DEPARTMENT OF TRANSPORTATION

Use of Relative Surface Technology for Creation of Relative Milling Surface Models and During the Automated Machine Guidance Milling Operation

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Office of Materials and Road Research

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The Minnesota Department of Transportation needed to correct the existing profiles of the eastbound and westbound lanes of TH2. This roadway was reconstructed 9 years ago, and since then, it has experienced significant pavement movement due to the presence of silt seams in the subgrade material. The movement of the roadway had stabilized and was still considered to be in good structural condition. Consequently, it was decided to move forward with correcting the profile to remove the significant irregularities that were present within the roadway profile. After evaluation of the project constraints, it was decided that the most cost-effective solution was to use a relative system (with respect to the existing surface) for creation of the existing surface and milling-depth models, in lieu of conventional survey and milling methods that later require use of robotic total stations during the milling operation. The project team selected the Topcon SmoothRide Resurfacing solution for both creation of the 3D model and use during the milling operation. The accuracy of the relative surface LiDAR scan was within 3 to 5 mm in the vertical direction and only required approximately 8 hours to collect, clean and review the relative surface measurements, while conventional methods would had required several days, or more. It was found that the relative surface measurements adequately identified and documented the magnitude of the vertical roadway movement and could be used to assist with the correction of irregular profiles of roadways. Consequently, the Topcon SmoothRide Resurfacing solution was also used during the milling operation and was considered successful.

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USE OF RELATIVE SURFACE TECHNOLOGY FOR CREATION OF RELATIVE MILLING SURFACE MODELS AND DURING THE AUTOMATED MACHINE GUIDANCE MILLING OPERATION

FINAL REPORT

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LIST OF ABBREVIATIONS

AMG	Automated Machine Guidance
DTM	Digital Terrain Model
GPS	Global Positioning System
IMU	Inertial Measurement Unit
IRI	Inertial Ride Index
LiDAR	Light Detection and Ranging
RAP	Recycled Asphalt Pavement
RD-M1	Realistic Dimension – Mapping One
RTK	Real-time Kinematics

EXECUTIVE SUMMARY

The Minnesota Department of Transportation (MnDOT) District 2 needed to correct the existing profiles of the eastbound and westbound lanes of TH2 between reference points 27.71 and 30.30. This roadway was reconstructed nine (9) years ago, and after reconstruction, it had experienced significant pavement movement due to the presence of silt seams in the subgrade. The movement of the roadway had stabilized, and the district believed the roadway was still in good structural condition, and therefore desired to correct the profile to remove the significant irregularities in the roadway profile. Additionally, snowplow blades were striking the changing profile and likely could have caused structural damage. There were also safety concerns for the public traveling on this roadway. The district desired to bring the roadway back to the original typical sections by completing a mill and overlay, by milling the surface down to a maximum depth of 2 inches, while correcting the mainline and shoulder cross slopes back to 2 and 4 percent, respectively.

After evaluation of the project constraints and needs, it was decided that the most cost-effective solution was to use a relative system (referenced to the existing surface) for creation of the existing surface and milling-depth model and for use during the milling operation. This option was in lieu of conventional survey and milling methods that require use of robotic total stations during the milling and paving operations. The project team selected the Topcon SmoothRide Resurfacing solution, which contains the following elements:

- RDM1 – provides relative surface using light detection and ranging (LIDAR) scanning technology.
- Topcon Magnet Collage – used for processing of the LIDAR scan measurements.
- Topcon Magnet Resurfacing software – used for creating relative surface models.

The RDM1 is a vehicle-mounted system that uses a downward facing LIDAR scanner to collect existing roadway conditions at highway speeds. The collected LIDAR data defines a relative surface, which is later processed to correct cross slopes and improve longitudinal smoothness. The proposed longitudinal and transverse profiles and existing relative surface data can be used in the automated machine guidance (AMG) application providing actual variable depth milling and/or paving. In addition to a LIDAR scanner, the RDM1 system also includes a global positioning system (GPS) unit, inertial measurement unit (IMU) and wheel encoder. The wheel encoder and IMU provide additional information to assist with correcting the horizontal accuracy during poor GPS signal reception. Additionally, a base station is used to collect static projection data during the LIDAR scan.

