U.S. Department of Transportation
Federal Highway Administration

Technical Brief

Utilizing 3D Digital Data in Highway Construction

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Figure 1: Automated Machine Guidance for concrete paving

RESEARCH SYNOPSIS

The greatest barrier to using 3D digital design data in highway construction is ineffectively managed uncertainty regarding whether the constraints assumed in design reflect actual field conditions. Verifying the original ground close to construction is an effective, digital preconstruction quality control method to avoid basic construction issues. Usually, resident engineers lack a facility to manipulate 3D data confidently; contractors have comparatively advanced expertise with 3D data. Construction partnering is a viable solution to collaboratively use 3D data to save time, improve transparency, and build confidence in 3D data uses. Inspectors can use 3D data that represents the design intent with field survey equipment for real-time verification and to measure quantities. This is a safe and efficient e-Construction practice.

Abstract

Using 3D digital design data (3D Data) in highway construction affords, among other benefits:

- Ability to identify and rectify constructability issues prior to mobilization.
- More accurate pavement material quantity estimates.
- Opportunity to supplement or replace plan sheets with more consumable data.
- Better control of pavement material quantities through Automated Machine Guidance (AMG).
- Faster construction execution with AMG, which has associated efficiency and safety benefits.
- Faster inspection using real-time verification with associated safety benefits.
- More efficient workflows to measure payment quantities using 3D data that provide ancillary transparency and repeatability improvements through reports to support the measurements, such as Figure 2.

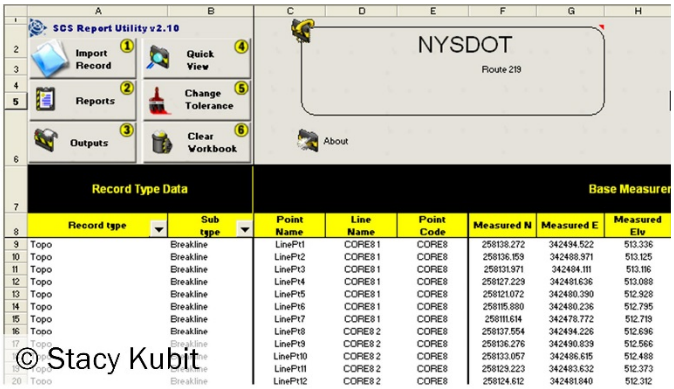

Figure 2: A report of 3D data collected to measure quantities

The key to these benefits is 3D digital design data. However, there are significant challenges to scaling the use of 3D design data in construction, especially for construction inspection. These are:

- Determining the right time to collect original ground survey at the needed accuracy.
- Generating sufficiently detailed design models.
- An absence of a complete and consistently implemented data schema and data format.
- A need for laborious, manual data exchange.
- A lack of standard protocols to review 3D data.
- Tedious and laborious 3D data reviews to verify that exchanged data is consistent with contract plans. Figure 3 is an example of how the process is performed.

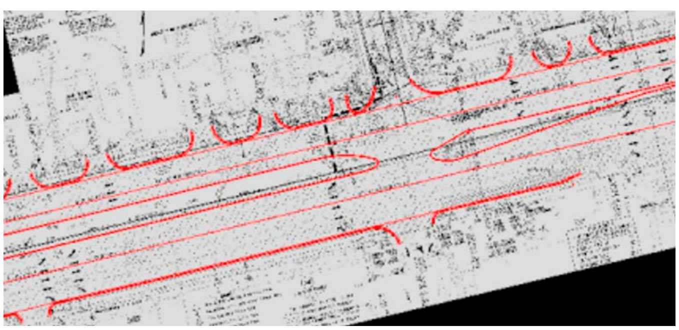
Figure 3: 3D data (red) viewed over contract plans

- Equipping resident engineers and inspectors with the hardware, software, and skill to use 3D data with confidence.
- Unequal facility for manipulating 3D data between the resident engineer and contractor

Shifting responsibility to the resident engineer to review and accept 3D data for inspection.

Informal construction partnering is one solution to this challenge. The contractor benefits from more expedient decision-making regarding how to manage issues such as field changes, and the resident engineer gains confidence that the 3D data used for construction is equivalent to plans.

