. 20 AMG system files (19-Moville [117]-Driving-16, 20-Moville [117]-Passing-16) were analyzed in detail.

PSD Analysis

The PSD analysis for U.S. 20 is shown in figure 30. The AMG system files were 19-Moville (117)-Driving-16 in the solid red line and 20-Moville (117)-Passing-16 in the dashed blue line. Both profiles were high-pass (at 300-ft cutoff) and low-pass filtered (0.4-ft cutoff).

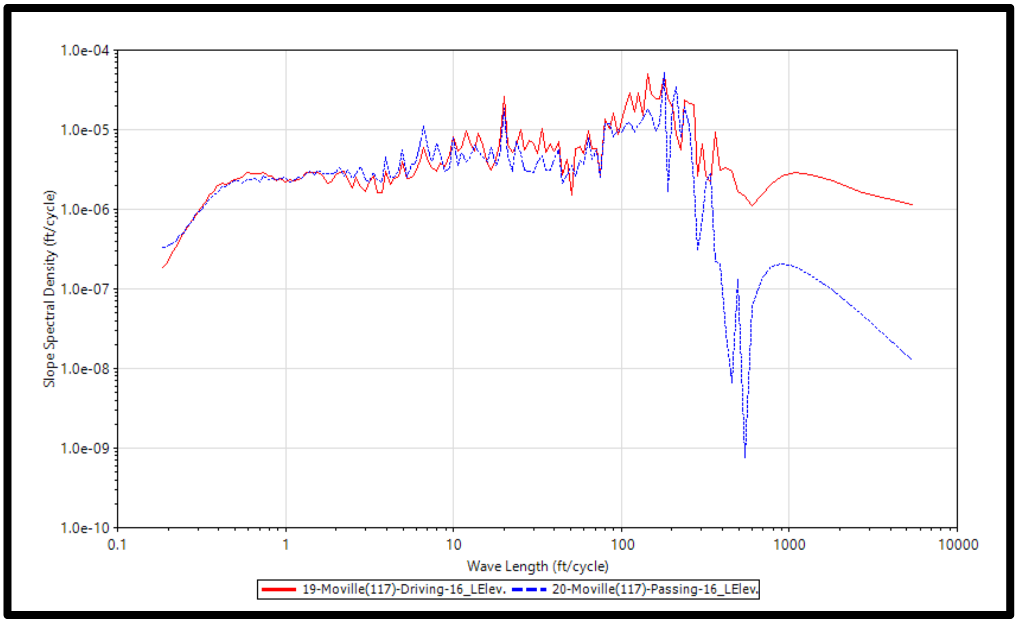

Figure 30. Graph. PSD analysis for Iowa DOT U.S. 20.(39)

Continuous Roughness Analysis

The continuous roughness results in figure 31 and figure 32 show that they are not significantly different from conventional non-AMG paving.

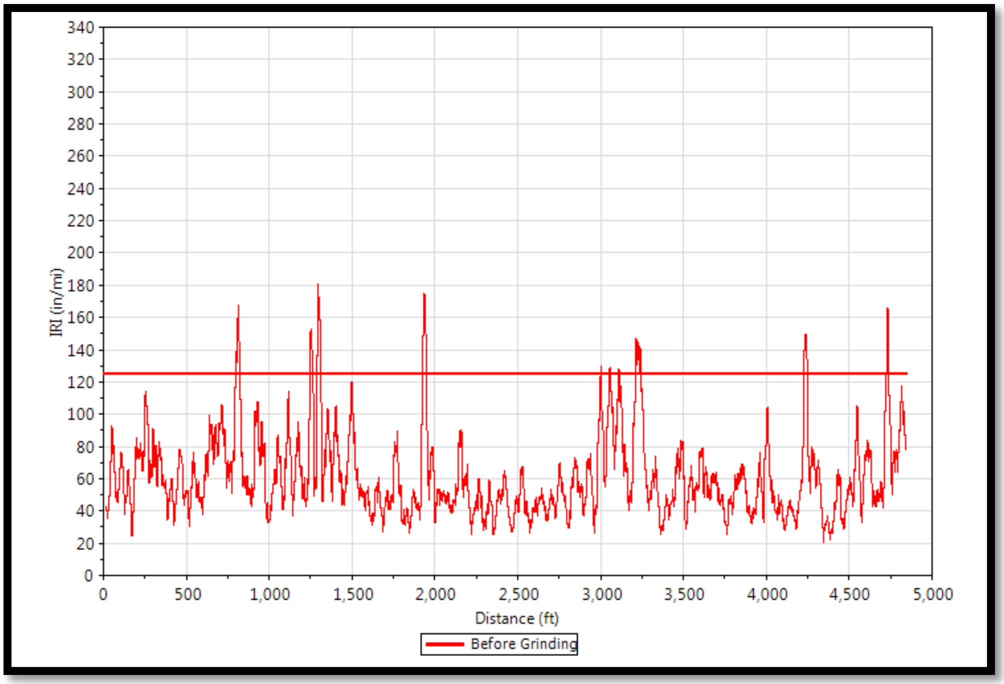

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Figure 31. Graph. Continuous roughness analysis before grinding.(39)

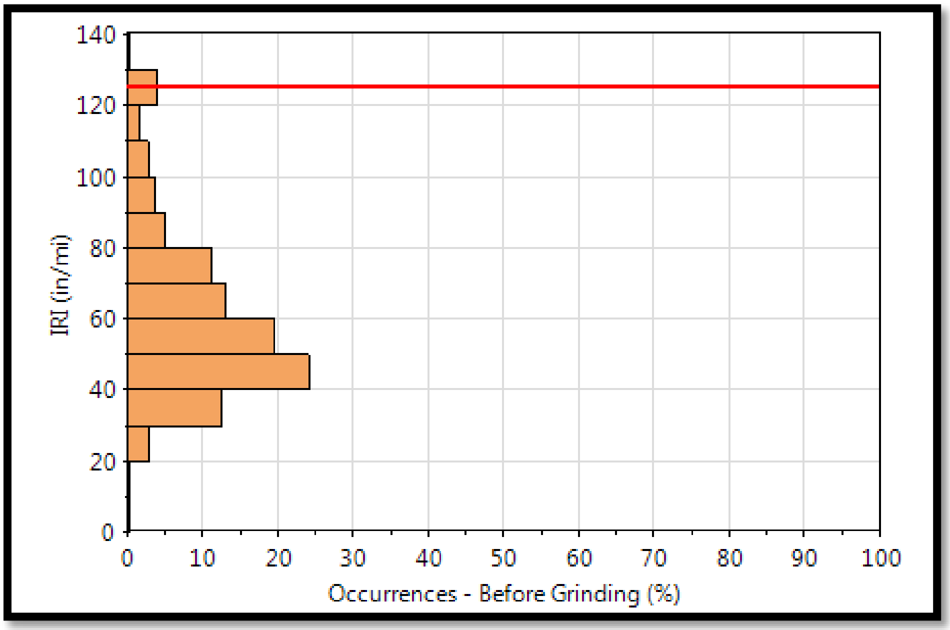

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Figure 32: Chart. U.S. 20 AMG files (19-Moville [117]-Driving-16).(39)

Statistical Summary

Table 10 and table 11 present the summary of results and descriptive statistics of IRI data between the AMG and non-AMG datasets, respectively. Figure 33 presents the cumulative frequency distribution of reported IRI values. Unlike the earlier trends, the smoothness outcomes of segments using non-AMG paving exhibited significantly better smoothness outcomes, in terms of average IRI and uniformity, than those with segments using AMG methods. However, it should be noted that the cohort sections were paved by different contractors.

Table 10. Iowa: summary results based on IRI reports at 0.1-mi base length.

IRI Report File Name	Lane/Direction	Paving Technology	Average	Standard Deviation
AMG	Driving	AMG	59.3	9.8
AMG	Passing	AMG	57.0	9.9
11015	Inside lane	Non-AMG	53.4	7.7
11015	Outside lane	Non-AMG	51.2	8.1
12003	Inside lane	Non-AMG	53.4	7.7
12003	Outside lane	Non-AMG	51.2	8.1
12003	Southbound lane	Non-AMG	72.5	10.3
12003	Northbound lane	Non-AMG	87.3	16.0

Table 11. Iowa: statistical summary of IRI by construction technology.

Statistic	AMG	String Line
Number of segments	170	1,028
Average IRI (inches/mi)	58.2	52.3
Standard deviation (inches/mi)	9.9	8.6
Maximum IRI (inches/mi)	93.1	105.7
Coefficient of variation (percent)	17.1	16.5
Number of 0.1-mi segments with IRI exceeding 99 inches/mi	0	2
Percentage of 0.1-mi segments with IRI exceeding 99 inches/mi	0	0.2

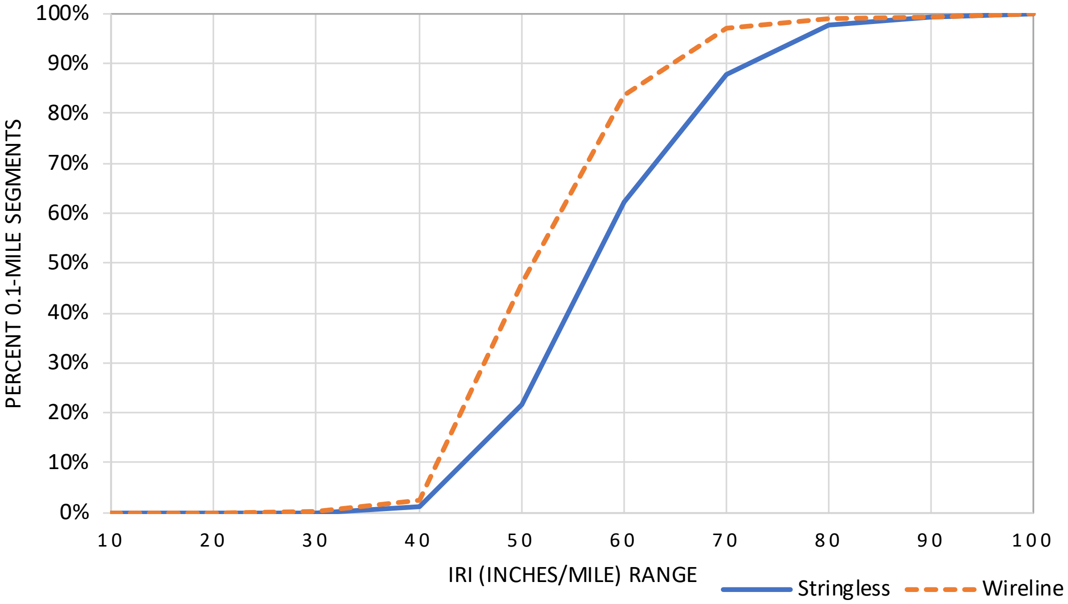

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Figure 33. Graph. Iowa: cumulative frequency distribution of IRI.(39)

Missouri U.S. 50

Project Background

The scope of work for this project was to expand a rural stretch of U.S. 50 of approximately 6.6 mi south of Jefferson City, MO, from two to four lanes between the Route 63/50 junction and just west of Route W (figure 34). The contract was awarded in September 2012, and substantial work was completed in October 2014.

Original Map © 2017 Google ®. Annotated by FHWA (see Acknowledgments).

Figure 34. Map. Location of Missouri U.S. 50.

The pavement design used in this project was 8-inch PCCP on 18-inch rock base. A similar project finished a few years earlier was used as the baseline comparison.

3D Modeling and AMG Specifications

Missouri Department of Transportation (MoDOT) does not have a standard specification for AMG construction methods. However, engineering policy 237.14 provides the requirements for creating and delivering electronic design files for AMG construction methods.(16) MoDOT provides electronic files for alignments, profiles, and cross sections or surfaces, if available, along with the plan sheets during the advertisement of the project. CADD files containing two-dimensional plan view geometry are also provided. The contractor used those electronic files to develop the model that was to be used by the AMG system equipment. The agency created the preconstruction survey using aerial photogrammetric methods, and the contractor set the local control points to guide the AMG paving operation. Figure 35 shows the paver used on this project.

Figure 35. Photo. Concrete AMG paving operation controlled with total stations on rural remote site on U.S. Route 50 (east of Jefferson City, MO).

Equipment and Operations

The contractor set up four stations along the side of the paver 150 ft apart to leapfrog to keep up with the paver and placed a grade checker behind the paver using an mmGPS unit. The contractor collected smoothness data with a light-weight profiler and provided the files to MoDOT to conduct smoothness analysis and compute IRI using the ProVAL software.

Source of Smoothness Data

Several files containing raw profile data were provided for the eastbound (EB) and westbound (WB) lanes for the case study in ERD format. An Ames high-speed inertial profiler with Roline 1K laser or TriODS on one channel was used for the profiling of the U.S. 50 project. The Roline 1K laser is a line laser that can scan 4 inches wide on pavements. The TriODS laser consists of three tiny dots. Both sensors are used to overcome alias of measurements using a single-dot laser on the pavement surface with aggressive textures (e.g., ground) or tined (especially longitudinal tined). Because the project selected for the baseline comparison was completed before the MoDOT switch to IRI smoothness acceptance, the smoothness data were collected using a

California profilograph. However, MoDOT provided historical pavement data (IRI) from the Pavement Management Database to conduct the analysis.

On current projects, including the project studied for this research, the profile data are collected by the contractor using an inertial profiler that meets the requirements of AASHTO Specification M-328.(31) These files are then provided to MoDOT, and IRI values and localized areas of roughness are computed using the ProVAL software. Acceptance is guided by MoDOT Construction Specification Section 610 "Pavement Smoothness."(32) A rolling 10-ft straightedge is used to check longitudinal elevation changes, and a 4-ft straightedge is used for checking transverse elevation changes. Table 12 and table 13 show MoDOT specifications for pavement smoothness acceptance based on posted speed. This contract had smoothness and pavement thickness incentives. Pavement smoothness incentives are shown in table 14.

Table 12. MoDOT specifications for pavement smoothness acceptance for pavements with a final posted speed greater than 45 mph, except multithin overlays or low-volume roads.[1]

International Roughness Index (Inches/mi)	Contract Price (Percent)
≤40.0	105
40.1–54.0	103
54.1–80	100
≥80.1	100 (after correction to 80.0 inches/mi or less)

Table 13. MoDOT specifications for pavement smoothness acceptance for pavements with a final posted speed of 45 mph or less, multilift overlays (3 inches or less), and low-volume roads.

International Roughness Index (Inches per mi)	Contract Price (Percent)
≤70.0	103
70.1–125.0	100
≥125.1	100 (after correction to 125.0 inches/mi or less)

Table 14. MoDOT incentives for pavement smoothness based on IRI.

IRI (Inches/mi)	Payment Amounts
0–22	$950 per segment
22–23.5	$800 per segment
23.5–26	$600 per segment
26–40	Market rate
40–45	Penalty or grinding required
>45	Mandatory correct

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[1] Multithin overlays are those with thickness of less than or equal to 3 inches. Low volume roads are those with AADT less than or equal to 3,500.

Smoothness Data Analysis Using ProVAL Software

Selected files from the AMG case study J5P0951B (Route 50, east segment) for both EB and WB were analyzed. Both of the baseline comparison profiles from non-AMG projects were also analyzed.

PSD Wavelength Analysis

The wavelength contents from these two types of profiler lasers are different, as seen in figure 36. Both profiles were high-pass filtered. The Roline profile appears to be low-pass filtered. It is unknown whether the differences are due to the different lasers used or simply reflect the differences of actual pavement surface characteristics. No more conclusions can be drawn since these profiles are not from the same sections (i.e., not a side-by-side comparison).

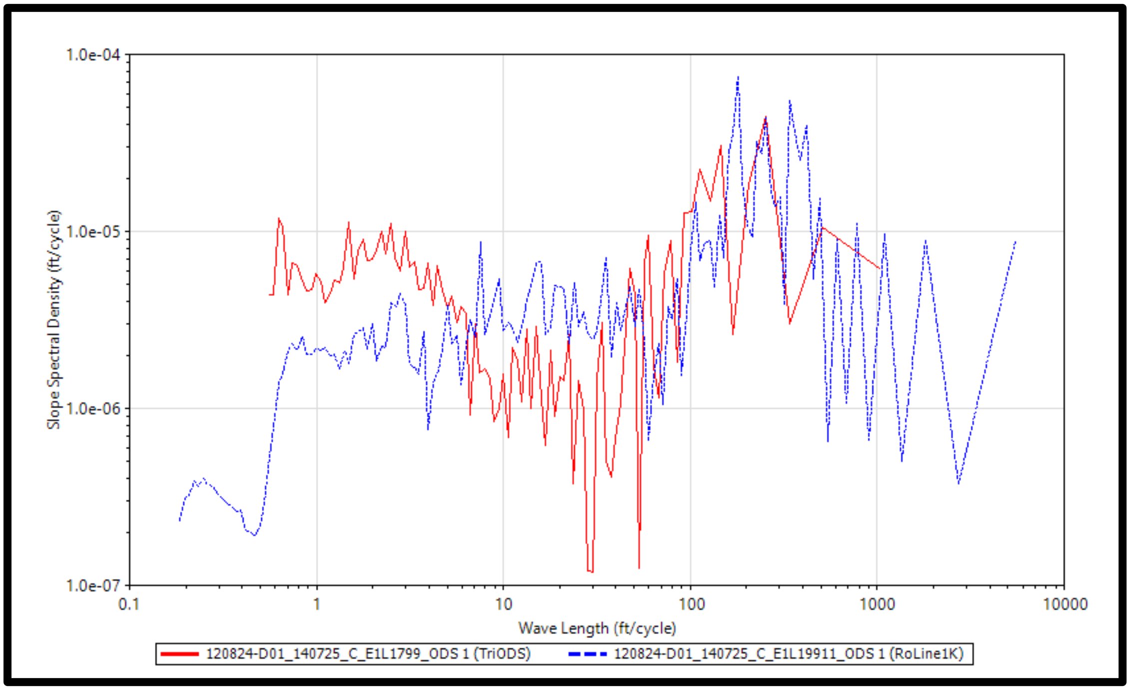

Figure 36. Graph. Comparison between TriDOS (120824-D01_140725_C_E1L1799) and Roline (120824-D01_140725_C_E1L19911) lasers.