The Topcon Magnet Collage software compiles the GPS, IMU and LIDAR files, removes noise, and provides a relative surface of the scanned area. Filtering takes into consideration the footprint of the sensor to be used during the milling operation (e.g., sonic tracker) to ensure the data set is reflective of how the sonic tracker will see the surface and optimize smoothness. Pavement targets can be used to tie the LIDAR scans back to the project coordinates within plus or minus 0.01 ft. This software contains user definable limits that can be placed for surface clearance and point decimation to remove unwanted points and creates a tin surface from the scanned data on a user definable level.

The Topcon Magnet Resurfacing software interactively assists the user during creation of 3D models to set design criteria, which optimizes both lateral and longitudinal smoothness. The software currently allows the following design criteria to be input, based on station limits and profile strings:

- Minimum and maximum milling depths, or paving depths
- Minimum and maximum cross slopes
- Rideability parameters

User defined averaging lengths and cross slope information can be applied over the entire project, or localized areas for a best-fit option.

The relative surface model generated by the Topcon Magnet Resurfacing software can be exported and uploaded to an AMG, variable depth, milling and/or paving solution. This solution consists of a control box, GPS real-time kinematic (RTK) system and a 2D machine-mounted control system (IE integrated or aftermarket). The Topcon control box uses a patented software to compare the existing, in-place surface (obtained by the RDM1) and the designed smooth model (created by the Topcon Magnet Resurfacing software) to compute cut depths for the mills cutting edge position, or conversely, paving heights of the screed for use during a paving operation.

After review of the relative surface scan, it was evident to the project team that the design slope of 4 percent on the outside shoulders would cause the model to be designed outside of the desired maximum milling depth due to the significant profile changes present. Consequently, the project team decided to create the final relative surface milling-depth model as follows:

- Inside, 3-ft shoulder, was designed at 2 percent cross slope with no breakline from the mainline paving.
- Driving lanes, were designed at 2 percent cross slopes.
- The outside, 9-ft shoulders originally designed at 4 percent cross slope, were excluded from the model to assist with optimization of smoothness and were to be milled using a conventional milling operation with a joint match.
- The model was not allowed to exceed a maximum milling depth of 2 inches for the mainline and inside shoulders.
- A 75-ft longitudinal average (digital ski) was applied to the centerline, in the Topcon Magnet Resurfacing software, to achieve smoothness and ride. The cross slopes generated from the smoothed centerline profile were then applied to the model.

During the preconstruction meeting, the milling contractor made it known that the AMG relative milling system could not record the as-built milled surface depths during the milling operation as per special provision requirements. It was noted that the system would record this information in the future but could not currently do so. Consequently, MnDOT required the quality-control data (including both slope and depth) to be recorded at 1 foot inside of the left and right edge of the milled surface as follows: (1) 50-foot linear intervals; (2) use of rover for recording of station number; (3) use of ruler or level for recording of depth and slope; and (4) shortening of intervals to 25-feet in areas of super-elevations.

The special provision designates a hold point, whereby no additional milling (requiring the AMG-milling method) may be completed until corrective action has occurred, or as accepted by the engineer when 5 percent or more of the as-built delta milling-depth nodes exceed the tolerance of plus or minus 0.02 feet. During the milling operation on the eastbound lanes, it was found that 10 percent of the as-built delta milling-depth nodes exceeded the 5 percent tolerance of plus or minus 0.02 feet. Consequently, MnDOT, the milling contractor, RDO and Topcon met to discuss potential causes. It was determined that the right gate of the milling machine appeared to not be set to zero correctly, and therefore, a 250- to 300-foot test strip would be completed at the start of the milling operation each day. Highly densified independent verification checks were to be captured in this test strip to ensure that the left and right gates were zeroed correctly. There was also insufficient staffing for collection of quality-control points immediately behind the milling machine. The individuals were unable to keep up with the milling machine/operation to ensure early identification of out-of-tolerance measurements, due to wearing of teeth, system setup, or potential system failures. This would have been resolved if the machine were able to record the as-built measurements; however, since an individual was manually collecting and recording these measurements, it was recommended that two crews collect measurements (one crew collecting measurements on each side of the cut lane). Additionally, it was recommended that the tablets (for recording of milling depth and slope measurements) be pre-loaded with the stationing and model of record milling depths and slopes to save on time for collection and verification of measurements.