Six case studies from four states were conducted to document how state transportation agencies are using 3D data in construction. The findings from the case studies are discussed in this document as a comprehensive collection, rather than individual accounts. The projects span new construction; urban and rural reconstruction; concrete overlay; and urban and rural asphalt mill-and-pave, with and without geometric corrections.

The research products developed to support the successful utilization of 3D digital design data in highway construction include:

- Evidence that a complete, open data format would save significant time and reduce risk for contractors and resident engineers.
- Guidance on the project characteristics conducive to the use of 3D data for AMG.
- A Level of Development (LOD) designation to identify and assess the uncertainty, risks, and impacts of using 3D data for construction.
- Guidance on the timing and priority areas for pre-construction survey verification to manage risks associated with uncertainty in 3D data.
- Guidance on the use of 3D data for real-time verification and measurement.

Using 3D Digital Design Data

The first step to using 3D digital design data for highway construction is to create a set of 3D data that represents the design intent in the contract plans. The process ultimately results in the same information conveyed in the plans in a different format. There are three main challenges to the process, which add inefficiency and risk. Using 3D design practices that prioritize the 3D model as the source of the contract plans is a significant mitigation for the first challenge.

The three challenges are:

- Current design practices often ensure that there are discrepancies between the 3D data and the plans that need correcting.
- Lack of an open data format makes data exchange an arduous, manual process.
- The data is often not sufficient for construction due to a variety of reasons. The most notable is that the original ground basis for the design differs to field conditions.

To resolve the second challenge, the industry needs to prioritize developing a more complete, open data schema and format that is consistently implemented in software. Solutions to the third challenge were explored by this research.

Identifying and Managing Uncertainty

The 3D data generated in design is an engineered approximation of the design intent. It is based on constraints arising from a depiction of the original ground conditions anticipated in construction, and the subsurface features such as existing utilities and pavements. There is uncertainty associated with these depictions that designers manage and should (but typically do not) communicate to the contractor and resident engineer.

The cost, safety, and practicality of reducing the uncertainty in these design constraints often means that more reliable information can only be collected during construction. The uncertainties, in particular relating to the original ground, must be eliminated before the data can be used for layout and AMG. Preconstruction quality control for 3D data involves checking the accuracy of the original ground and/or subsurface features where necessary, and determining the impact and need for design revisions where there are differences.

The process can identify issues with tie-ins to hard, immovable features (such as curbs or saw cuts), transitions (such as lane tapers), clearances, and differences in estimated material quantities. The impacts of these differences may be small. Still, they must be resolved before using the data for AMG construction. Small adjustments to the 3D data would not affect the design intent.

The timing of preconstruction quality control has a direct impact on the agency's ability to control when and how the 3D data changes. Once the contractor has mobilized equipment to the site, the cost impact of delays may be larger than the cost impact of quantity reductions that might have been possible with 3D data revisions. Unexpected differences between the original ground survey used for design and the actual field conditions can cause delays, rework, and even work stoppages. When the contractor and resident engineer are forewarned of potential issues, these can be proactively managed for the best outcomes.

Level of Development (LOD) Designation

The LOD concept describes two attributes of the 3D data. Model Density (MD) is how much detail is incorporated into the model. Confidence Level (CL) is a qualitative statement of the uncertainty associated with the original ground depiction. CL uses a graded scale similar to that used for subsurface utility information. (1)