Comparison between EB and WB profiles

Figure 37 shows that with Roline lasers there are no significant differences between EB and WB files.

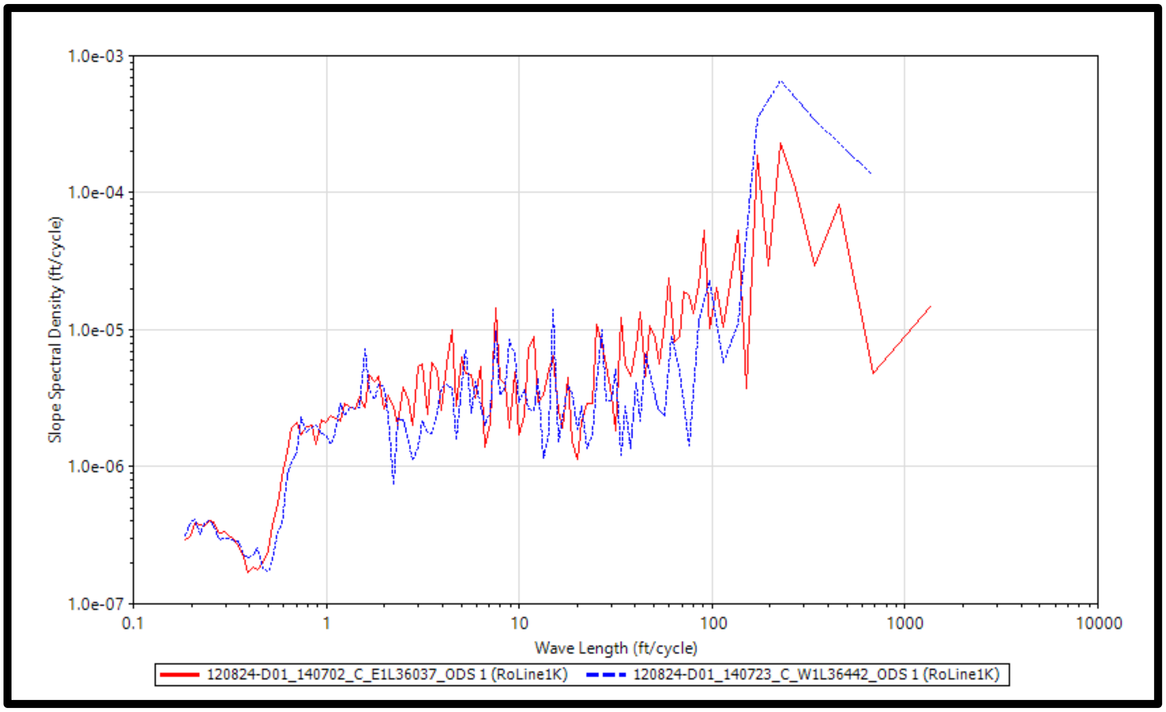

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Figure 37. Graph. Comparison between Roline lasers.

Figure 38 shows that, with TriODS lasers, there are light differences between EB and WB, but the differences may be due to actual differences in pavement smoothness.

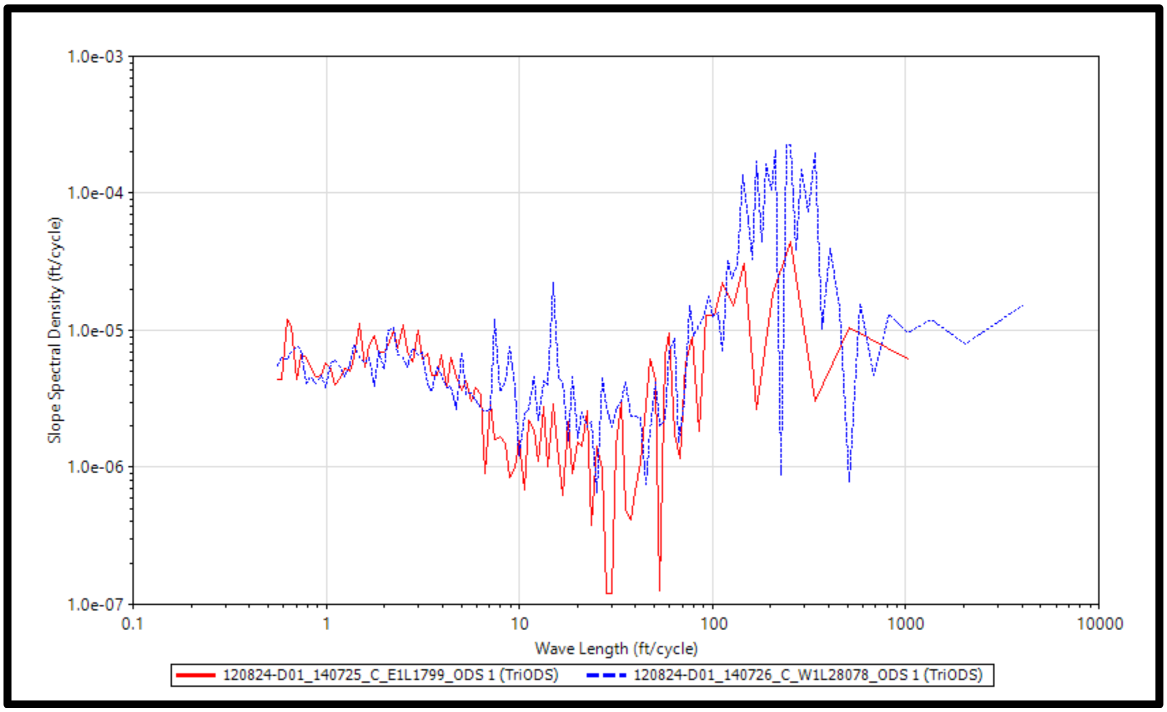

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Figure 38. Graph. Comparison between TriODS lasers.

The PSD results from the comparison profiles, seen in figure 39, indicates both profiles were high-pass filtered (at 200-ft cutoff) and low-pass filtered (at 1-ft cutoff). The 28G0M00 PSD results show a joint spacing of 24 ft.

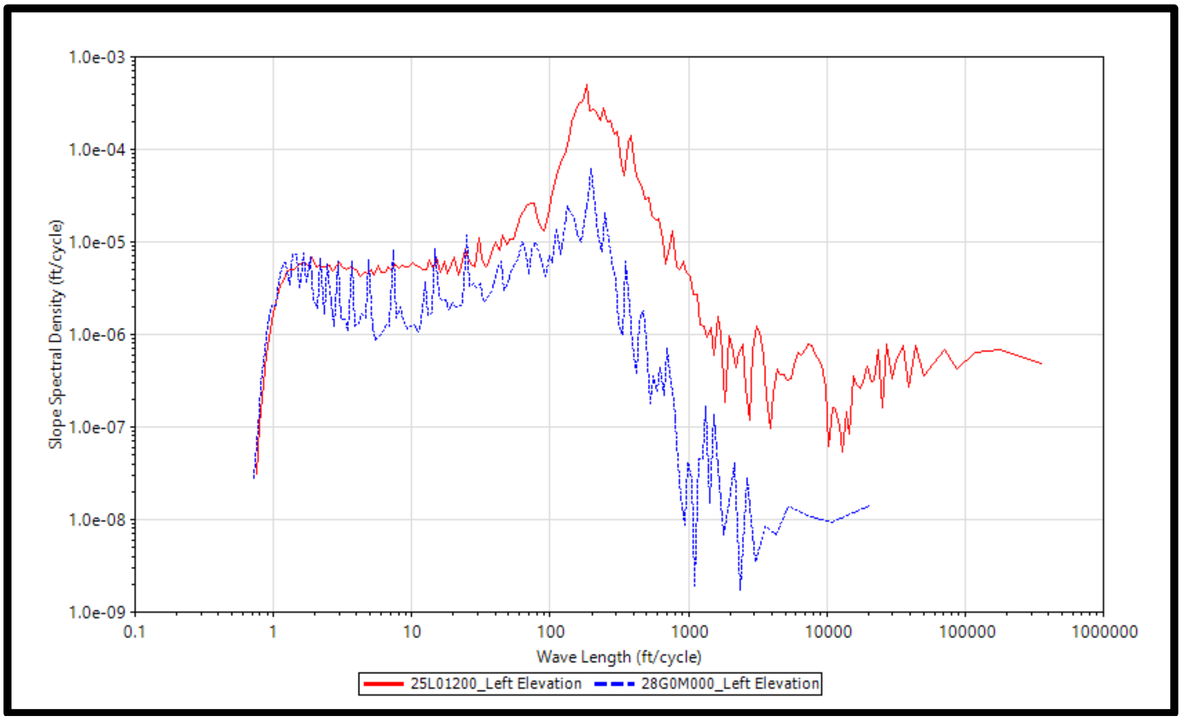

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Figure 39. Graph. PSD comparison between profiles.

Ride Quality Analysis

Example of AMG EB/WB files show some localized roughness areas, but it is not significantly different from conventional non-AMG files. Localized roughness reports for the AMG Roline profile examples from EB and WB are shown in figure 40 and figure 41.

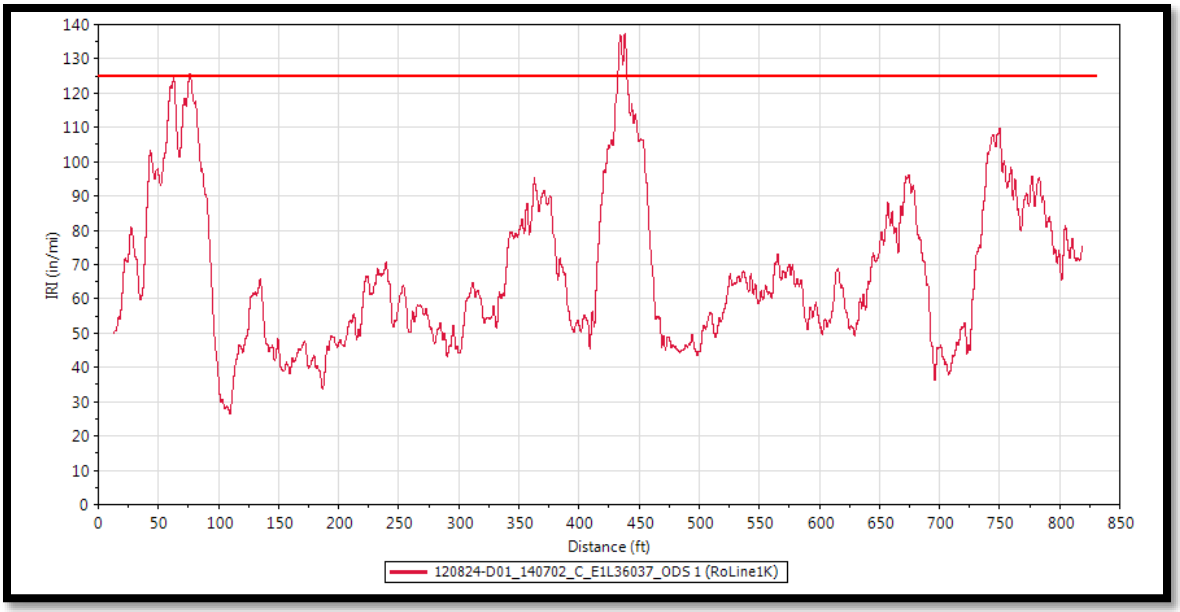

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Figure 40: Graph. Example of localized roughness report from an AMG Roline profile.

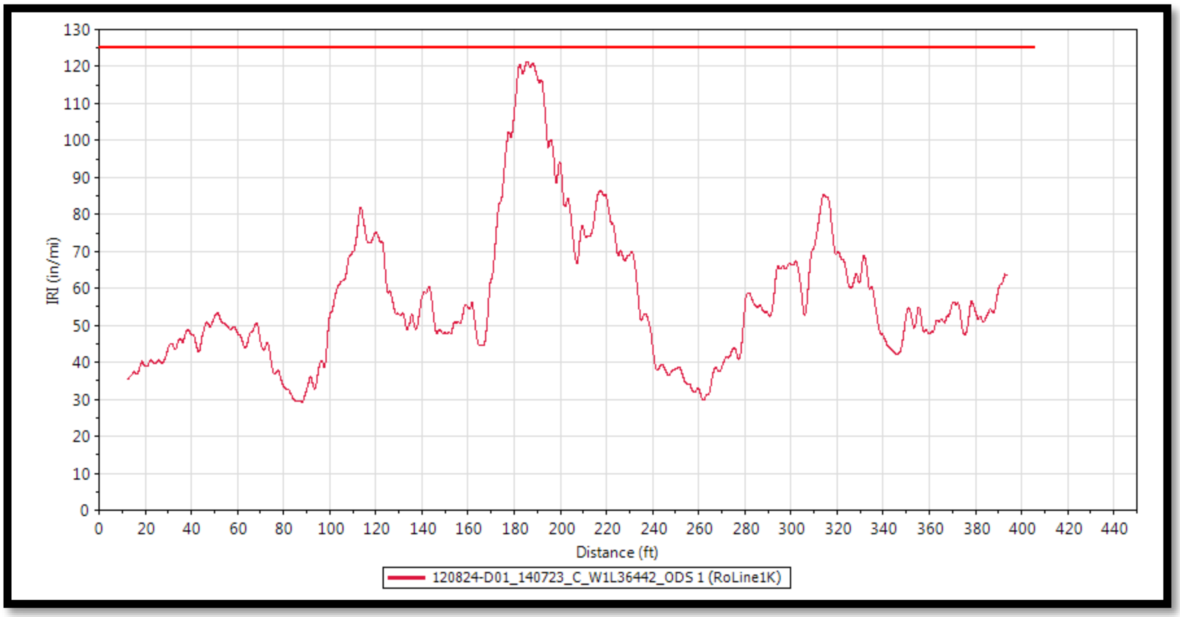

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Figure 41. Graph. Example of localized roughness report from a Roline profile.

The localized roughness reports for the AMG TriODS examples are in figure 42 and figure 43.

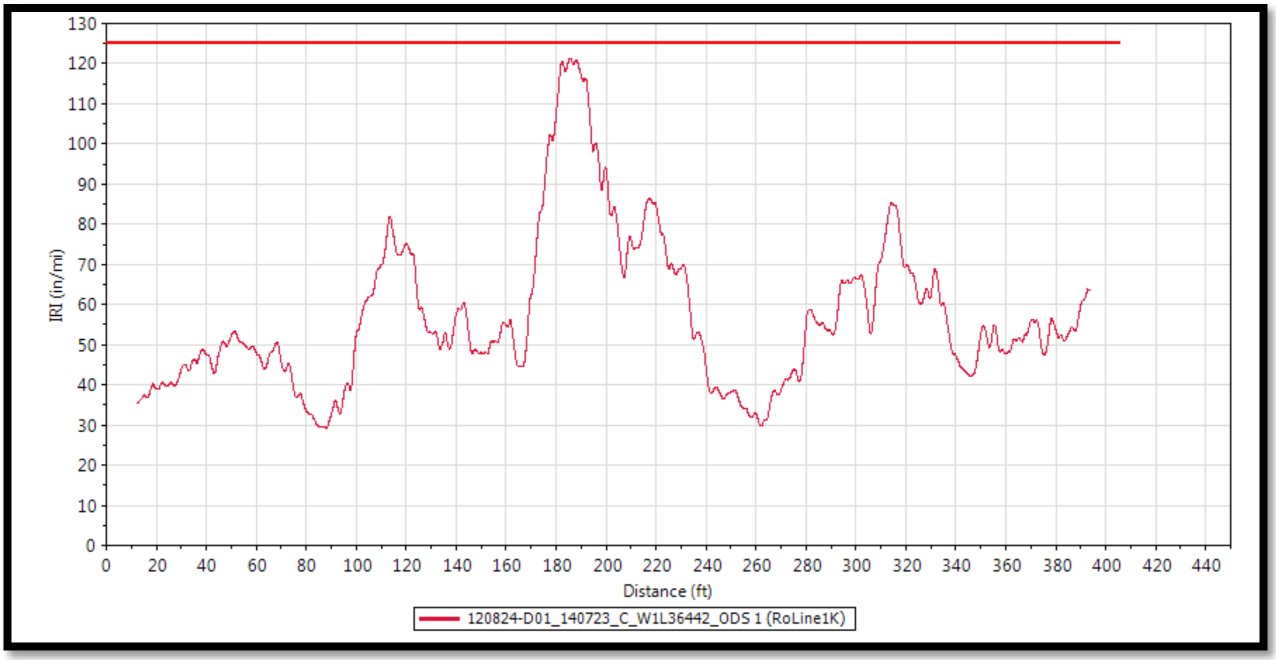

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Figure 42. Graph. Example of localized roughness report from TriODS profile example.