After review of the verification measurements, it was determined that a large percentage of the as-built delta milling-depth measurements were within plus or minus 0.03 feet (slightly exceeding the tolerance of plus or minus 0.02 feet), thereby indicating that there was difficulty collecting the manual measurements accurately using the ruler and at the rate of the milling operation. Consequently, additional staffing was recommended, along with the use of a carpenter’s square to assist with more accurate milling-depth measurements. The tolerance requirements were left at plus or minus 0.02 feet, as this tolerance was consistently achieved on other projects using an AMG milling operation with robotic total stations.

Lastly, due to the amount of manual labor required to accurately collect measurements and continue to keep up with the milling operation, the data collection interval was increased as follows: (1) 100-foot intervals during continuous sections, with data collection measurements decreased down to 50-foot intervals when measurements exceed the tolerance; and (2) 50-foot intervals in super-elevations, with data collection measurements decreased down to 25-foot intervals when measurements exceed the tolerance.

These modifications appeared to address the issues, because during the milling operation on the westbound lanes, 100, 99 and 99 percent of the as-built delta milling-depth nodes were within tolerance (within plus or minus 0.02 feet) for the nodes collected at 12 feet left of the centerline, at the centerline and 12 feet right of the centerline.

The following summarizes the conclusions resulting from scanning the existing surface, creation of the relative milled surface model, and use of the relative AMG milling system during the milling operation on TH2:

- The accuracy of the relative surface measurements was within 3 to 5 mm in the vertical direction.
- It required approximately 8 hours to collect, clean and review the relative surface measurements.
- It was found that the relative surface (RDM1) LIDAR scan adequately identified and documented the magnitude of the vertical roadway movement and could be used to assist with the correction of irregular roadway profiles.
- The Topcon Magnet Resurfacing software allowed designers to iteratively modify cross slopes and milling depths for optimization of smoothness, while maintaining maximum and minimum milling-depth criteria.
- The relative surface measurements could be used for creation of the relative surface existing and milling-depth models.
- The relative surface solution would help address safety concerns associated with conventional survey methods for establishment of digital terrain models and/or the use of string-lines to allow for profile milling operations.
- MnDOT, the milling contractor, prime contractor, RDO and Topcon all agreed that the relative AMG system successfully followed the model of record and were pleased with the milled surface and final pavement smoothness.
- MnDOT, the milling contractor, prime contractor, RDO and Topcon would like to see the technology continue to be used on future projects and the development of a roadmap for deployment of this technology on future projects with asphalt paving – with the goal of full deployment.
- The milling contractor thought the model of record could have been set to mill a little deeper to ensure that the milling operation was out of the wearing course and to reduce daylighting that occurred at the west end of the project. It was discussed that this would have been difficult, as the rapid changes in profile that were being corrected prevented this from being done when trying to optimize smoothness and overall maximum and minimum milling depths.
- There was poor ride on one super-elevation. It was determined that this was due to an error in the model of record. Two grade breaks were not addressed in the milling model. While the AMG milling system was following the model correctly, it was outputting incorrect milling depths due to this error. Review of inertial ride index (IRI) values for the exported model, prior to the milling operation, may have caught this modeling error.
- Two crews are needed to adequately capture milling depths for detailed as-built measurements when AMG milling systems are unable to record the as-built milling measurements. This allows the crew to keep up with the milling machine to capture more accurate measurements. Additionally, a carpenter’s square is needed for increased accuracy in milling-depth measurements.