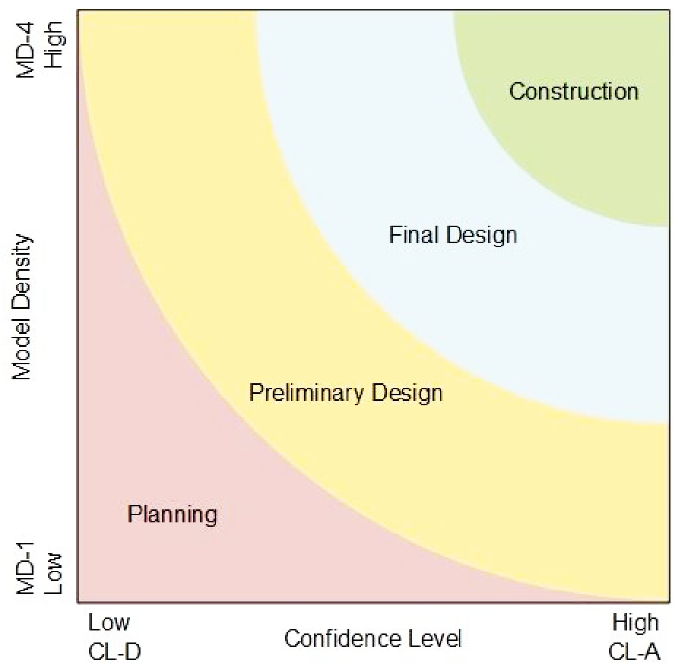

Figure 4: MD, CL, and appropriate 3D data use.

When creating 3D digital design data for use directly in construction, it is important to both add detail to define the design intent and reduce the uncertainty associated with the original ground. Figure 4 illustrates the relationship between MD, CL, and appropriate uses for 3D digital data.

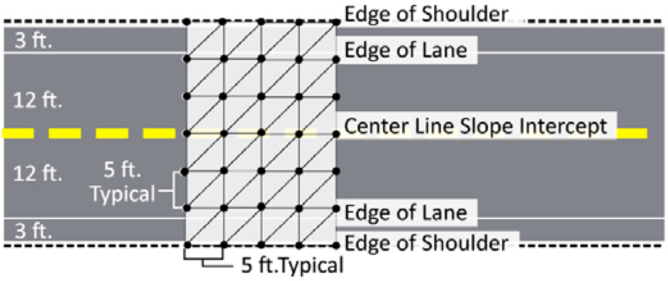

Figure 5: High Model Density with less approximation

MD is a measure of how completely and accurately the 3D data conveys the design intent. MD is essentially a measure of the density of data points. At higher MD (e.g. MD-4), such as Figure 5, there are more frequent data points and thus less interpolation and approximation.

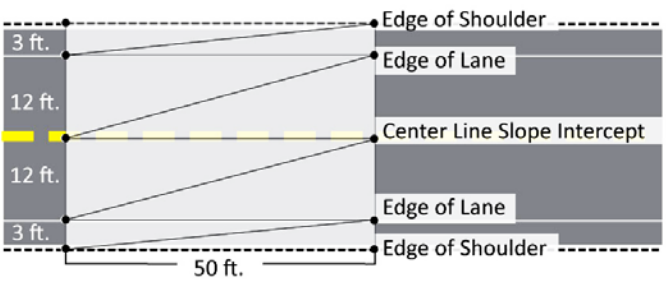

Figure 6: Low Model Density has more approximation

Lower MD (e.g. MD-1), such as Figure 6, has fewer data points and more approximation. The data intervals need to be small enough that transitions are fully developed, and material quantities are accurate. MD-1 through MD-4 define how the 3D data relates to the idealized design.

The intent of introducing CL designations is that designers will be more risk-aware and modulate their effort toward refined geometric designs against the confidence they have in the original ground survey matching field conditions, as well as the impact if field conditions are different. It is a wasted effort to create high MD if the CL is low. Figure 7 uses color to illustrate the probability and impact of 3D data changes in construction for combinations of MD and CL.

The optimal LOD for designing different features varies by feature type, location, and the probability and impact of unexpected field conditions. Figure 8 illustrates the different impacts of low CL for different aspects of an inside shoulder widening design. A LOD designation is a tool by which the risks can be managed and informed decisions can be taken in design and construction.