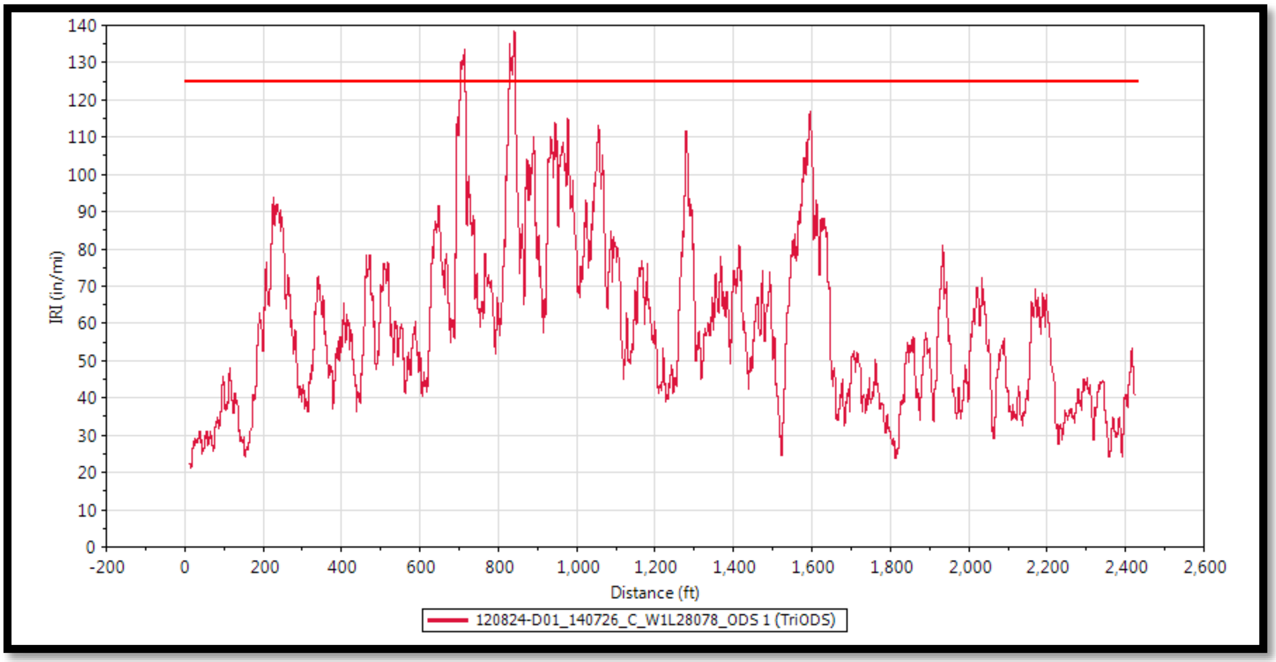

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Figure 43. Graph. Second example of localized roughness report from a TriODS profile example.

Since the comparison non-AMG profile (25L01200) is a 200,000-ft-long profile, the shorter non-AMG profile (28G0M000) file is used for further analysis, presented in figure 44. The localized roughness report of the comparison profile indicates relatively smooth pavements with a few localized roughness events, with only one exceeding 125 inches/mi.

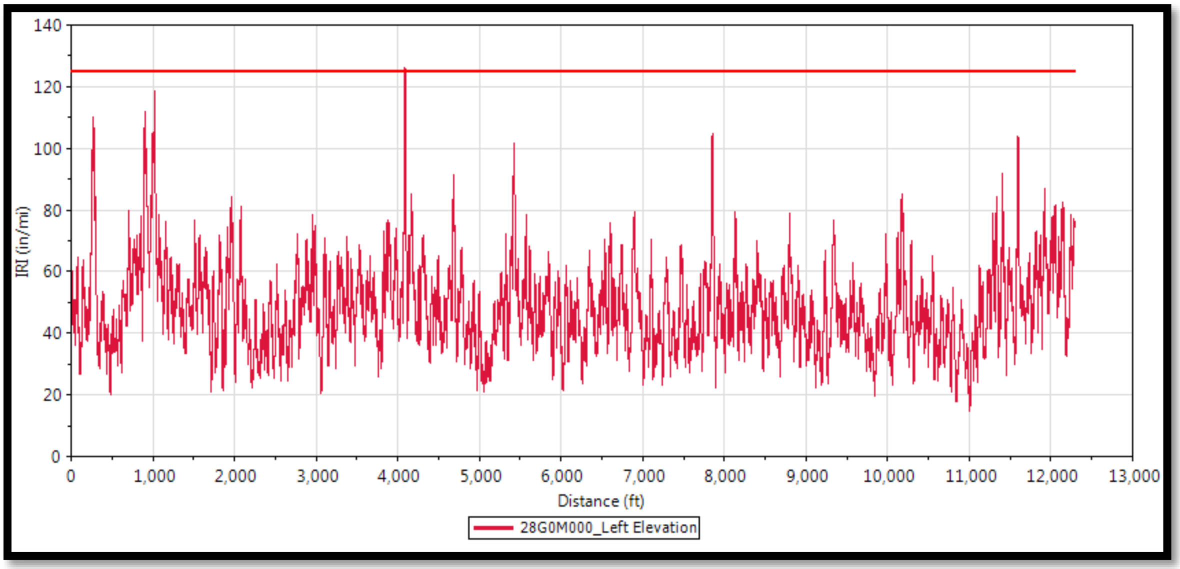

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Figure 44. Graph. Localized roughness report for non-AMG profile (28G0M000).

Histograms of continuous roughness reports in figure 45, figure 46, and figure 47 indicate that the improvement of smoothness by the AMG system method is mixed.

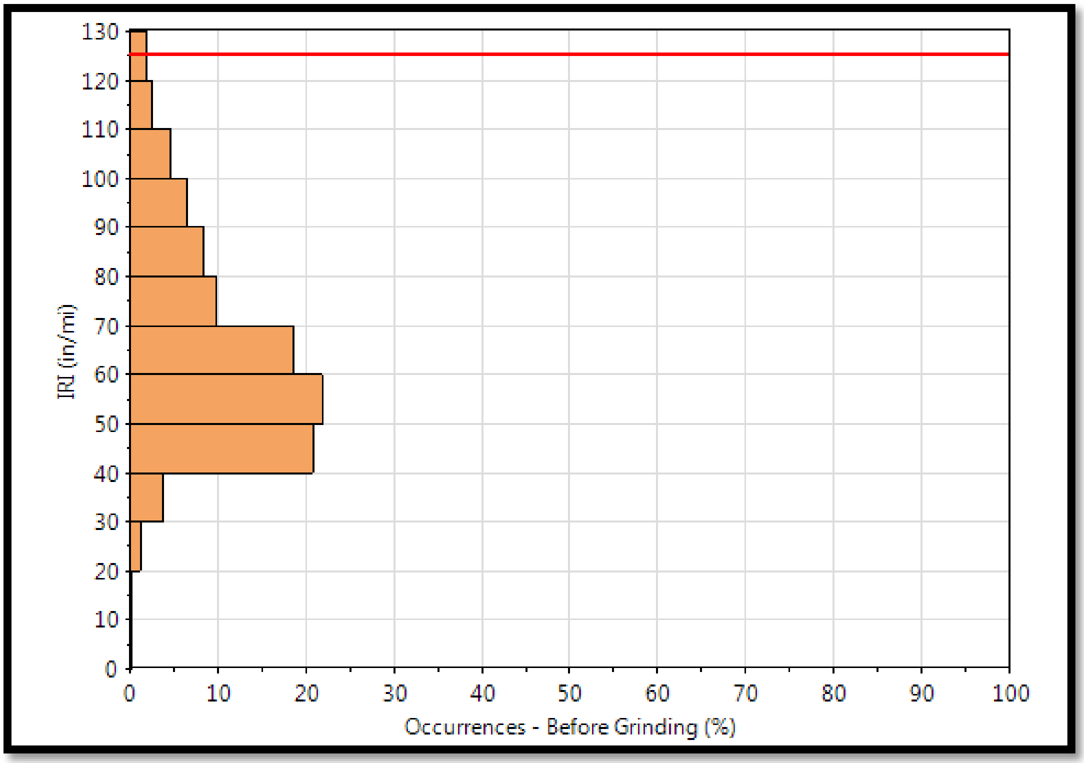


Figure 45. Chart. Histogram of localized roughness for AMG file (1208824-D01_140702_CE1L3637).

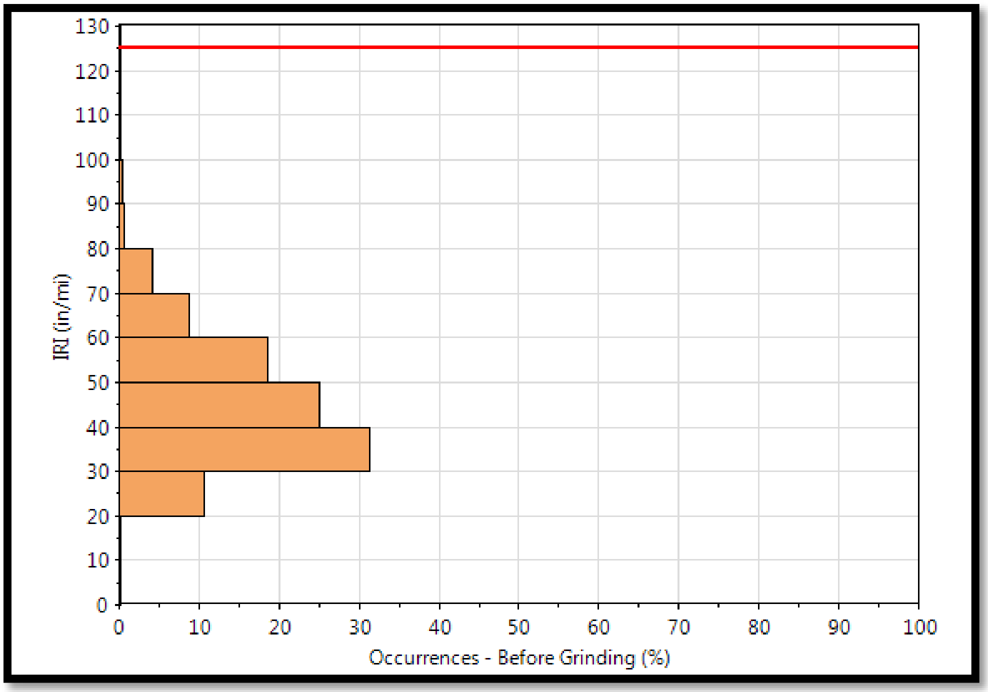


Figure 46. Chart. AMG file (1208824-D01_140725_C_E1L1799) (same as the comparison file).

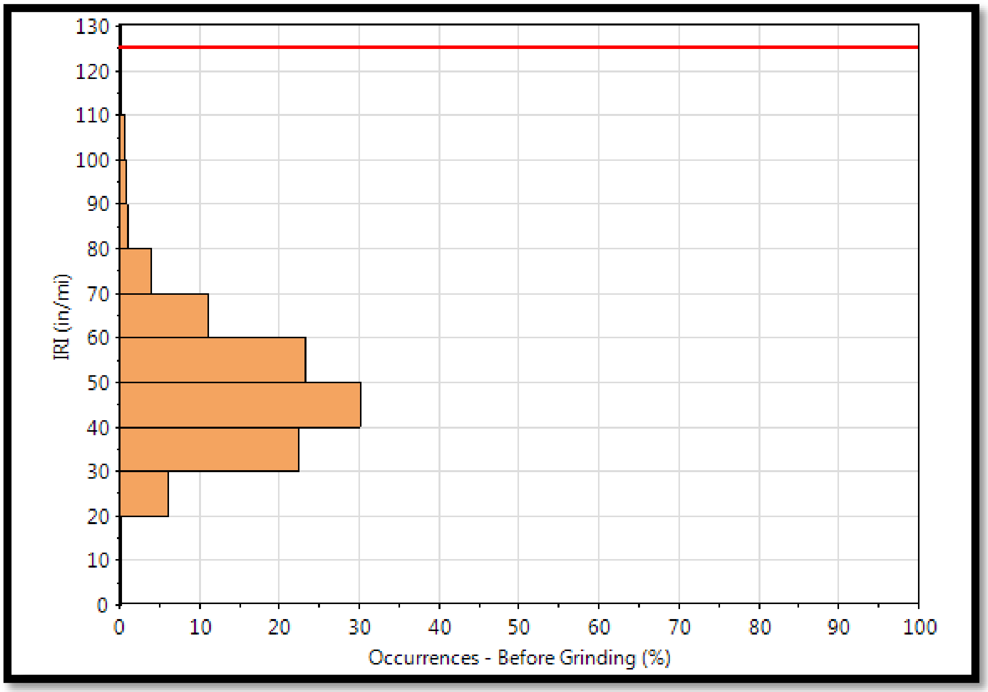


Figure 47. Chart. Histogram of localized roughness for non-AMG file (28G0M000).

Limited analysis was conducted on selected U.S. 50 AMG raw profile data. The PSD wavelength analysis indicates that there are differences in profiles using Roline versus TriODS lasers. However, no conclusions can be drawn because they were not collected side by side on the same section.

Statistical Summary

The MoDOT utilized different smoothness measures, IRI and PrI for construction acceptance for the AMG and non-AMG segments of U.S. 50, respectively. Note that the agency was using PrI as the acceptance criteria in the specifications when the non-AMG segment was built. However, the agency has already switched from PrI to IRI for construction acceptance in smoothness specifications by the time the AMG segment was paved.

The as-constructed IRI data were available for the AMG segment; however, only historical IRI data, which are collected annually on in-service pavements for pavement management purposes, were available. Recognizing the incompatibility between the two IRI datasets, an effort was made to gather as-constructed PrI data from MoDOT for the non-AMG segment, whereas the profilograph simulation was conducted for the AMG segment using available smoothness profiles. The profilograph simulation was performed using ProVAL at 0.0 blanking band at 0.1-mi base length with a scallop rounding increment of 0.01 inch.

Table 15 presents the statistical summary of smoothness measures for segments using AMG and non-AMG paving methods. The table summarizes descriptive statistics of both IRI and PrI for the AMG segments and only PrI for the non-AMG segments. The results indicate that the smoothness outcomes of both AMG and non-AMG segments were comparable. The segments using AMG paving exhibited better average smoothness but with higher variability compared with those using non-AMG paving. Only a few segments reported disincentives.

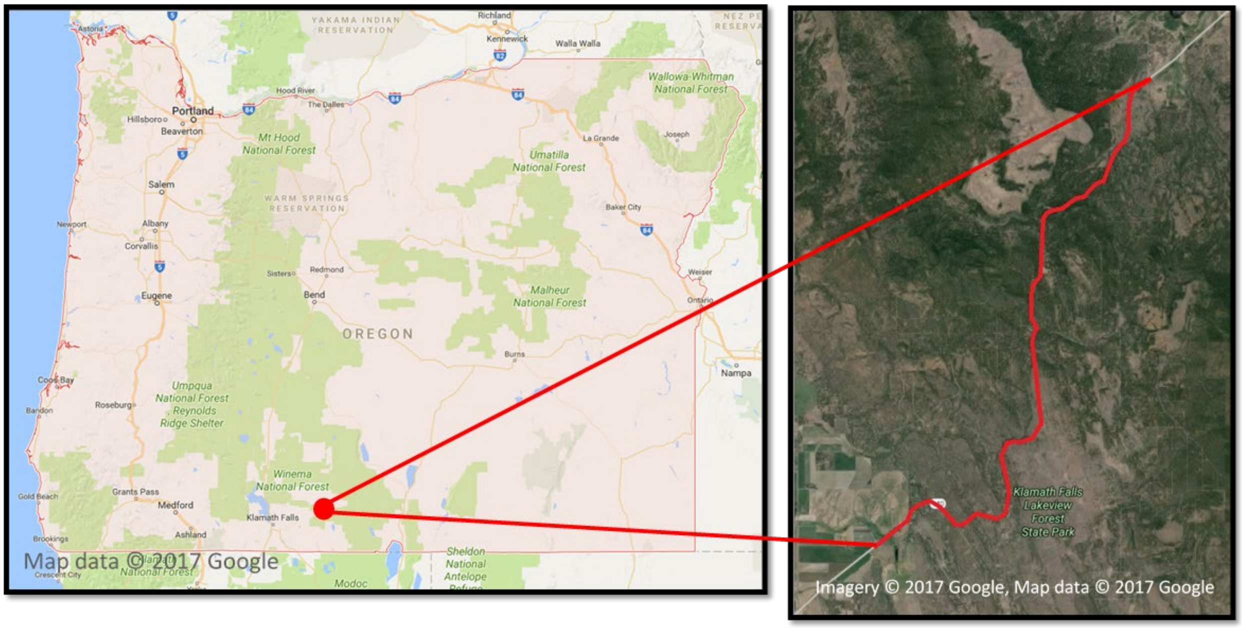
Table 15. Missouri: statistical summary of IRI and PrI by construction technology.