- A tolerance of plus or minus 0.02 feet was achievable and will continue to be used for requirements on future projects.

The following summarizes recommendations resulting from scanning the existing surface, creation of the relative milled surface model and use of the relative AMG milling system during the milling operation on TH2:

- Project selection criteria should be developed to describe projects where the relative surface solution should be used.
- The relative surface solution is recommended for use during the milling operation on asphalt overlay projects with significantly irregular profiles.
- Additional verification should be completed by MnDOT to increase comfort level with respect to the vertical accuracy of the relative solution for use on unbonded concrete overlays and whitetopping projects.
- It is recommended that the relative surface solution is used on reclamation projects. Reclamation projects often run into problems due to the non-uniform pavement thicknesses. Conventional, variable depth milling is not cost effective on these projects, and therefore designers often have to split the project into sections, with set milling depths for use with conventional milling operations. This often results in varying amounts of recycled asphalt pavements (RAP) being ground into the existing base materials on full-depth reclamation and stabilized full-depth reclamation projects and variable amounts of RAP (thereby affecting the mix designs) being used in cold in-place recycling and cold central plant recycling projects. This cost-effective relative surface solution would allow for more uniform and stable reclaimed materials, thereby significantly improving long-term performance of the roadway.
- Design software currently used by state agencies and consultants should be evaluated to determine whether these platforms can be used as the preliminary design software, because designers are already experienced with this software and pre-made template drops, etc. are already available for use in these applications.
- Ground penetrating radar and core measurements should be collected for determination of asphalt pavement thicknesses in both the inner and outer wheel paths of each lane to capture any crown corrections prior to building the 3D models.
- Model vertices should be established at 5-foot intervals in all tangents and 1-foot intervals in curves.
- 3D models should be reviewed for smoothness to ensure that there are not significant irregularities present within the model to cause bumps in the resulting as-built milled surface. These irregularities are typically located at design templated drops, station equations and super elevations. An IRI of 15 inches/mile, or less, is recommended for the wheel paths extracted from the milled surface model (e.g., 3L, 9L, 3R and 9R of centerline). Smoothness analyses should be run at 1-foot intervals.
- Relative AMG milling requirements should include a 250- to 300-foot control/test strip, with highly densified independent verification checks, to be completed at the start of the milling operation each day to ensure that the left and right gates are zeroed correctly.

- Relative AMG milling systems are recommended to record the as-built milled surface at intervals of 10 feet or less. Independent quality-control measurements should continue to be continuously collected behind the milling machine; however, the measurements collected by the AMG system will provide a more densified digital terrain model (DTM) for verification of the system.

CHAPTER 1: BACKGROUND

1.1 PROJECT OVERVIEW AND GOALS

1.1.1 Project History

The Minnesota Department of Transportation (MnDOT) District 2 was in need of correcting the existing profiles of the eastbound and westbound lanes of TH2 between reference points 27.71 and 30.30. This roadway was reconstructed nine (9) years ago, and since then, it has experienced significant pavement movement due to the presence of silt seams in the subgrade. The movement of the roadway stabilized, and the district believed the roadway was still in good structural condition, and therefore desired to correct the profile to remove the significant irregularities in the roadway profile. Additionally, the snowplow blades were striking the changing profile and likely could cause structural damage. There were also safety concerns for the public traveling on this roadway. The district desired to bring the roadway back to the original typical sections by completing a mill and overlay, milling the surface down to a maximum depth of 2 inches, while correcting the mainline and shoulder cross slopes back to 2 and 4 percent, respectively. Figure 1.1 shows an image of the original, typical section.