	CL-D	CL-C	CL-B	CL-A
MD-4	Design and material quantity changes are expected and may be significant. Change orders are likely. Greater risk of delays.	Changes may affect design intent and/or may result in change orders.	Resident Engineer may need to sign off on field fits and/or material quantity changes.	No changes anticipated.
MD-3				Contractor may densify 3D data. Minor material quantity differences.
MD-2			Resident Engineer will need to sign off on transition areas and/or material quantity changes.	Resident Engineer may need to sign off on field fits and/or minor material quantity changes.
MD-1				
KEY	High Probability of 3D Data Changes High Impact of 3D Data Changes Low Value 3D Data			Very Low Probability of 3D Data Changes Very Low Impact of 3D Data Changes Very High Value 3D Data
	Design role in Construction	Construction Partnering to establish model of record		3D data can stand as contract document

Figure 7: Probability and Impact of 3D Data Changes, and Recommended Approach to Manage

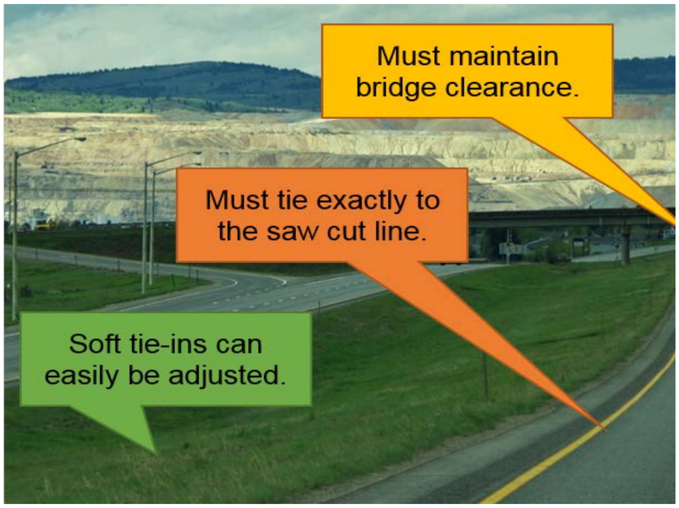

Figure 8: CL differs by proximity to hard constraints

While each use of 3D data in design has its own minimum data needs, higher density data can support the uses at lower bands, except for MD-5. Table 1 defines the MD for intended authorized uses for the data. MD-5 is for interim or final as-built conditions.

Table 1: MD definitions and authorized uses

MD	Typical Density	Authorized Uses
MD-1	Regular stations and key geometry points. Transitions in 2D.	Preliminary design Right-of-way engineering Permit applications
MD-2	25-foot tangents 10-foot curves 5-foot transitions	Final design Bid documents Quantity take-off
MD-3	10-foot tangents 2-foot curves 2-foot transitions	Quantity take-off Pre-construction quality control Construction orientation
MD-4	5-foot tangents 1-foot curves 1-foot transitions	Construction layout AMG construction Real-time Verification
MD-5	25-foot tangents 10-foot curves 5-foot transitions	As-built record documentation Measure pay quantities Asset inventory

Since topographic accuracy is limited by the accuracy in the primary control, there are two components to the CL definition. The first is the accuracy of the primary control and the presence of the survey metadata. The second is the accuracy of the topographic survey. Table 2 defines the different CL designations. CL is a qualitative designation; the uncertainty does not change linearly and can vary significantly within each designation.

Table 2: Definition of CL designations

CL	Definition
CL-A	Control is sufficient for AMG construction Control and topographic accuracy have been verified as: • < 0.15 ft on natural surfaces • < 0.05 ft on hard surfaces
CL-B	Control is sufficient for AMG construction Metadata indicates topographic accuracy is: • < 0.15 ft on natural surfaces • < 0.05 ft on hard surfaces
CL-C	Complete metadata is available for control and topographic survey Low probability that field conditions have changed since survey was collected
CL-D	Basis of original ground survey is unknown or low probability that original ground survey accurately reflects field conditions.

The impact of the accuracy of the original ground survey varies by feature. The impact of uncertainty for cut slopes differs to fill slopes, or for excavation in dirt versus rock. Proximity to utilities or sensitive environmental features reduces the appetite for uncertainty. For many reasons, the optimal LOD varies by feature type, location, and the probability and impact of unexpected field conditions.

Controlling Changes to 3D Design Data

In most cases, the probability of design changes or significant quantity differences in construction can be reduced by collecting more accurate initial topographic survey. The probability of successfully using the design data directly can be increased by verifying the original ground survey in areas where design changes would have the highest impact. The most desirable timing to verify the original ground is immediately prior to construction, but while the 3D data is still in the designer's domain.