Statistic	AMG IRI	AMG PrI	Non-AMG PrI
Number of segments	199	183	137
Average IRI (inches/mi)	52.6	12.3	13.8
Standard deviation (inches/mi)	16.7	6.6	3.1
Maximum IRI (inches/mi)	87.9	29.0	22.2
Coefficient of variation (percent)	31.7	53.5	16.5
Number of 0.1-mi segments with IRI exceeding 80 inches/mi or PrI exceeding 25 inches/mi	4	2	1
Percentage of 0.1-mi segments with IRI exceeding 80 inches/mi	2.0	1.1	0.7

Oregon State Highway 140

Project Background

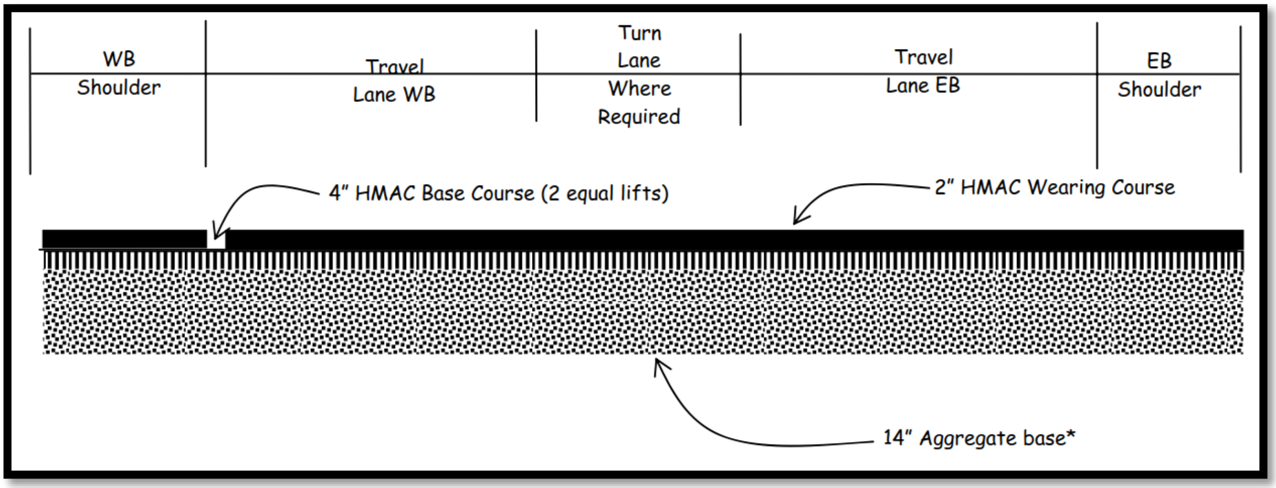
The scope of work for this project was to realign and widen approximately 9.2 mi of Oregon State Highway 140, which is a rural road approximately 25 mi east of Klamath Falls, Oregon (figure 48). The contract was awarded in May 2014 and was completed in the fall of 2016.



Original Map © 2017 Google ®. Annotated by FHWA (see Acknowledgments).

Figure 48. Map. Location of Oregon State Highway 140.

The pavement design used in this project was 6-inch dense hot mix asphalt concrete, laid in three 2-inch lifts, on a 14-inch aggregate base (figure 49). A similar project on the Milwaukie Expressway south of Portland that was finished a few years earlier was used as the baseline comparison.



*Pulverized material may be used in place of fill and/or aggregate base for shoulder, median, and turn lane construction provided it is deeper than 6 inches from final aggregate base surface. Pulverized material may be used in place of fill in a travel lane but may not be used as a substitute for aggregate base.

Figure 49. Drawing. Typical section per the final pavement design.

3D Modeling and AMG Specifications

Oregon Department of Transportation (ODOT) provides guidance and defines the requirements for providing electronic files to support AMG construction methods in the design manual. ODOT provided a bid package containing alignments, profiles, and surfaces to supplement the plan sheets during the advertisement of the project. The contractor used those electronic files to finalize the model needed by the AMG equipment (figure 50). The agency created the preconstruction survey using aerial photogrammetric methods supplemented by field surveys. The contractor had dedicated staff to review and check the models received from ODOT and indicated data preparation for the AMG equipment was minimal as ODOT provided quality design files.

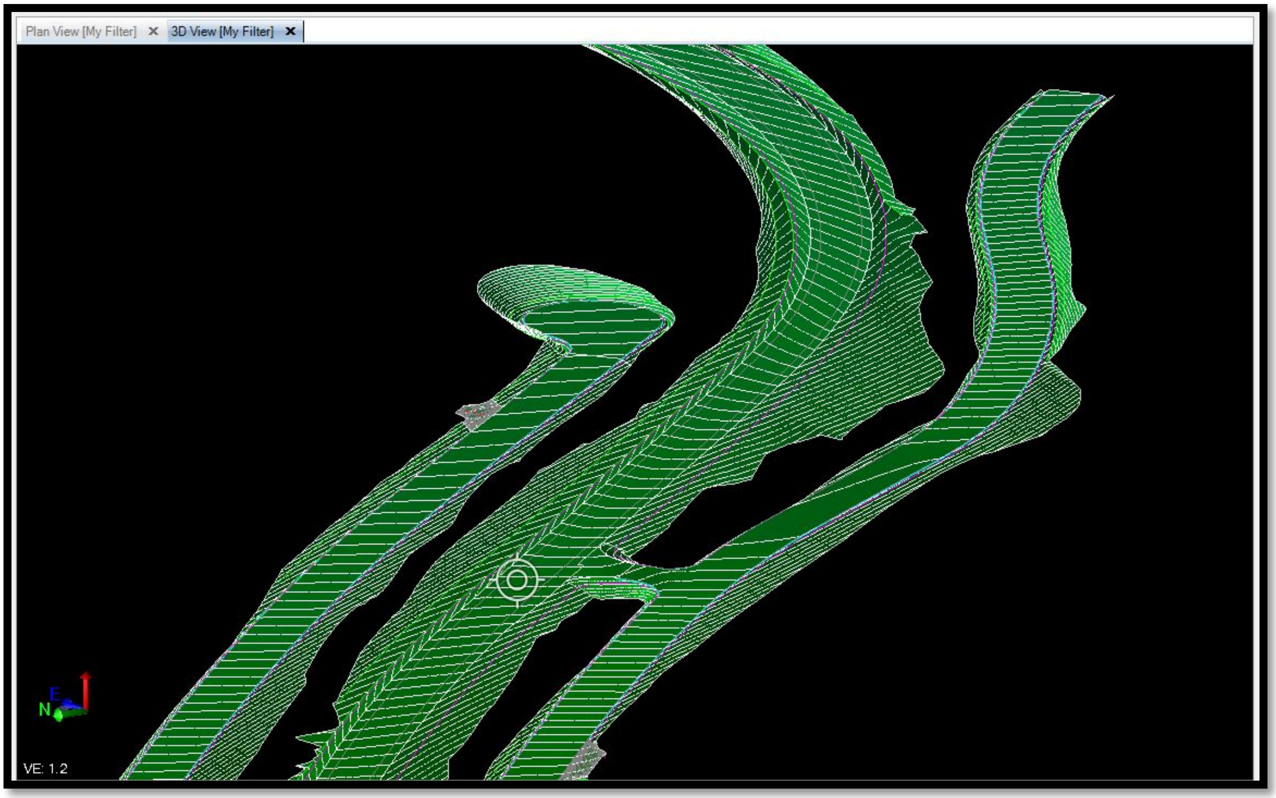


Figure 50. Screen capture. 3D model authorized by ODOT to use for AMG grading.

Equipment and Operations

The contractor had been using GPS-guided equipment for 5 yr. The contractor was responsible for all the survey activities in the field and set up control points every 500 ft. The contractor tried to use some of the control points set up by ODOT survey staff but found some discrepancies. Several level loops were performed to correct the elevation issues. A total of three base stations were set up on the project to guide the grading equipment. Also, universal total stations were placed where GPS coverage was not adequate, which was only in a couple of spots throughout the project. Two survey crew members provided independent checks, which involved comparing confidence points to the model. Although there were some discrepancies (0.04 ft), all confidence points met the tolerance per ODOT's specifications. ODOT requires 67 percent of all confidence points to be within 0.03 ft, and no points can be more than three times the tolerance (0.09 ft). Typical total station setup for independent checks is shown in figure 51. Traditional paving operation is shown in figure 52.

There were no major issues reported, and the paving operation was ahead of schedule.

Source: FHWA.

Figure 51. Photo. Total stations are used for checking the grade and confidence points.

Source: FHWA.

Figure 52. Photo. Asphalt paving equipment did not use AMG technology. All rough and fine grading used AMG equipment (GPS technology).

Source of Smoothness Data

ODOT provided raw profile data for both the case study and the baseline comparison projects. Contractor collected profile data using a light weight profiler, and ODOT conducted the smoothness analysis to compute IRI values in accordance with ODOT unique special provision SP00745-IRI.(33) The contract included incentives for smoothness as shown in table 16.

Table 16. ODOT's incentives for pavement smoothness based on IRI.

Average IRI (Inches/mi)	Equation Used to Determine Incentive Amount
≤50	A = \$300.00
50.1–65.0	A = (−\$20.00 × B) + \$1,300.00
65.1–75.0	A = \$0.00
75.1–95	A = (−\$20.00 × B) + \$1,500.00
≥95.0	Corrective action and retesting

A = the price adjustment for the segment or partial segment; B = the averaged IRI value for the segment or partial segment.

It is important to note that, for each paving season, ODOT will make changes to the smoothness price adjustment for the next monthly progress estimate following the satisfactory completion of all corrective work and the submission of all test data for all traffic lane paving on the project.

Smoothness Data Analysis Using ProVAL Software

One pair of profiles on EB/WB were analyzed.

PSD Wavelength Analysis

The profile was neither high-pass filtered nor low-pass filtered. The unfiltered comparison in figure 53 shows EB in the solid red line and WB in the dashed blue line.

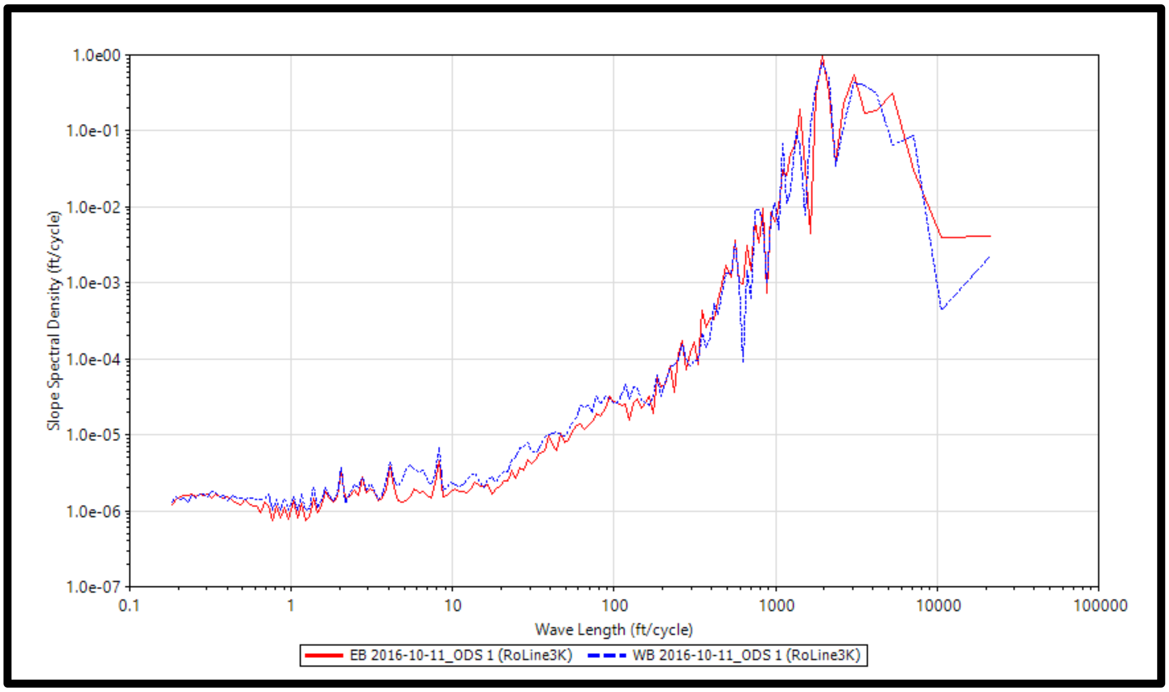


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Figure 53. Graph. Comparison of EB/WB files (unfiltered)—log scale.

The WB profile consists of dominating wavelength at 80 ft seen in figure 54. Both profiles have slight peaks at short wavelengths, but they are not significant.

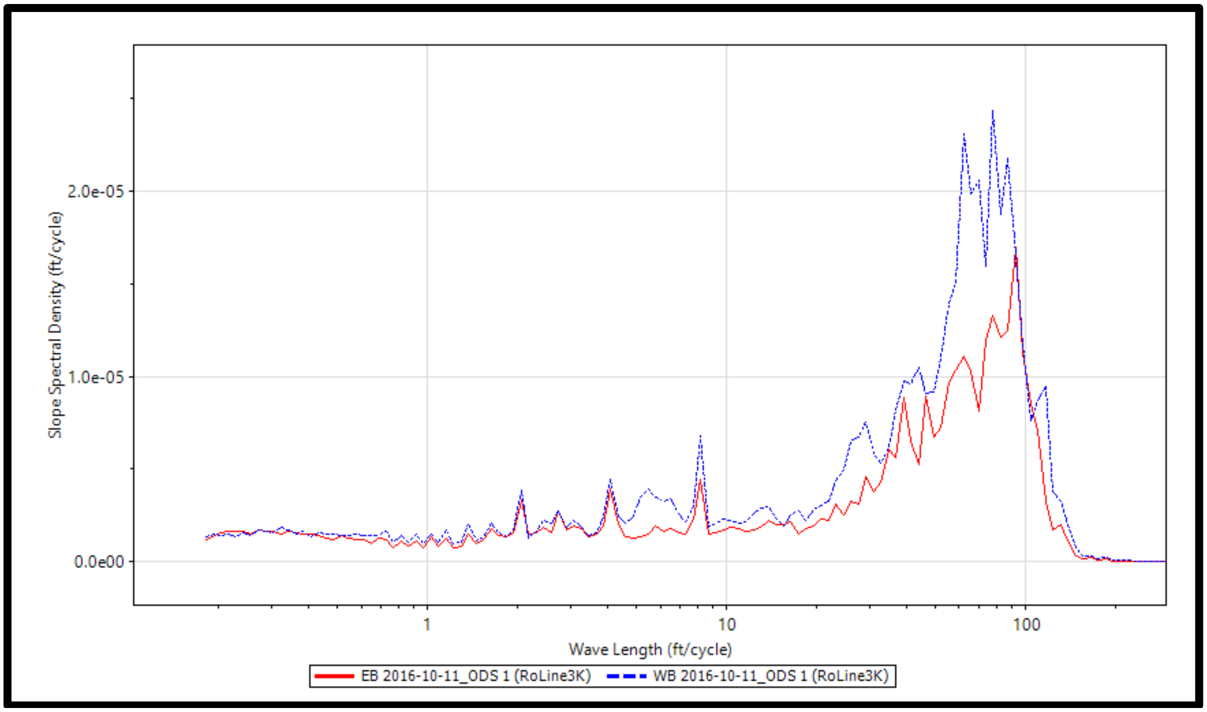

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Figure 54. Graph. Comparison of EB/WB files (high-pass filtered at 100-ft) linear scale.

In figure 55, the IRI roughness is mostly from the 50- to approximately 60-ft "body bounce" range. There is a small peak at 8 ft (although not significant) that may be caused by paving equipment or a process. As shown in figure 55, figure 56, and figure 57, the PSD wavelength analysis for the non-AMG and AMG profile data did not indicate significant differences.

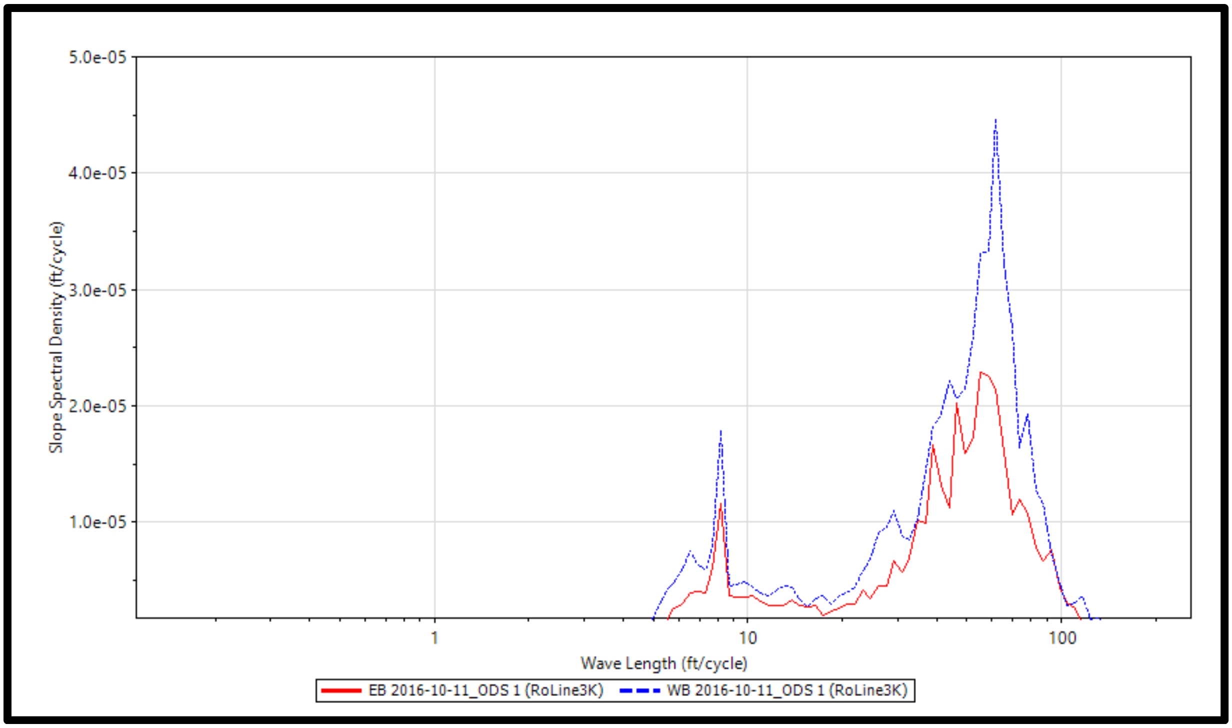

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Figure 55. Graph. Comparison of EB/WB files (IRI filtered) linear scale.