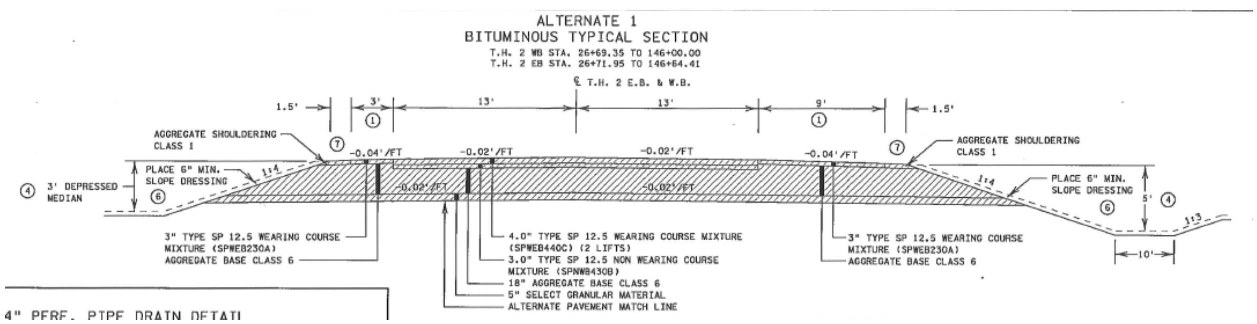

Figure 1.1 TH2 Original Typical Section.

1.1.2 Project Goals

After evaluation of the project constraints and needs, it was decided that the most cost-effective solution was to use a relative system (referenced to the existing surface) to create the existing surface and milling-depth models and for use during the milling operation. This option was in lieu of conventional survey and milling methods that require use of robotic total stations during the milling and/or paving operations. It was anticipated that the following benefits would be realized through the use of a relative system:

(1) Construction Savings

  (1.1) Decreased Labor

Decreased labor was anticipated because a digital terrain model using conventional survey methods, or the conventional use of light detection and ranging (LIDAR) technology, would not be required. Also, the relative surface technology captures a highly densified relative surface for vertical precision at highway speeds. Consequently, there would be no need for the placement of photo targets and control during the LIDAR scan. A few control points could be installed if the user desired to geospatially locate the vertical in the models for later use. Additionally, robotic total stations would not be required during the milling operation. Construction personnel also would not need to leap-frog total stations during the milling operation, since the technology follows a relative surface.

(1.2) Reduced Scope

The relative surface solution would provide the ability to correct an existing roadway, without the need for doing a full reconstruction effort.

(1.3) Improved Quality

Using a relative surface solution would allow significant improvements to ride, both laterally and longitudinally. Numerous studies have shown that improved ride translates into improved long-term pavement performance. This solution would allow for optimization of the 3D model through interactive changes of milling depths, cross-slopes, etc. Quality would also be improved by allowing for variable depth milling and preventing the need to complete "piece-meal" milling operations, where set milling depths are required within given station limits.

(2) Increased Safety

This solution removes the need for a survey team to conventionally collect the digital terrain model (DTM) and/or placing of photo targets along the roadway where safety is continuously a concern near live traffic. Additionally, prior to the milling operation, the surveyors would not need to place string-lines along the right of way of the roadway to allow for variable depth milling when using this technology.

(3) Decreased Engineering and Administrative Costs

It is anticipated that the engineering and administrative costs would decrease during creation of the 3D model, since the software for this solution is optimized to allow for iterative changes during the model creation.

(4) Use of E-Construction

MnDOT is moving toward e-construction in various facets of construction projects. Collection of relative surface measurements and creation of 3D models will support the department's goals of moving toward 100 percent deployment of electronic documentation by providing digital assets of the roadway (i.e., existing surface, proposed milled surface, and actual milled surface).

1.2 RELATIVE SURFACE SOLUTION

The project team selected use of the Topcon SmoothRide Resurfacing solution. This solution contains the following elements:

- Realistic Dimension – Mapping One (RD-M1) – provides relative surface using LIDAR scanning technology.
- Topcon Magnet Collage – used for processing of the LIDAR scan measurements.
- Topcon Magnet Resurfacing software – used for creation of relative surface models.

The following subsections briefly describes these components.