This may not be practical; it is safer to use high precision survey instruments when construction traffic control is in place. Accurate survey may be impossible until construction has started. In one studied project, seen in Figure 9, woods needed to be cleared and grubbed before the original ground could be surveyed accurately. In another case, the asphalt pavement had to be milled off to expose the concrete base. In such cases, design changes may affect the design intent and the design role should extend into construction.

Figure 9: Topographic survey was collected after clearing woods

Where the differences between the original ground survey and the encountered field conditions are slight, the resident engineer and contractor may resolve these without the designer's involvement. However, there may also be opportunities to make refinements to reduce material volume quantities. These cases could employ formal or informal construction partnering to maintain the owner's ability to direct how the changes are made.

Construction Partnering

The Construction Partnering process promotes teamwork, trust, and open communication. (2) The contractor, resident engineer, and a professional facilitator hold regular meetings to advance mutually beneficial goals and objectives. The facilitator acts as a neutral party and helps facilitate communication between the contractor and the resident engineer. (3)

Formal or informal Construction Partnering can facilitate sharing a single set of 3D data, called a Model of Record, (4) which avoids data exchange and the associated issues. Through Construction Partnering, a neutral facilitator can bring the skill to manipulate 3D data, resulting in an equal facility between the contractor and the resident engineer. This advances other mutually beneficial goals of enabling fast, collaborative decisions to resolve issues detected through preconstruction quality control. Construction Partnering enables the resident engineer to be equally conversant with 3D data without the burdens of software licenses, software proficiency, and data exchange.

Verification and Measurement

Digital delivery has a relatively minor impact upon surveyors, designers, construction surveyors, and contractors, who use tools and data that they are familiar with in new ways. Using 3D data for real-time verification and measurement is a significant change for inspectors. The 3D data, survey equipment and field survey methods are new tools for inspection. However, the safety and efficiency improvements, as well as opportunities to collect more consumable, transparent, accurate, and repeatable measurements, make real-time verification and measurement worth pursuing.

Figure 10: Real-time verification uses field survey equipment

The purpose of real-time verification is to provide quality assurance during construction operations with minimal interruption and minimally exposing the inspectors to safety hazards such as moving construction equipment. In Figure 10, a concrete paving foreman checks depth in real-time from the back of the paver. The data collector records station, offset, and elevation and outputs a report with depths in a spreadsheet format. The work orders containing survey observations can be attached to an inspection daily report.

AMG is not dependent upon stakes, which creates an opportunity to substantially reduce, or entirely eliminate, stakes and hubs. The 3D data and field survey tools provide an alternate way for inspectors to check tolerances and collect survey data to measure payment quantities. This offers significant efficiency, safety, and transparency benefits. In Figure 11, an inspector has an upright body position with good peripheral vision near active, large equipment.

Figure 11: Inspector waits safely to take observations

Processes for real-time verification

Real-time verification requires 3D data consistent with the design intent, field survey equipment, and a control network. Inspectors use the tools to perform quality assurance activities that relate to geometric properties. Inspectors can verify:

- Primary acceptance factors such as slopes and material depths.
- Dimensions such as lengths, and clearances.
- Elevations, such as inverts and beam seats.
- Pavement horizontal locations and grades.
- Correct use of safety devices like excavation shoring and fall prevention equipment.
- Erosion prevention and sedimentation control device compliance, such as sedimentation basins having sufficient capacity.

Not only does real-time verification offer the opportunity to replace the method by which locations are checked, but it can also replace or enhance the methods employed for other inspection tasks. The main barrier is acquiring a set of 3D data consistent with the design intent. Inspectors and resident engineers must also build trust in the data and real-time feedback.

The prerequisites for real-time verification are:

- Inspectors have access to survey equipment.
- Access to a control network and a source of real-time kinematic correction for Global Navigation Satellite Systems (GNSS) receivers.
- Inspectors are trained in tool selection, field survey methods and data collection standards.
- The resident engineer verifies that the 3D data used by inspectors matches the design intent.
- The inspectors become comfortable with how the 3D data on the survey equipment relates to the contract plans and the field conditions.
- Standards and resources for data collection and management.
- Proper oversight by a licensed professional to ensure data quality.