In figure 56, the ride quality is rougher toward the EB ends but still within ODOT's MRI thresholds for full payment.

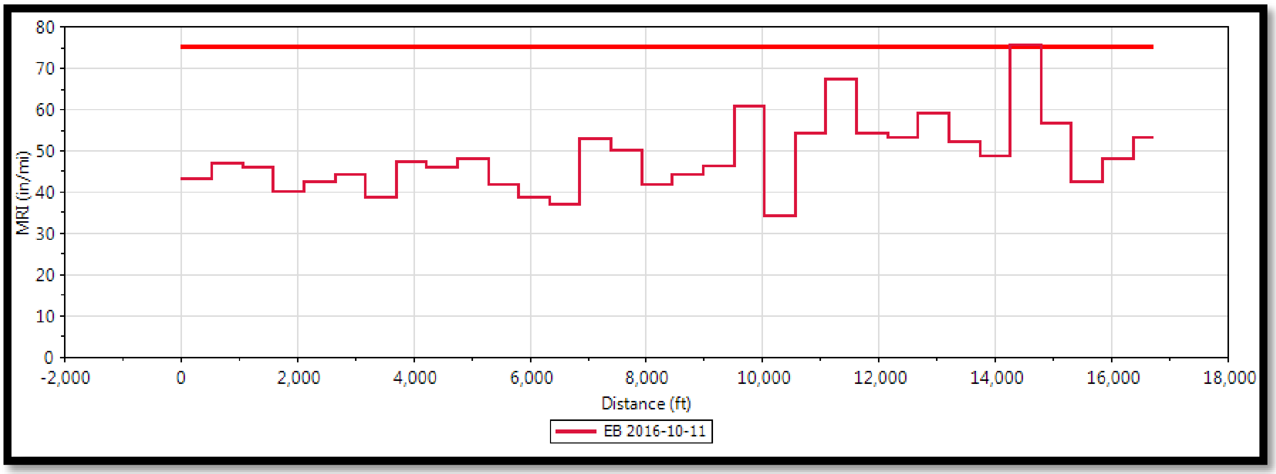

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Figure 56. Graph. Ride quality analysis (528-ft fixed interval, 75 inches/mi threshold for MRI) for EB.

In figure 57, the ride quality is rougher at the beginning of WB with two sublots exceeding ODOT's MRI thresholds for full payment (i.e., disincentive pay factors apply to those lots).

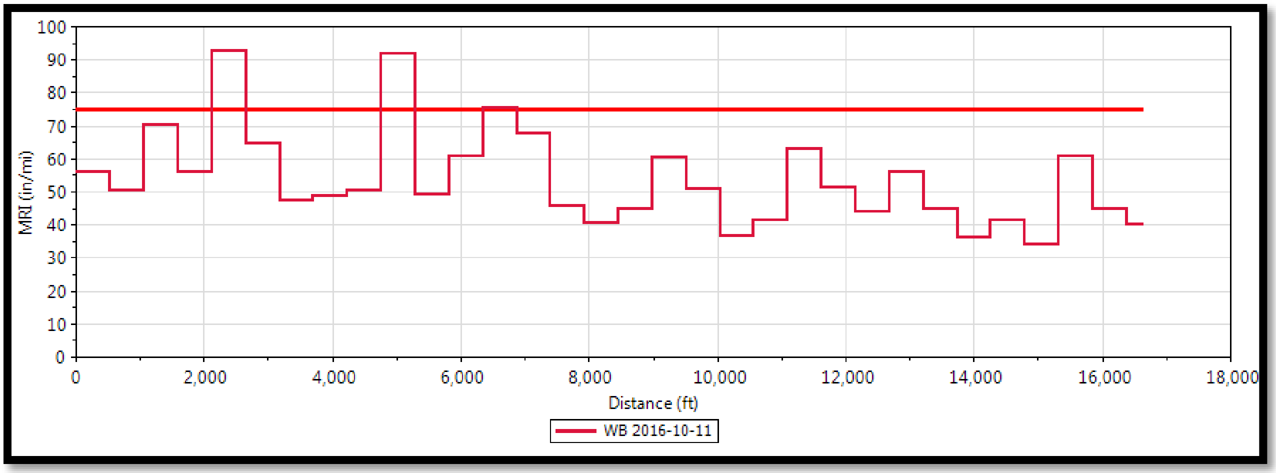

Figure 57. Graph. Ride quality analysis (528-ft fixed interval, 75 inches/mi threshold for MRI) for WB.

Statistical Summary

Table 17 presents the IRI datasets provided by ODOT and used in this comparison. Table 18 presents the statistical comparison of IRI data between the baseline (i.e., non-AMG) and AMG datasets. The statistical summary indicates that there is no overall significant difference in average IRI between segments paved with AMG and non-AMG methods. The segments with AMG paving were observed to produce more uniform smoothness outcomes than those with non-AMG paving.

Table 17. Oregon SH 140: IRI datasets provided by Oregon DOT.

IRI Report File Name	Direction	Paving Technology	Average	Standard Deviation
OR140-2015-10-11 to 12-RQ-EB 2016-10-11	EB	AMG	48.5	8.8
OR140-2015-10-11 to 12-RQ-WB 2016-10-11	WB	AMG	53.7	14.4
OR140-2015-10-11 to 12-RQ-EB 2016-10-12	EB	AMG	52.8	5.6
OR140-2015-10-11 to 12-RQ-WB 2016-10-12	WB	AMG	62.6	11.6
OR-Sunrise-RQ- SR1-SR2 Fast NB T1 & T2	NB	Non-AMG	49.7	13.9
OR-Sunrise-RQ- SR1-SR2 Fast SB T1 & T2	SB	Non-AMG	58.2	29.4

Table 18. Oregon SH 140: statistical summary of IRI by construction technology.

Statistic	AMG	Non-AMG
Number of segments	132	27
Average IRI (inches/mi)	54.5	54.4
Standard deviation (inches/mi)	11.7	23.8
Maximum IRI (inches/mi)	132	143.5
Coefficient of variation (percent)	21.4	43.7
Number of 0.1-mi segments with IRI exceeding 75 inches/mi	6	3
Percentage of 0.1-mi segments with IRI exceeding 75 inches/mi	4.5	11.1

However, a closer examination of the distribution of reported IRI values, as presented in the cumulative frequency distribution chart of figure 58, reveals an apparent inconsistent trend with the smoothness achieved in the segments using non-AMG paving. Noting that the sample size of segments using non-AMG paving is small, about two-thirds of segments reported better smoothness values with IRI values all less than 48 inches/mi, whereas the remaining one-third of segments reported disproportionately higher IRI values, ranging between 62 and 143 inches/mi on both northbound and southbound sections of the Milwaukie Expressway (non-AMG dataset). It is unknown whether the cause of disparity within the dataset was due to poor process control or the presence of bridge approach and departure areas.

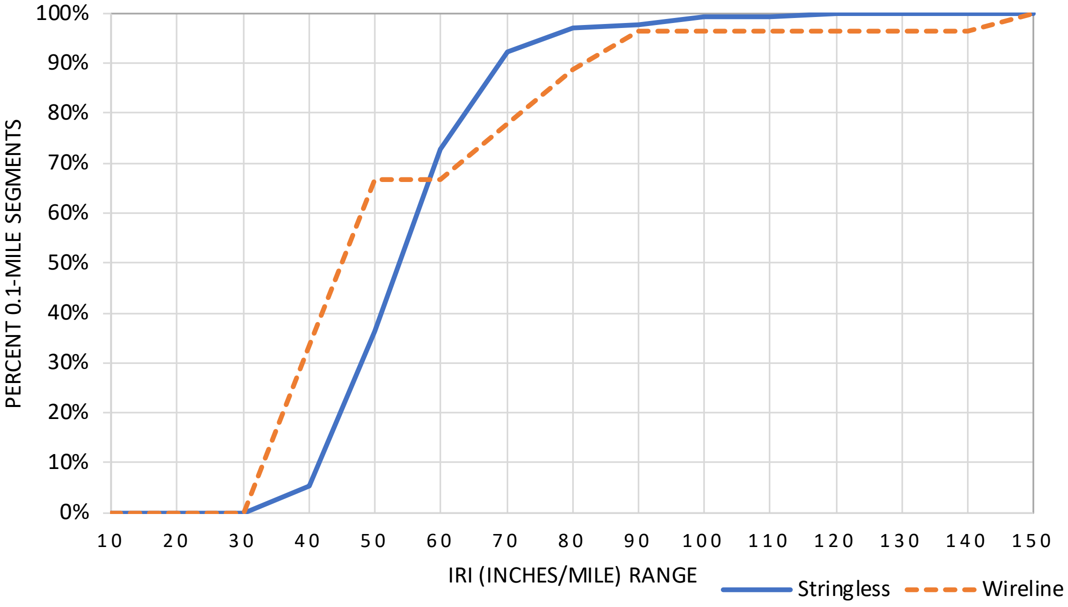

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Figure 58. Graph. Oregon SH 140: cumulative frequency distribution of IRI.

CHAPTER 4. DATA ANALYSIS

HYPOTHESIS TESTING AND STATISTICAL ANALYSIS APPROACH

The hypothesis for this study is whether the use of 3D modeling and AMG technology on highway projects will result in improved rideability. The key questions of interest for this study include the following:

- Does the use of AMG paving result in overall initial smoothness improvements compared with those projects using non-AMG paving?
- Does the use of AMG paving result in reduced variability in initial smoothness measurements compared with those projects using non-AMG paving?
- How does the AMG compare with conventional methods in controlling the number of disincentive sections?
- Given the variability in site conditions and construction practices among case study projects, is the observed evidence consistent enough to conclude that the use of AMG results in improved initial smoothness over conventional methods?

The smoothness data collected from five case study paving projects were utilized to find answers to the preceding questions. Table 19 summarizes the mean, standard deviation of smoothness measures, as well as the number of segments with 0.1-mi base length for each case study. The descriptive statistics presented in this table do not provide categorical evidence to support that one paving technology offered improvements in smoothness over the other.

Table 19. Summary of smoothness measures by case study.

Case Study	AMG: No. of 0.1-mi Segments	AMG: Mean	AMG: Standard Deviation	Non-AMG: No. of 0.1-mi Segments	Non-AMG: Mean	Non-AMG: Standard Deviation
Arizona Loop 101	223	34.3	5.8	310	35.6	7.9
Illinois Tollway I-90	6	56.2	10.1	26	60.3	10.1
Iowa U.S. 20	170	58.2	9.9	1,028	52.3	8.6
Missouri U.S. 40*	183	12.3	6.6	137	13.8	3.1
Oregon SH 140	132	54.5	11.7	27	54.4	23.8

*Profile index is reported for Missouri U.S. 40, whereas IRI is reported for other sites.

Meta-analysis was used to combine results and synthesize evidence from these original studies to arrive at statistically acceptable conclusions about the differential improvements offered by these paving methods.

Introduction to Meta-Analysis

Meta-analysis provides a quantitative framework to conduct a systematic review of empirical evidence provided by various case studies and summarizing them.(34) Meta-analysis is particularly suitable when the empirical evidence from multiple studies might not clearly favor either acceptance or rejection of statistical significance. In other words, a meta-analysis allows the evaluation of the consistency of empirical evidence derived from multiple case studies.

Meta-analysis allows fewer case studies (i.e., smaller sample size) and those with different attributes that would otherwise influence changes in smoothness outcomes due to the use of AMG. Statistical metrics used in meta-analysis are not fundamentally different from those of conventional statistics but adopt a better approach to answer questions of interests from quantitative summaries of multiple case studies, without violating the assumptions made in conventional statistics.

Meta-analysis utilizes the effect size to evaluate the anticipated changes in smoothness outcomes with the use of AMG. Effect size is defined as a standardized mean difference in effect (i.e., smoothness metrics) between two independent groups. The effect size measures how much difference there is in pavement smoothness between the AMG and non-AMG case studies.

SMOOTHNESS DATA ANALYSIS BETWEEN AMG AND NON-AMG PROJECTS

The data analysis approach entailed computing effect size values for each case study, plotting them on a forest plot to evaluate their consistency, and assessing their summary effect. Three sets of parameters were used to evaluate the effect sizes on smoothness outcomes.

Effect Sizes Based on the Standard Mean Difference of Smoothness Outcomes

Four measures were used to describe information on the magnitude, direction, and strength of the difference in smoothness between AMG and non-AMG groups.

Cohen’s d

This measure is the mean difference in smoothness outcomes between AMG and non-AMG groups. Cohen’s *d* is computed as the difference between means of two data groups divided by the pooled standard deviation. Pooled standard deviation is computed as the square root of the weighted average of two group’s variances, while weight is given based on their sample size. This measure, which was computed for individual case study and aggregated, is defined as follows (figure 59):

$$d = \frac{\mu_{AMG} - \mu_{nonAMG}}{S_{within}}$$

$$S_{within} = \sqrt{\frac{\left((n_{AMG} - 1)S_{AMG}^2\right) + \left((n_{nonAMG} - 1)S_{nonAMG}^2\right)}{n_{AMG} + n_{nonAMG} - 2}}$$

Figure 59. Equation. Formula for determining Cohen’s *d*.

Where:

μ_{AMG} and μ_{nonAMG} are the sample means.
S_{AMG} and S_{nonAMG} are the standard deviations.
n_{AMG} and n_{nonAMG} are the sample sizes of AMG and non-AMG groups, respectively.

Standard error (s_e) is the square root of the sum of two components. The first component is the sum of the sample sizes of two groups divided by the product of the sample sizes of two groups. The second component is the square of Cohen's *d* divided by twice the sum of the sample sizes of two groups. The s_e of *d* is defined as follows (figure 60):

$$s_e = \sqrt{\left(\frac{n_{AMG} + n_{nonAMG}}{n_{AMG} * n_{nonAMG}} + \frac{d^2}{2(n_{AMG} + n_{nonAMG})}\right)}$$

Figure 60. Equation. Formula for determining the standard error of *d*.

The interpretation of effect size *d* (table 20) is presented in Cohen's *Statistical Power Analysis for the Behavioral Sciences*.(35) While Cohen's definition has been widely accepted, it is noted that Cohen was intentionally vague about precise cut points and decision rules relating to their interpretation and further encouraged researchers to interpret effect size based on the context. Note that the interpretation applies to Hedges' *g* as well.

Cohen provided further guidance on interpreting effect size:

> The terms "small," "medium," and "large" are relative, not only to each other, but to the area of behavioral science or even more particularly to the specific content and research method being employed in any given investigation. In the face of this relativity, there is a certain risk inherent in offering conventional operational definitions for those terms for use in power analysis in as diverse a field of inquiry as behavioral science. This risk is nevertheless accepted in the belief that more is to be gained than lost by supplying a common conventional frame of reference which is recommended for use only when no better basis for estimating the [effect size] index is available.

Table 20. Interpretation of effect size measures.

Cohen's *d*	Description of Difference	Nonoverlap (Percent)	Probability of Superiority (Percent)
0.0	None	0	50
0.2	Small	14.7	55.62
0.5	Medium	33.0	63.82
0.8	Large	47.4	71.42

Hedges' g

Hedges' *g* is a product of Cohen's *d* and a correction factor. The correction factor is a numerical function of sample sizes of two data groups. Considering the inherence bias of *d* with sample size, Hedges' *g* provides a correction for smaller sample size and is defined as follows (figure 61):

$$g = d * \left(1 - \frac{3}{4(n_{AMG} + n_{nonAMG} - 2) - 9}\right)$$

Figure 61. Equation. Formula for determining Hedges' *g*.

The standard error of Hedges' *g* is a product of standard error of Cohen's *d* and a correction factor. The correction factor is a numerical function of sample sizes of two data groups. The standard error of *g* is defined as follows (figure 62):

$$s_e = \sqrt{\left(\frac{n_{AMG} + n_{nonAMG}}{n_{AMG} * n_{nonAMG}} + \frac{d^2}{2(n_{AMG} + n_{nonAMG})}\right)} * \left(1 - \frac{3}{4(n_{AMG} + n_{nonAMG} - 2) - 9}\right)$$

Figure 62. Equation. Formula for determining the standard error of *g*.

Table 21 summarizes both mean and estimates of Hedges' *g* at 95 percent confidence interval, and Cohen's U_3 for each case study.

Table 21. Summary of effect sizes based on the standard mean differences.

Case Study	**Cohen's *d* (LL-UL) at 95% CI**	**Hedges' *g* (LL-UL) at 95% CI**	**Cohen's U_3 Degree of Overlap (Percent)**	**Probability of Superiority (Percent)**
Arizona Loop 101	0.18 (0.008, 0.353)	0.18 (0.008, 0.352)	57.1	55
Illinois Tollway I-90	0.40 (−0.489, 1.297)	0.39 (−0.477, 1.265)	65.7	61
Iowa U.S. 20	−0.67 (−0.839, −0.510)	−0.67 (−0.838, −0.509)	25.0	32
Missouri U.S. 40	0.274 (0.052, 0.497)	0.274 (0.052, 0.495)	60.8	58
Oregon SH 140	0.00 (−0.419, 0.409)	0.00 (−0.417, 0.407)	49.8	50

LL = lower limit; UL = upper limit.