1.2.1 RD-M1 Relative Surface Scanner

The RD-M1 is a vehicle mounted system that uses a downward facing LIDAR scanner to collect existing roadway conditions (see figure 1.2 for a photo image of the system). The collected LIDAR data is processed and corrected to supply a relative surface, which is later processed to correct cross slopes and improve longitudinal smoothness. The proposed and existing data can later be used in an automated machine guidance (AMG) application, providing actual variable depth milling and/or paving. Please note that it takes approximately 15 to 30 minutes to setup the system.

Figure 1.2 Image of RD-M1 system mounted to a truck.

In addition to a LIDAR scanner, the RD-M1 system also includes a global positioning system (GPS) unit, inertial measurement unit (IMU) and wheel encoder. The wheel encoder and IMU provide additional information to assist with correcting the horizontal accuracy during poor GPS signal reception due to overpasses and under urban or rural canopies. Additionally, a base station (set by conventional survey or network real-time kinematics [RTK]) is used to collect static projection data during the duration of the LIDAR scan. These static measurements can then be used for latitude and longitude verification (i.e., to post process the RD-M1 GPS positions for more accurate point locations). However, this step is not needed for all applications and is dependent on accuracy needs. Please note that LIDAR measurements should be within approximately a 30-mile radius of the base station.

The RDM Collect software is used inside the vehicle to execute the scan and store the resulting data. This software can be used either on a laptop or tablet and will collect data at 100 cross-sections per second (approximately 28,500 points/second).

The LIDAR data can be collected at normal highway speeds (approximately 50 to 55 mph). Faster data collection speeds can be used; however, this may require additional measurement passes to ensure that the needed measurement accuracy is maintained. Conversely, slower speeds will provide a larger, denser point cloud. Figure 1.3 illustrates a typical point cloud density obtained at highway speeds. As previously stated, safety is significantly enhanced because data collection occurs at highway speeds, rather than by conventional methods, where surveyors are on or near the roadway and exposed to traffic. Additionally, highway speeds allow the roadway to remain fully functional (i.e., no traffic closures) during the data-collection efforts.