To perform real-time verification, an inspector will load 3D data onto a data collector and select the appropriate survey tool to check the tolerances of the specific construction activities. (4) The first and last observations should be a control point to ensure the equipment is functioning as expected. Then and inspector will take observations of the completed work and compare the real-time feedback to the 3D data on the data collector.

Positional tolerances for grade checking should take into consideration that the sources of error in the 3D data (from approximation), instrument tolerance, and AMG instrument tolerance can be cumulative. Table 3 identifies different sources of error recommends how to mitigate the impacts.

Table 3: Variables to control for Real-time Verification.

Variable	Impact	Mitigation
3D data	Mid-ordinate distances (approximation due to chording) are cumulative.	Use a Model of Record, which has been accepted by the contractor and resident engineer.
Survey instrument	Different types of instruments have different precisions and will provide different solutions for the same point.	Use the same type of instrument to check construction that was used to execute it. Set appropriate tolerances.
Survey control	Measurements using different control are not comparable.	Use the same control to check the work that was used to execute it.

Location is often a minor acceptance factor; for instance, smoothness and slope—local accuracy concerns—are paramount for pavements, but a three inch offset in any direction would only be problematic if material quantities overran. The 3D design data is only needed to verify locations. The verification tolerances that the inspector needs to check on the data collector must be defined in the section of the specification that relates to each activity. It is important not to confuse the staking tolerances and the tolerances that the inspector will read on the data collector.

Measurement and Documentation

The equipment used for real-time verification is a powerful tool for measuring pay quantities and documenting construction progress. These tools enable inspectors to work more quickly to capture repeatable, verifiable, and transparent 3D data to support pay quantity measurements. The 3D data also serves as a record of construction at the time. Observations are taken in a matter of seconds, and recorded at the push of a button on the data collector. The measurements can be processed in safety at the construction office and appended to the inspection daily report. This is a valuable addition to emerging e-Construction practices.

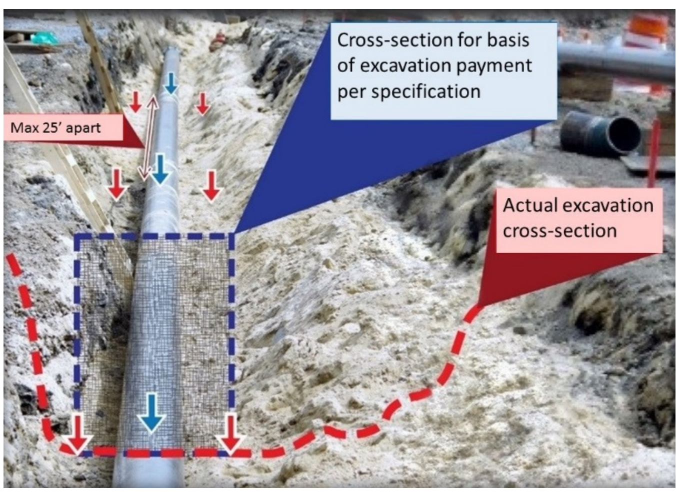

Figure 12: Payment section compared to actual excavation

By tagging observations with field survey codes, field-to-finish automation can generate surfaces and lines to compute and report volume, area, length, and unit quantity measurements. The resident engineer can review the reports and verify that the inspector interpreted the specification correctly. For example, trench excavation may be paid for by regular area, shown in blue in Figure 12, rather than by the actual excavated volume shown in red. Errors can be corrected without needing to repeat the measurement in the field.

While real-time verification requires an investment in 3D data that represents the design intent and a robust survey control network—which usually is in place for projects with AMG—using the equipment for measurement and documentation has a lower opportunity cost. If GNSS rovers are available, they can be used to collect 3D data to measure pay quantities and record as-built locations.

Figure 13: Traffic control installations can be documented quickly

Even on mill-and-pave projects, GNSS rovers can save time to document full and partial depth patches, temporary traffic control devices (such as in Figure 13), and myriad other measurements and observations. A range of features can be documented before opening the facility to traffic.