Cohen's U_3

Cohen's U_3, which is defined as a measure of non-overlap, is a cumulative distribution function of Cohen's *d*. This measure returns the normal distribution for Cohen's *d*, illustrated in figure 65, which describes the degree of overlap and more precisely the percentage of the AMG group that is above the mean of the non-AMG group. This measure is defined as follows (figure 63):

$$U_3 = \Phi(d)$$

Figure 63. Equation. Formula for determining Cohen's U_3.

Where Φ is the cumulative distribution function of the standard normal distribution. These measures are schematically described in figure 65.

Common Language Effect Size

Often referred to as probability of superiority, this measure is the probability 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 (figure 64).

$$CLES = \Phi\left(\frac{d}{\sqrt{2}}\right)$$

Figure 64. Equation. Formula for determining the probability of superiority.

Where CLES is the common language effect size.

Table 21 also summarizes the estimated probabilities of superiority for each case study.

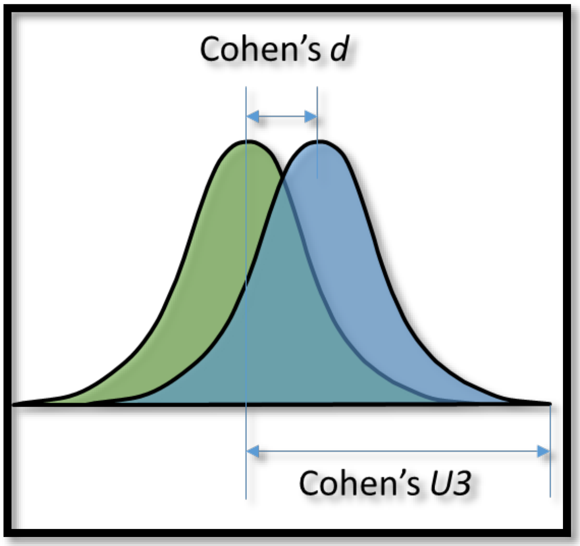
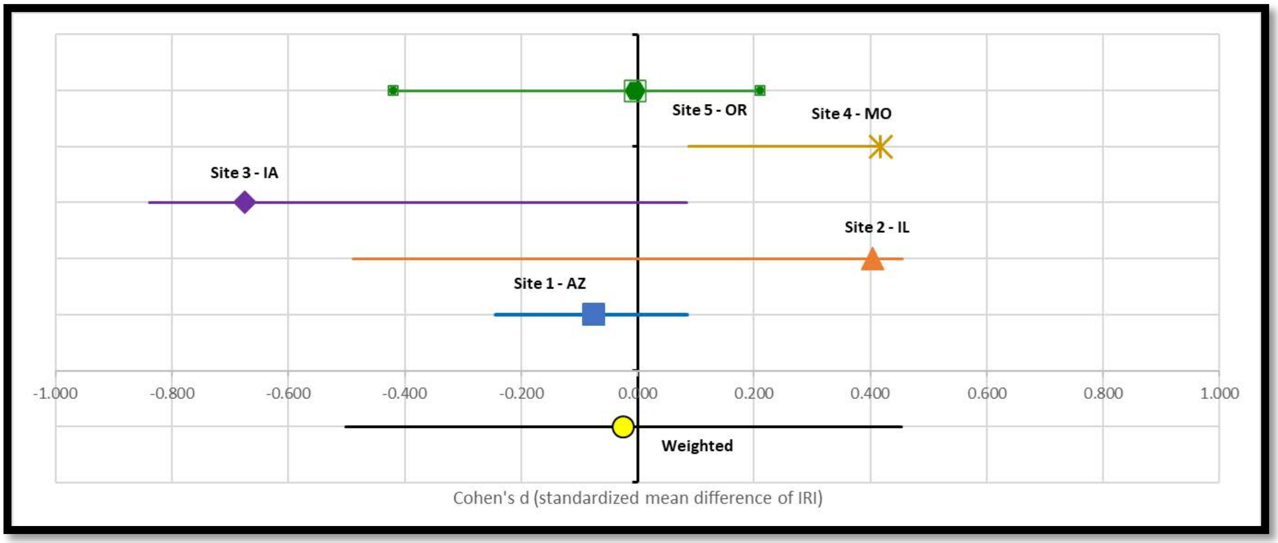


Figure 65. Graph. Schematic representation of effect size and degree of overlap.

Lastly, table 21 presents Cohen's *d* effect size estimates for all case studies at 50 (i.e., mean) and 95 percent confidence intervals. A forest plot, as shown in figure 66, presents the effect size estimates or standardized mean differences of each case study with their corresponding prediction intervals. Each site was assigned a weight that is inversely proportional to the spread the site exhibited. The weights were assigned on a scale of zero to one. The sum of all weights is equal to 1.0. The positive difference indicates that the standardized mean difference of IRI or PrI of segments using the AMG method was smoother than that using non-AMG paving and vice versa. The closer the positive standardized mean difference is to zero, the weaker is the advantage of AMG over non-AMG methods in producing better smoothness outcomes. The horizontal line in the figure shows the lower and upper limits of the effect size estimates.



Source: FHWA.
*Positive difference indicates that the standardized mean difference of IRI of segments using AMG is smoother than those not using AMG.

Figure 66. Graph. Forest plot presenting standardized mean differences of smoothness of different case studies.

The effect size estimates indicate that the use of AMG methods resulted in slightly better smoothness outcomes than non-AMG paving for three of the five case studies, whereas the Oregon dataset exhibited no difference between them. The effect size of the Iowa dataset substantially favored the use of non-AMG over AMG paving.

However, effect size estimates of individual case studies at 95 percent confidence interval indicate that there is no conclusive evidence whether the use of AMG paving resulted in better overall smoothness outcomes than the use of non-AMG paving. This inconclusive trend was reflected in the degree of overlap and probability of superiority estimates. In other words, the probability that one technology is superior to the other is roughly equivalent to a coin toss. While the Iowa case study moderately but consistently favored the conventional over the AMG method, both Illinois and Missouri indicated otherwise.

Effect Sizes Based on the Occurrence of Disincentives

One of the advantages of using AMG is to reduce opportunities for errors that may otherwise result in unacceptable smoothness or localized areas of roughness. Per AASHTO R54[1], any 25-ft segment of roadway that contributes disproportionately to the overall smoothness index is identified as an "area of localized roughness."(36) Highway agencies establish their own thresholds, which typically vary with roadway design speed, smoothness measure, and profiler type to identify localized areas where measured smoothness exceeds acceptable thresholds. These areas are typically subjected to pay deductions and/or corrective actions, such as grinding or rework.

To evaluate the relative performance of AMG and non-AMG projects in meeting desired quality levels and percent within tolerance limits, a statistical measure called "odds ratio" was utilized. Odds ratio is the ratio of two components: the probability of success over the probability of failure. Using the preset acceptance criteria for ride smoothness in existing specifications as the benchmark, the percentage of 0.1-mi segments not receiving disincentives is counted toward the probability of success, whereas the percentage of segments receiving disincentives was counted toward the probability of failure.

This measure evaluates the hypothesis that the proportion of segments receiving disincentives will decrease with the use of AMG in comparison with traditional alternatives. In other words, odds ratio is a single summary score of the AMG's effect on reducing the number of segments receiving disincentives. Odds ratio, which will utilize a two-by-two frequency table (table 22), will be computed based on the number of 0.1-mi segments where the measured smoothness exceeds a specific threshold for both AMG and non-AMG groups. The numerator is the number of 0.1-mi segments paved using the AMG method with acceptable smoothness over those with unacceptable smoothness. The denominator is the number of 0.1-mi segments paved using a non-AMG method with acceptable smoothness over those with unacceptable smoothness. The computation of odds ratio is presented as follows (figure 67):

Table 22. Computation of odds ratio parameters.

Projects	Number of 0.1-mi Segments with Acceptable Smoothness	Number of 0.1-mi Segments with Unacceptable Smoothness	Number of Segments
AMG	a	c	a + c
Non-AMG	b	d	d + d

a = number or percentage of 0.1-mi segments with acceptable smoothness on AMG projects; b = number or percentage of 0.1-mi segments with acceptable smoothness on non-AMG projects; c = number or percentage of 0.1-mi segments with unacceptable smoothness on AMG projects; d= number or percentage of 0.1-mi segments with unacceptable smoothness on non-AMG projects.

---

[1] AASHTO R54 is a standard practice for accepting pavement ride quality when measured using inertial profiling systems.

$$OddsRatio = \frac{(\frac{a}{c})}{(\frac{b}{d})}$$

Figure 67. Equation. Formula to determine the odds ratio.

Where:

OddsRatio is odds ratio.

a is a number or percentage of 0.1-mi segments with acceptable smoothness on AMG projects.

b is number or percentage of 0.1-mi segments with acceptable smoothness on non-AMG projects.

c is number or percentage of 0.1-mi segments with unacceptable smoothness on AMG projects.

d is number or percentage of 0.1-mi segments with unacceptable smoothness on non-AMG projects.

The guidance on the interpretation of odds ratio is briefly summarized as follows:

- OR of 1.0: There is no difference between AMG and non-AMG paving in influencing the odds of meeting smoothness thresholds.
- OR greater than 1: AMG has the higher odds of influencing the process toward meeting smoothness thresholds than non-AMG paving.
- OR less than 1: Non-AMG paving has the higher odds of influencing the process toward meeting smoothness thresholds than AMG paving.

Table 23 presents the summary of odds ratio analysis. The results indicate that the AMG paving generally resulted in higher odds of meeting smoothness thresholds than non-AMG paving, although its degree of consistency can be described to range between marginally and moderately better odds. Furthermore, the range of odds ratios estimated at 95 percent confidence interval was much wider for all case studies, thus indicating high magnitudes of uncertainty with the estimated odds. In other words, the estimated odds are not robust enough to make a conclusive case that the use of AMG will reliably result in achieving the smoothness thresholds. Note that the odds ratio could not be estimated for the Iowa dataset because none of the AMG segments received any disincentive.

Table 23. Summary of odds ratio analysis.

Case Study	Paving Technology	Percent 0.1-mi Segments with Acceptable Smoothness	Percent 0.1-mi Segments with Unacceptable Smoothness	Odds Ratio (LL-UL) at 95% CI
Arizona Loop 101	AMG	0.91	0.09	1.46 (1.71E-04, 1.25E+04)
Arizona Loop 101	Non-AMG	0.87	0.13	1.46 (1.71E-04, 1.25E+04)
Illinois Tollway I-90	AMG	0.67	0.33	1.71 (5.61E-03, 5.24E+02)
Illinois Tollway I-90	Non-AMG	0.54	0.46	1.71 (5.61E-03, 5.24E+02)
Iowa U.S. 20	AMG	1.00	0.00	NA
Iowa U.S. 20	Non-AMG	0.99	0.01	NA
Missouri U.S. 50	AMG	0.99	0.01	0.63 (5.39E-14, 7.46E+12)
Missouri U.S. 50	Non-AMG	0.99	0.01	0.63 (5.39E-14, 7.46E+12)
Oregon SH 140	AMG	0.95	0.05	2.63 (3.28E-05, 2.10E+05)
Oregon SH 140	Non-AMG	0.89	0.11	2.63 (3.28E-05, 2.10E+05)

Evaluation of Random Effects and Heterogeneity

It is well understood that the observed smoothness, as achieved in the case study projects, are a confluence of many influencing factors, of which the use of AMG or non-AMG methods is a clear discriminating factor; however, there are many other influencing factors, known or unknown, such as the pavement type, project type, terrain, and workmanship, that are likely to cause variations in smoothness outcomes across case studies. It is, therefore, necessary to distinguish the effects of AMG from other covariates (i.e., factors influencing changes in smoothness outcomes).

Conducting a controlled experiment to quantify covariates systematically was beyond the scope of this study. However, to account for confounding factors, “random effects” meta-analysis was conducted. The “random effects” models provide information on how much of the observed effects (i.e., grand mean of smoothness change) are “true effects” (i.e., change resulting from the AMG use) and “random effects” (i.e., change caused by other influencing factors). Both true effects and random effects are analogous to “treatment effects” and “experimental error” terms, respectively, used in conventional analysis of variance. Furthermore, each case study is expected to produce effects estimate (i.e., changes in smoothness outcomes) of different magnitude (i.e., percent changes) and direction (i.e., positive or negative change). These observed variations across case studies could be attributed to random effects or inconsistency in true effects (i.e., heterogeneity) of the AMG.

This study utilized two key statistical measures to evaluate heterogeneity among case studies: the summary effect (*M*) and the I^2 statistic.

Summary Effect M

This measure quantifies the grand "weighted" mean of the effects estimate of AMG, taking into consideration that these effects might not be the same across different case studies. This measure considers two sources of variance: experimental error within each case study captured as the difference between measured and true effect, and heterogeneity captured as variation in true effects across case studies.

The summary effect is calculated as a statistically weighted mean of all effect sizes from individual case studies where the contribution of each case study is assigned with a numerical weight based the inverse of observed variance within the case study. Table 24 summarizes the variance estimates and weights assigned to each case study. The higher the variance within each case study, the lower the priority given to the calculated effect of that study. Note that both Illinois I-90 and Oregon State Highway 140 case studies, which had higher statistical variation, are assigned with lower weights in the summary effect estimation.

Table 24. Variance estimates for summary effect computation.

Case Study	Effect Size	Variance Within	Variance Between	Variance Total	Weights Assigned to Each Study (Percent)
Arizona Loop 101	0.180	0.008	0.289	0.296	22.6
Illinois Tollway I-90	0.394	0.197	0.289	0.486	13.0
Iowa U.S. 20	−0.674	0.007	0.289	0.296	22.6
Missouri U.S. 50	0.274	0.013	0.248	0.261	22.1
Oregon SH 140	−0.005	0.044	0.289	0.333	19.7

I^2 Statistic

This measure, analogous to signals-to-noise ratio, provides a degree of inconsistency in AMG effects across case studies. This measure describes the percentage of total variation across studies that is due to heterogeneity rather than chance. Note that this measure is an indicator of inconsistency across the findings of the case studies but not as a measure of the real variation across the underlying true effects. This statistic is typically interpreted in table 25.

Table 25. Interpretation of I^2 statistic.

Statistic (Percent)	Description of Difference
0	No observed heterogeneity
Less than 30	Low heterogeneity
30 to 60	Moderate heterogeneity
60 to 80	Substantial heterogeneity
80 to 100	Considerable heterogeneity

Table 26 presents the summary effect computation results. The summary effect indicates the statistical mean of standardized mean differences observed in all individual case studies, while the estimates at 95 percent confidence intervals describes the uncertainty in the estimation of the mean effect. Table 27 presents the I^2 estimates that describe the statistical heterogeneity in the smoothness data.

The summary effect estimates indicate that the positive difference in smoothness that AMG method produces over non-AMG is negligible. Both the *p*-value and the prediction intervals, which show both moderately negative and positive differences, suggest the lack of evidence to demonstrate one method had the advantage over the other in producing better smoothness outcomes.

Furthermore, the I^2 estimate of 94.2 percent indicates a very high level of heterogeneity. In other words, the I^2 estimate suggest that the 94.2 percent of the observed dispersion is due to real differences in the standardized mean differences of smoothness outcomes between AMG and non-AMG segments.

The summary effect and I^2 estimate collectively suggest that there is no statistically conclusive evidence in the smoothness data of five case studies to support the hypothesis that the use of AMG paving alone would "reliably" produce better smoothness outcomes than the non-AMG paving. There could be other factors that significantly confound smoothness outcomes during paving.

Table 26. Summary effect.

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

Table 27. Estimate of heterogeneity.

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

Interpreting the Results

The smoothness data collected from the five case studies indicate the lack of statistically conclusive evidence to show that the use of AMG paving results in overall initial smoothness improvements compared with those projects using non-AMG paving.

The standardized mean differences in smoothness data of Arizona and Missouri case studies demonstrate the marginal superiority of AMG paving over non-AMG paving. The probabilities of superiority for the Arizona and Missouri case studies show that the AMG paving has an average of 5 percent and 8 percent advantage, respectively, over non-AMG paving.

The smoothness outcomes of the Oregon case study are comparable for both methods, with no or negligible difference between them. The Iowa case study produced a conflicting but robust trend where the segments using non-AMG paving had consistently better smoothness than those using AMG paving. Although the use of AMG on the Illinois Tollway I-90 site produced moderate improvements in measured smoothness, the prediction intervals show uncertainty with the estimated effect size. The computed summary effect at 50 and 95 percent confidence intervals suggests that the overall initial smoothness improvements with the use of AMG paving are statistically negligible.

As table 19 suggests, there is inconclusive evidence to support that the use of AMG paving resulted in reduced variability in smoothness measurements compared with non-AMG paving. The standard deviations of smoothness datasets of Arizona and Oregon case studies showed that the AMG paving produced more uniformity in smoothness outcomes than non-AMG paving. However, at other sites, where different contractors were involved in paving of AMG and non-AMG cohort segments, the observed variation did not support the hypothesis.

The odds ratio was used to measure the differences in risks relating to the specification compliance between AMG and non-AMG methods. The computed odds ratios suggest that the effectiveness of AMG paving in achieving smoothness thresholds can be described as marginal or moderately better than those of non-AMG method; however, there is a high degree of uncertainty in concluding the ability of AMG in reducing the number of segments exceeding specification thresholds.

Meta-analysis of data gathered from five case studies suggests the lack of statistically adequate and conclusive data to support the hypotheses. The observed variability in the “true effects” among the case studies is too high to establish that the use of AMG can produce reliably better smoothness outcomes over traditional methods. During construction, the deployment of AMG technologies is apparently beneficial in preparing a more uniform and stable base as well as guiding the paving operations with better elevation and alignment control; however, the smoothness outcomes cannot be solely improved using AMG alone. The effects of other contributing factors must also be considered.

EFFECTS OF CONTRIBUTING FACTORS

There are many other factors, relating to existing base condition, terrain, geometric alignment, pavement layer types and design features, concrete/asphalt mix properties, concrete/asphalt delivery and compaction/finishing, and contractor means and methods that may influence smoothness during construction. These factors, which are difficult to segregate to conduct a controlled experiment, are often manifested in the form of contractor skill and workmanship. For example, the Iowa case study was constructed by contractor A and compared with a project paved by contractor B who is known for consistently paving roadways with superior smoothness. Furthermore, in the same case study, it was noted that, even though contractor A had been using AMG paving systems, he chose to set up the guiding instruments using the minimum manufacturer recommendations. Using the minimum manufacturer recommendations may result in signal interruptions, forcing the equipment to unnecessarily stop and restart. Some contractors set up additional guiding instruments to provide redundancy to avoid this problem. This concept is further explained in chapter 5.

The alignment and profile geometry are also contributing factors for initial pavement smoothness. 3D design data (i.e., profiles) can be exported from the model to calculate a theoretical IRI using ProVAL during the design phase. This is not a current practice, but adding this relatively small level of effort can help determine the best achievable smoothness under ideal conditions. A non-smooth design profile may result in poor initial pavement smoothness, regardless of the construction means and methods used in the field. Thus, profile optimization using 3D design software should be a consideration for achieving the best possible initial pavement smoothness. Optimization of the design profile was not performed on any of the datasets used for AMG paving in the case studies documented in this research.

Lastly, the collection method of profile data for acceptance should match the methods used for reporting annual pavement conditions (e.g., IRI smoothness data). This recommendation will ensure that initial and long-term pavement smoothness are comparable.

The case studies documented in this research provide a foundation to understand the potential effects of AMG technology on initial pavement smoothness. However, to truly measure the effects of AMG technology on pavement smoothness, several controlled experiments should be explored concurrently. It is highly recommended that these controlled experiments exhibit at a minimum the following characteristics:

- Project constructed by a single contractor in which half of the sections are built with traditional non-AMG methods and the other with an AMG for each layer of the pavement structure.
- Field crews for each type of construction method with equivalent experience.
- Paving sections with same number of samples for each construction method.

- Same type of geometry per construction method (e.g., tangent versus superelevated curve sections).

- Similar terrain and site conditions (e.g., both construction methods paved in rolling terrain under live traffic).

It is important to note that conducting such a controlled experiment is not an easy task. However, it may be easier to conduct a more controlled experiment, if requirements are specified during the advertisement of the project to ensure contributing factors can be kept to a minimum.

CHAPTER 5. GUIDANCE FOR MITIGATING RISKS WHEN USING AMG TECHNOLOGY FOR PAVING OPERATIONS

The primary benefit of using AMG technology for guiding pavement equipment is the ability to have better grade control during the operation. However, it is important to note that paving operations using AMG systems heavily depend on the surveying setup and appropriate QC during and after the placement of each layer of the pavement design and the data files used by the on-board system. Thus, the guidance for mitigating risks when using AMG technology for paving operations should focus on survey and data management specifications. The guidance provided herein assumes that all other specifications related to the QC and QA of paving operations are also being referenced during construction.

CONTRACTOR QUALITY MANAGEMENT PLAN

Whether the contractor plans to use AMG systems for one or multiple activities (e.g., grading, paving), the QMP should include a section specific to the use of this technology. It is important for the SHA to know how the contractor will manage the setup of the equipment, files used on the on-board sensors, and any discrepancies in grade and elevations. Furthermore, 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 contractor should add language to the QMP specific to the use of AMG equipment for either one or multiple activities. The sections described herein are general guidelines to consider when creating a QMP for AMG system operations. jane

Sourcing, Management, and Validation of 3D Design Files

This section 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 files necessary for the 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. If any changes are made to the model data files, and the equipment operator does not have the most up-to-date information loaded on the on-board system, or there are any errors not caught during the data validation process, the consequences may be drastic, causing rework and delays.

Procedures Establishing, Verifying, or Augmenting Survey Control

Whether the contractor plans on using AMG constructions methods, 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 construction methods used for paving operations require a higher density of control points than are needed for construction staking. Thus, at a minimum, the contractor should consider the following items to include in the QMP:

- Process for validating, using, and/or augmenting the SHA-provided survey control points that were used for creating the preconstruction survey.

- Approach for densification of survey control network of a higher order of vertical accuracy to support AMG paving equipment.

- Protocols for managing interference to the GNSS satellite signals from canyons, buildings, trees, and so on.

Lastly, a professional surveyor should create and verify the survey control report as required by the SHA survey manual or specifications.

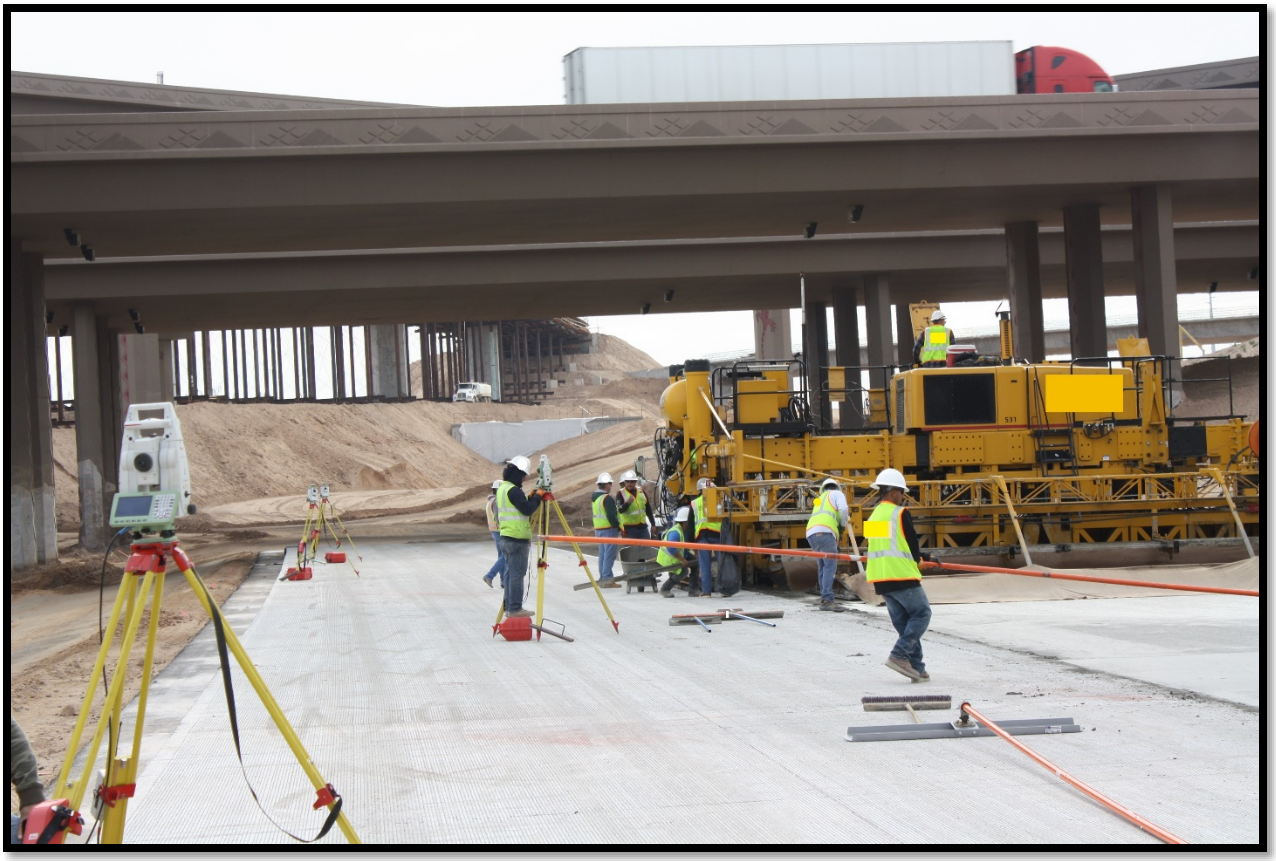
Proposed AMG Construction Methods, Equipment Guiding Sensors, and Setup

The contractor should provide an overview of what activities will be performed with AMG systems (e.g., grading, trimming, paving), and name the person overseeing the AMG operation or AMG QC manager. This person 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 the machine computer systems. Furthermore, the QMP should describe what positioning technology method is going to be used to guide the systems (e.g., GNSS, 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 the positioning of the equipment is being controlled, and it helps the survey crew troubleshoot any issues that may arise during construction. Figure 68 shows a GNSS-guided grader, and figure 69 shows a robotic total station-guided concrete paver.

[redacted] [redacted]

Source: FHWA.

Figure 68. Photo. GNSS-guided grader.



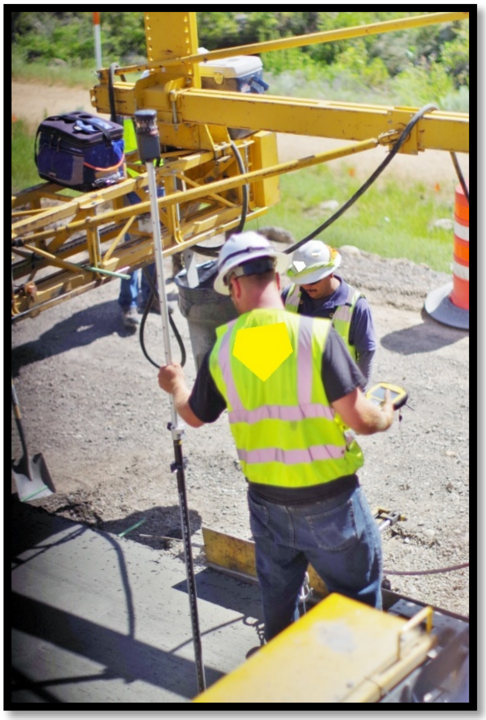
Source: FHWA.

Figure 69. Photo. Robotic total station-guided concrete paver.

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

The contractor should describe how elevations, depths, and cross slopes will be checked during the operation. If a checker will be available to perform real-time QC checks with high precision surveying equipment, it should be stated in the QMP. In addition, the contractor should describe the equipment and approach for performing these real-time checks. The paving foreman can store information being collected with the data collector used for real-time checks. Information such as station, offset, and elevations can be used to produce a report showing pavement depths in a spreadsheet format that can be attached to the inspection daily reports. Examples of real-time checks are shown in figure 70 and figure 71.

While contractors are well versed in using high-precision surveying equipment as a tool to perform QC work, SHA inspection staff typically do not have access to the same equipment for real-time verification. Perhaps this is the biggest gap to close to be able to leverage the benefits of AMG 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 QA purposes. If the contractor is furnishing this equipment, it should be noted in the QMP. Furthermore, there should be some language describing the approach for training the inspector to use the field survey equipment.



Source: FHWA.

Figure 70. Photo. One example of checking elevations behind paver.[8]

Source: FHWA.

Figure 71. Photo. Another example of checking elevations behind paver.

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 the QMP describing the procedure for resolving any survey discrepancies.

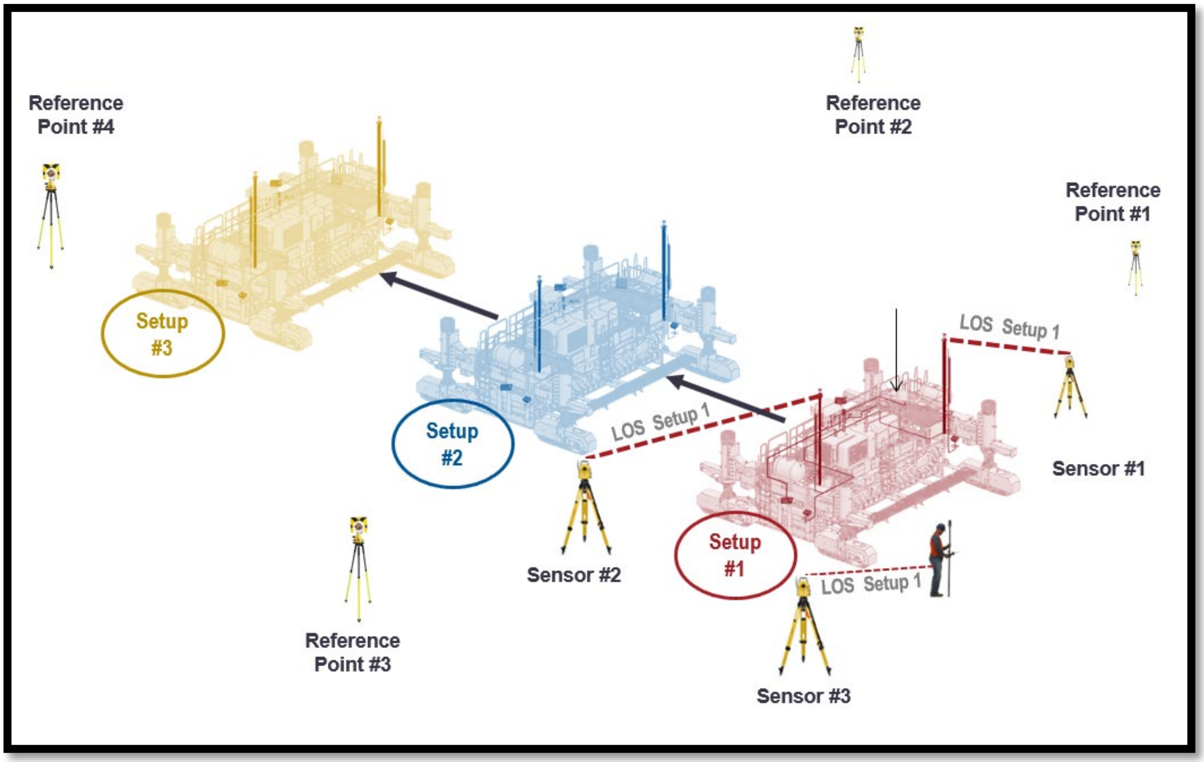
Documenting and Managing Site Conditions

The AMG systems depend on the communication between the referencing positioning survey equipment on the ground and the receivers on the paver. Thus, the contractor being the one providing the QC should try to 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.

There are times when the signal between the reference positioning equipment and the receivers on the paver is blocked by moving vehicles or people. So the person responsible for setting up and maintaining the surveying equipment that guides the paver should be familiar with the site before the paving operation. All equipment stops and restarts should be properly documented, and comments should be made if any of the stops were due to the issues with the surveying equipment guiding the paver. Over time, both the contractor and SHA will learn what situations to avoid or, better yet, how to mitigate them.

MINIMUM VERSUS OPTIMAL EQUIPMENT SETUP

Most manufacturers require a minimum of three robotic total stations to guide AMG systems for mainline pavers. Two robotic total stations control the paver, and the third one is used for real-time verification and storing any data to produce electronic reports. The third total station is also used to leapfrog as the paver moves down the grade. The purpose of this leapfrogging movement of the sensors is to ensure the paver can receive the signals from the two controlling sensors, and there is always a third sensor connected to the checker surveying equipment for quality control. As illustrated in figure 72, figure 73, and figure 74, the total stations must continue to leapfrog to relinquish control of the machine from one sensor to another.



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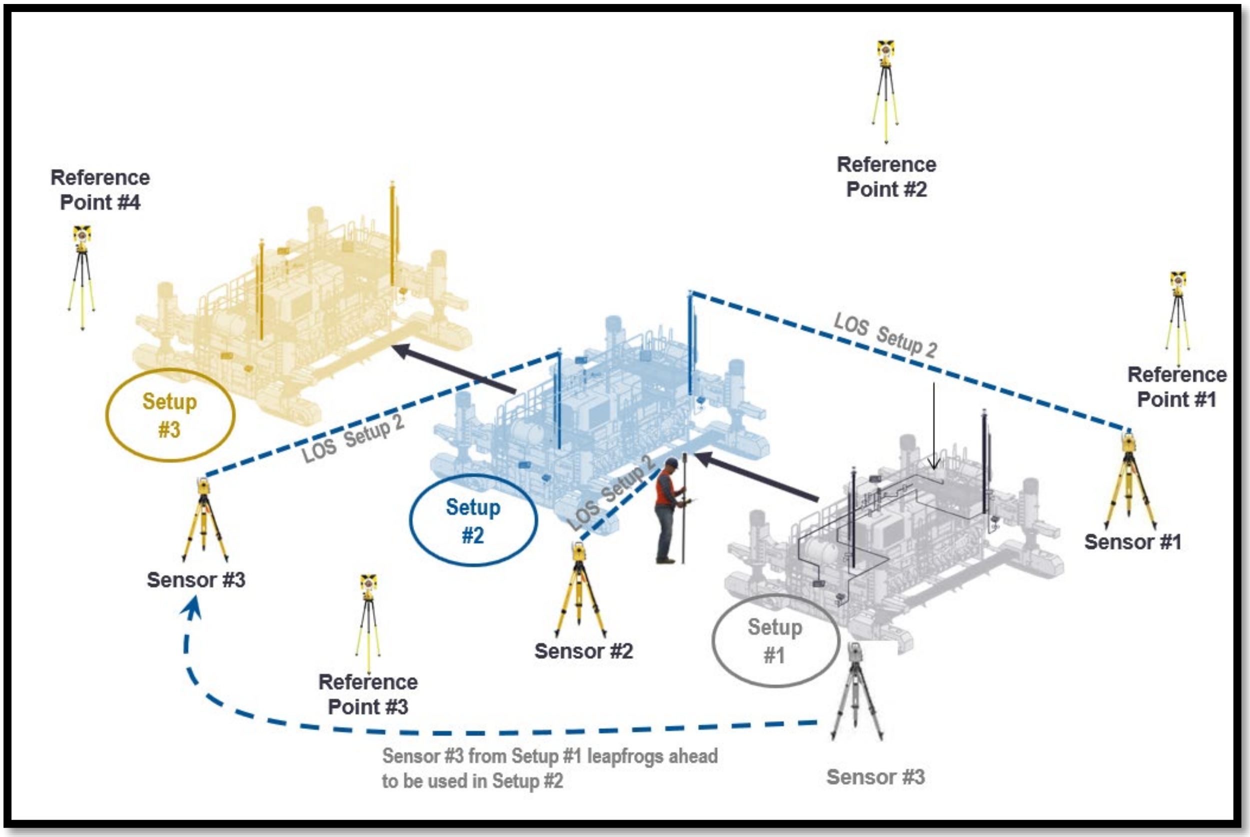
LOS = line of sight.