Project Characteristics for AMG

There is more frequent and more sophisticated AMG use, such as paving and variable depth milling. The research sought to identify the extent to which AMG construction is suitable for common, smaller projects to reconstruct, restore, resurface, or remediate existing facilities.

Benefits of Using 3D Data for AMG

The projects studied had many benefits to using AMG and 3D data to predict, avoid, or react to construction issues and control material balance. This helped projects stay on schedule or recover from start-up delays and a work stoppage.

Specifically, on the studied projects there was:

- Accurate prediction and management of pavement material quantities.
- Time savings from avoiding the need to set and tear-down string lines for concrete paving.
- A 10% fleet reduction for hauling concrete with stringless paving from better access.
- Better smoothness with concrete paving.
- A low opportunity cost for real-time verification.
- Rapid responses to issues, avoiding work stoppages or quickly resuming work.
- Less rework because issues were identified and resolved in the office using 3D data.
- An absence of claims, in part because of partnering and transparency with 3D data.

Identifying Favorable Characteristics for AMG

Asphalt paving generally does not appear to benefit from AMG, perhaps because the paver and screed are less reactive slope and grade changes. There is less opportunity to control yields at the paver with asphalt. Irregularities in the asphalt base, such as seen in Figure 14, affect yields because of the relatively thin placement depths. There is a preference for grade control on the base, and sonic averaging on the paver.

Figure 14: Irregularities in the base affect asphalt yields

Sonic averaging is faster than AMG for milling, and significantly cheaper. The cost to establish a survey network, prepare the data, and operate the AMG system is prohibitive for most partial depth asphalt paving. Smoothness incentives alone are insufficent for optional 3D milling. The need for geometric improvements is the most significant factor indicating AMG for 3D milling.

Figure 15: Asphalt mill-and-pave in an urban area without AMG

Currently, the limiting cost for 3D milling is the survey cost. The presence of hard tie-ins like the curb and gutter in Figure 15 make the survey cost prohibitive. Early completion bonuses may incentivize use of 3D data for preconstruction quality control when there are tie ins to fixed features or geometric improvements. The impact from delays is greater in urban areas, which may further drive use of preconstruction quality control. The cost increment from preconstruction quality control to AMG is the cost of running the AMG equipment, so AMG may follow, but the ability to identify and resolve issues preemptively is the larger driver. Generally, sonic averaging can be used on a mill in combination with maintaining specific cross-slopes. Non-AMG approaches are faster, less expensive, and safer because they do not need staff for total stations.

There are a constellation of AMG inclusion factors for both full and partial depth concrete paving. In addition to the efficiencies noted above, strong disincentives for thin pavement depths leads to AMG use to control the grade both on the base and paver. Often, how concrete paving is paid places the risk of material overruns on the contractor. The opportunity cost of AMG for concrete paving is within the benefit range of yield control, reduced labor costs for string lines, increased paving speed, and hauling efficiencies. As Figure 16 shows, there is also better access for the finishers, who do not have to step over string lines.

Figure 16: AMG improves access to the concrete paving work area

Opportunities exist to extend AMG into smaller reconstruction and restoration projects where risk allocation motivates the contractor to control quantities, control grade when geometrics are challenging, or predict outcomes such as for accelerated construction. Evolving high precision survey technologies continue to lower the cost of the control and mapping needed for AMG.

References

1. American Society of Civil Engineers, *Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data (38-02).* Reston, VA. American Society of Civil Engineers, 2002.
2. California Department of Transportation, *Field Guide to Partnering on Caltrans Construction Projects.* Division of Construction, Sacramento, CA. California Department of Transportation, 2013.
3. California Department of Transportation, *Partnering Facilitator Standards and Expectations.* Division of Construction, Sacramento, CA. California Department of Transportation, 2013.
4. Maier, Francesca, Mallela, Jagannath, Torres, Helga N., Ruiz, Mauricio, and Chang, George K., *Automation in Highway Construction Part II: Design Guidance and Guide Specification Manual.* Washington, DC. Federal Highway Administration, 2016.

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