Figure 72. Illustration. Initial setup of equipment to guide an AMG concrete paver.



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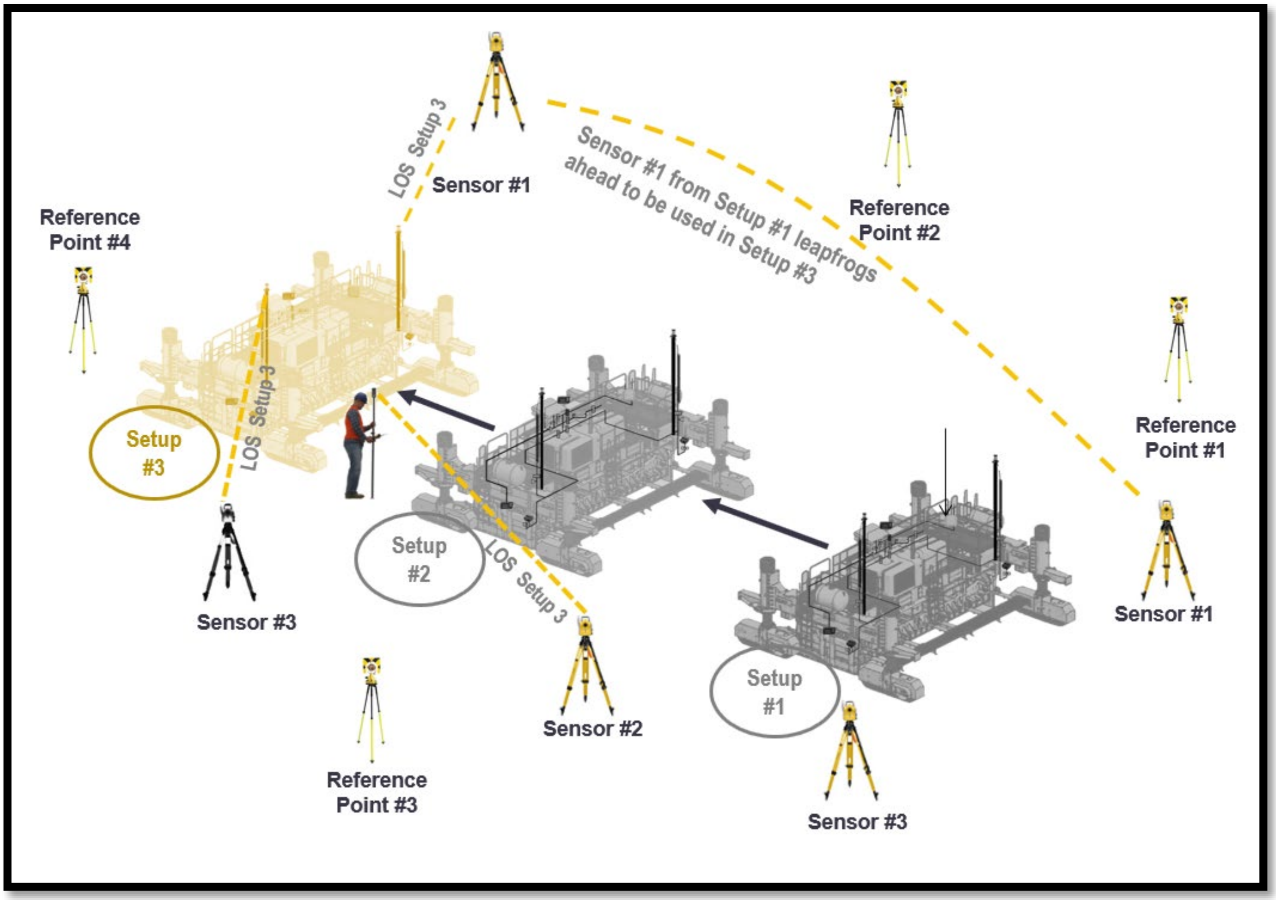
LOS = line of sight.

Figure 73. Illustration. The first leapfrog movement takes place during this operation.



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LOS = line of sight.

Figure 74. Illustration. The second leapfrog movement takes place during this operation.

Often, this leapfrogging process cannot keep up with the speed of the paver, forcing unnecessary stops and restarts, which may result in bumps on the pavement increasing the areas of localized roughness. Furthermore, setting up the minimum pieces of guiding equipment provides no contingency for malfunctioning equipment. More experienced contractors recommend having as many robotic total stations as possible. An average of six pieces of equipment is considered a good practice. Also, it is highly recommended to have two surveyors to move the equipment and to continuously check the machine computer for proper operation. The machine computer is used to monitor positioning of the paver. Just like when using non-AMG control, adjustments may be made to the front and rear of the paver independently. An advantage of computer on-demand adjustments is that the paver does not need to stop to adjust non-AMGs.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This study set to test the hypothesis that AMG construction methods used for grade control can also improve initial pavement smoothness outcomes by comparing projects constructed using AMG on successive pavement layers to projects that did not. To test this hypothesis, five paving projects in which AMG technology was planned to be used or was used were selected for case study documentation. Each of the case studies was compared with a similar project in scope and size in which AMG technology was not used for the paving operation. The projects ranged from reconstruction to new construction, and only one of the projects was an asphalt project.

It was found that asphalt paving contractors are not using AMG technology for roadway projects because the current technology (e.g., leveling skis) provide sufficient control to meet SHA smoothness requirements. During the literature review and the case study selection process, contractors shared that 3D engineered models and AMG-guided asphalt paving equipment are only used when profile correction or variable depth paving is the main objective.

On the other hand, concrete paving contractors are increasingly incorporating AMG technology in roadway projects, not because the equipment improves smoothness outcomes, but because it has been proven to control quantity yields and accelerate the construction schedule. Nevertheless, some contractors expressed optimism in the potential for AMG technology to also improve pavement smoothness outcomes, provided all other factors contributing to ride quality are equal.

The study had practical challenges in obtaining a large sample size and cohort projects with adjacent AMG and non-AMG applications to control other influencing factors. To overcome these challenges, the research team used the application of meta-analysis techniques to evaluate the improvements offered by the AMG technology over conventional methods. A meta-analysis provides a quantitative framework for conducting a systematic review of empirical evidence provided by various case studies and summarizing them.

The smoothness data collected from the five case studies indicate the lack of statistically conclusive evidence to show that the use of AMG paving results in overall initial smoothness improvements compared with those projects using non-AMG paving. In this context, although there is inadequate and inconclusive evidence to support the hypothesis, there is preliminary evidence to support that using AMG may produce smoother pavements. At best, the AMG technology serves as a tool to eliminate or mitigate risks that adversely affect smoothness; however, like any other tool, the realization of benefits depends on the contractors who use it.

RECOMMENDATIONS FOR FUTURE WORK

The proliferation of AMG construction methods used by contractors along with the advancements in geospatial technology continue to elevate the awareness of how digital data can be used for multiple transportation applications. Geospatial tools can collect more and richer data than ever before, and newer, better, and less cost prohibitive sensors continue to be introduced by the industry. Remote sensing technologies like LiDAR and GNSS continue to improve data collection to support the tolerances needed for many construction applications, including collection of profile data to determine smoothness. Furthermore, modern civil design modeling software can now handle the large geospatial datasets, and the tools available to designers are making it possible to deploy 3D design data as a standard practice. Until recently, the focus had been on providing data to facilitate contractor means and methods, but that is quickly changing. The attention is now turning to enable construction inspection and acceptance processes to optimize digital data during and after construction This unprecedented availability of digital data created in design should be leveraged to investigate ways to improve pavement smoothness during preconstruction.

As technology evolves, and preconstruction data collection methods become more affordable, is it possible to conduct smoothness evaluation during design? Does AMG technology provide opportunities to raise the bar when it comes to pavement smoothness requirements? Should the smoothness requirements, incentives, and disincentives be based on theoretical or actual preconstruction profiles?

The benefit and costs of utilizing AMG for better paving outcomes are yet to be fully understood. Contractors expect returns on their investments made in AMG systems through accelerated construction timelines and material yields; however, some hypothesize that AMG also helps achieve smoothness incentives. Thus, it is suggested to examine the influence of AMG on the unit prices of relevant pavement bid items and smoothness-related pay incentives compared with the non-AMG paving. Future studies can investigate further to answer 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 systems in paving operations?

One of the key observations of this study is how contractors use AMG as a tool in their process control. Pavement smoothness is an outcome of contractor’s workmanship and the quality of paving operations. Field observations show that some contractors effectively utilize AMG for grade control, whereas others with excellent process control might not tangibly benefit from AMG. Nevertheless, contractors desiring to embrace AMG technology for paving operations may benefit from additional guidance on incorporating AMG into the paving process with a recommended list of “do’s and don’ts” as well as a check list of unique factors, such as those relating to calibration and vertical level adjustments. The AMG-related specifications can also be potentially incorporated for design-bid-build contracts.

APPENDIX. SMOOTHNESS COMPARISON INSPECTION RECORD FOR ADOT CASE STUDY

Table 28 demonstrates the relationship between pour numbers, HOV lane average PRI, HOV lane number of must grinds, shoulder average PRI, shoulder number of must grinds, and the total incentive in U.S. dollars for wireless paving in segment 1. Table 29 includes the same categories but for segment 2, string-line paving results.

Table 28. Segment 1: wireless paving.

Pour Number	HOV Lane Average PRI	HOV Lane Number of Must Grinds	Shoulder Average PRI	Shoulder Number of Must Grinds	Total Incentive (U.S. dollars)
AA	6	6	3	2	188.80
AB	5	5	2	5	622.07
AC	4	5	1	3	988.67
AE	5	7	4	3	668.80
AF	3	8	2	2	1,723.20
AG	2	1	2	NA	321.33
AH	4	12	4	4	1,971.00
AI	5	4	2	1	1,185.07
AJ	3	7	2	1	1,777.73
AK	15	2	10	1	(106.67)
AL	6	11	3	4	(3.01)
AM	4	4	2	3	783.73
AN	3	6	3	3	940.27
AO	4	10	2	2	1,462.67
AP	4	4	7	6	2,003.87
AQ	4	6	4	3	904.53
AR	6	5	3	2	33.60
AT (NB)	6	2	9	1	70.13
AT (SB)	3	9	0	3	1,259.31
AU	5	3	4	2	196.53
AV	11	2	8	7	NA
AW	6	7	4	3	62.80
AX	2	1	1	NA	1,813.87
AY	3	6	2	3	1,481.60
AZ	1	NA	2	1	1,650.00
BA	12	4	4	NA	NA
BB	2	2	2	2	1,374.53
BC	2	3	2	1	2,091.73
BE	4	3	3	3	1,048.13
BF	2	3	3	2	1,502.13

Pour Number	HOV Lane Average PRI	HOV Lane Number of Must Grinds	Shoulder Average PRI	Shoulder Number of Must Grinds	Total Incentive (U.S. dollars)
BG	8	4	0	NA	(352.00)
BH	4	9	5	3	1,251.33
BI	6	10	6	5	769.60
BJ	6	9	8	5	394.67
BL	5	9	4	5	1,024.27
BM	4	2	3	1	377.07
BM (NB)	4	4	5	2	973.20
BO	5	9	5	8	1,350.80
BP	9	4	8	2	(308.33)
BQ	3	6	2	4	1,548.81
BS	2	2	2	1	542.67
BT	7	5	6	NA	NA
BU	4	14	3	3	1,589.93
BV	2	8	2	2	1,609.33
BX	3	8	3	2	1,690.67
BY	2	7	1	3	2,360.93
BZ	3	7	1	3	1,327.20
CA	3	6	1	1	1,298.00
CB	4	7	3	3	769.80
CC	2	5	1	1	1,471.47
CD	3	9	3	3	1,857.33
CE	4	8	3	3	1,252.67
CJ	7	4	9	3	(20.00)
CK	9	2	8	2	(333.33)
CL	9	2	9	1	(211.00)
Average/Total	**4.7**	**NA**	**3.7**	**NA**	**50,251.51**

Note: A total of 15 hand-pour lots were measured concurrently with adjacent machine pour lots in segment 2.

Table 29. Segment 2: string-line paving results.

Pour Number	HOV Lane Average PRI	HOV Lane Number of Must Grinds	Shoulder Average PRI	Shoulder Number of Must Grinds	Total Incentive (U.S. dollars)
1	4	2	1	1	795.87
2	3	7	3	4	1,178.40
3	2	3	2	2	1,468.00
4	5	4	9	1	1,379.20
5	3	5	3	1	763.60
6	2	NA	1	NA	1,420.40
7	5	7	4	4	16.67

Pour Number	HOV Lane Average PRI	HOV Lane Number of Must Grinds	Shoulder Average PRI	Shoulder Number of Must Grinds	Total Incentive (U.S. dollars)
8	0	NA	0	NA	1,510.00
9	6	4	6	2	207.33
10	1	NA	1	NA	984.00
12	5	7	4	3	360.40
13	5	3	3	2	1,549.87
14	1	NA	1	NA	651.33
15	0	NA	0	NA	1,648.00
16	3	7	3	3	762.00
17	1	3	0	2	1,485.60
18	3	NA	3	NA	973.60
20	2	3	4	NA	1,326.67
21	4	4	3	1	850.53
22	4	5	3	3	675.07
23	5	4	4	2	396.27
24	5	NA	7	NA	352.00
26	4	1	1	1	868.80
28	4	10	6	5	962.13
29	6	5	5	3	920.67
30	2	3	2	2	1,138.13
31	NA	NA	2	2	NA
33	1	1	1	2	1,197.87
34	2	5	1	3	2,052.53
35	1	2	1	1	1,250.00
36	1	4	1	2	2,847.33
37	0	NA	1	1	1,707.33
39	1	4	2	2	2,005.07
40	1	2	1	1	2,483.20
41	2	6	1	1	2,475.60
42	3	4	1	2	933.60
43	2	2	2	1	1,090.00
44	3	3	3	1	947.67
45	2	4	6	1	957.60
46	4	6	3	3	816.13
47	6	5	NA	NA	381.94
48	3	5	2	1	1,716.27
49	1	5	1	3	1,991.33
50	2	2	2	3	1,001.87
52	2	2	2	1	1,122.67
54	1	4	1	--	1,377.33
55	2	2	1	1	704.00
56	2	NA	1	NA	1,170.67

Pour Number	**HOV Lane Average PRI**	**HOV Lane Number of Must Grinds**	**Shoulder Average PRI**	**Shoulder Number of Must Grinds**	**Total Incentive (U.S. dollars)**
57	7	3	6	3	NA
58	3	2	1	2	792.80
59	3	3	2	2	1,652.80
60	3	NA	1	NA	489.20
61	7	3	6	2	NA
62	2	NA	1	1	328.93
63	3	11	3	6	1,789.47
66	3	15	4	8	2,622.80
68	1	3	1	1	2,142.27
69	1	5	1	NA	1,816.27
71	5	6	8	3	921.60
73	12	3	8	3	(900.67)
74	6	2	8	3	331.00
75	12	7	7	3	(474.93)
76	0	1	0	NA	1,526.66
77	1	4	1	1	1,880.00
78	10	7	9	3	1,332.40
79	2	2	4	2	1,207.33
80	3	2	4	2	1,152.73
81	4	4	4	2	625.33
82	8	1	14	1	(98.33)
83	6	4	10	8	28.80
Average/Total	**3.3**	**NA**	**3.2**	**NA**	**74,041.01**

Note: A total of 15 hand-pour lots were measured concurrently with adjacent machine pour lots in segment 1.

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- Iowa DOT.
- Illinois State Toll Highway Authority.
- MoDOT.
- ODOT.

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- Florida DOT.
- Mississippi DOT.

The original illustration in Figure 9 is the copyright property of Topcon® and was permitted to be used in this report to illustrate the components of the AMG paving system. The original illustration was modified to replace the labels that showed proprietary equipment terms with more generic ones.

The original illustrations shown in figure 72, figure 73, and figure 74 used the illustration of the paver, the copyright property of Trimble® as a foundation for the graphics. The original illustration was changed in color and used as one of the basic components for the graphics. Trimble® permitted the used of the graphic in this report to convey the message within the context of the leading paragraphs.

The original map is the copyright property of Google® Earth™ and can be accessed from https://www.google.com/maps.(37) Maps for each of the case study locations were created using Google® images.

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