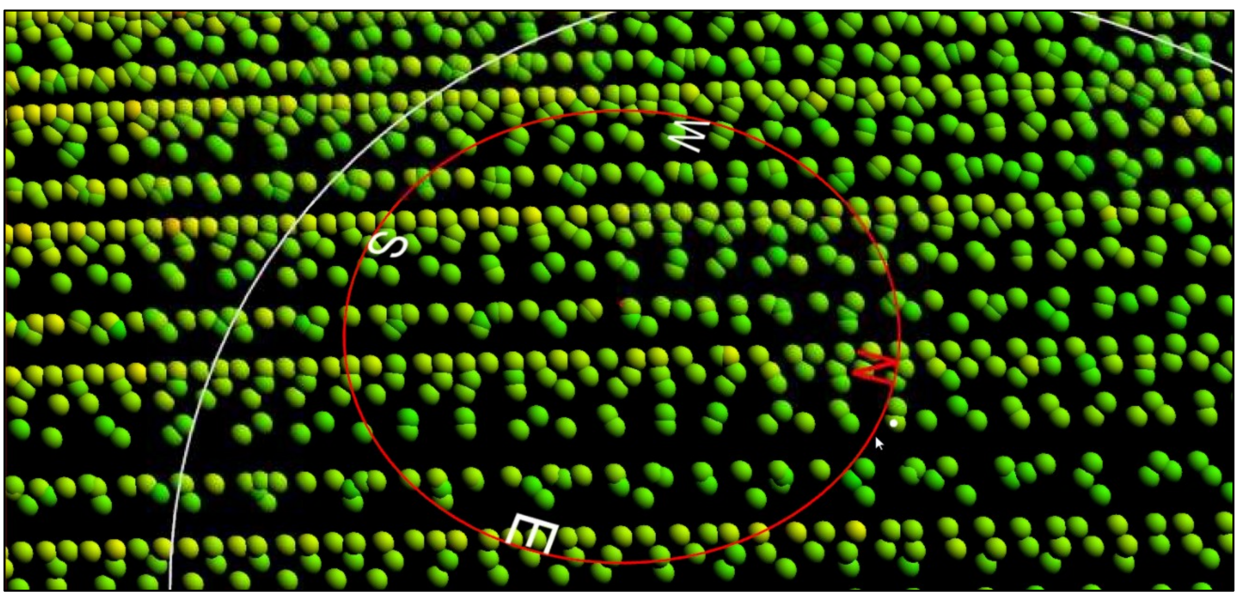

Figure 1.3 Zoomed-in image of density of point cloud.

Typically, three (3) scans are completed per lane to aid in the scan data filtering, the cleanup process and to densify the point cloud. It is recommended that a 70-percent overlap in adjacent scans be used to aid in this process. Often noise, which does not represent the surface, is present that requires multiple passes of the LIDAR scan to provide additional data to determine an accurate surface at the given location. Figure 1.4 illustrates an example in which a passing vehicle was present during one of the data-collection scans, and consequently, the second and third scans were used to remove the effects of this passing vehicle on the measurements. Figure 1.5 illustrates how the additional scans in each lane assisted with the removal of the unneeded scanned measurements, which resulted from the passing truck.

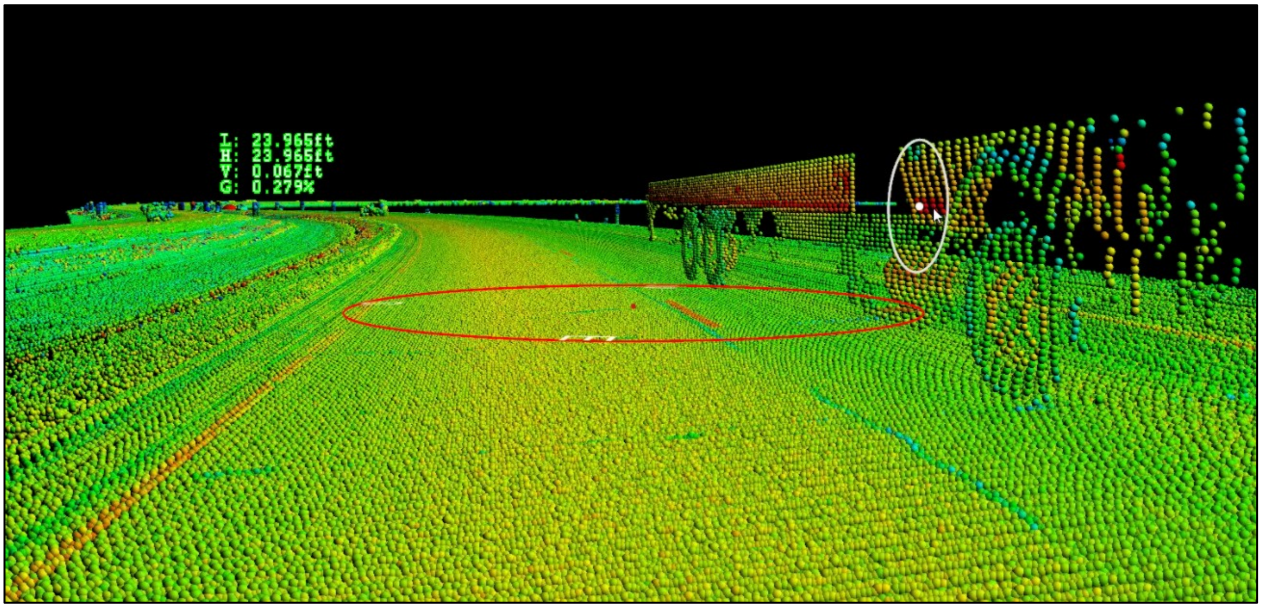

Figure 1.4 Image of passing truck presented in point cloud measurements.

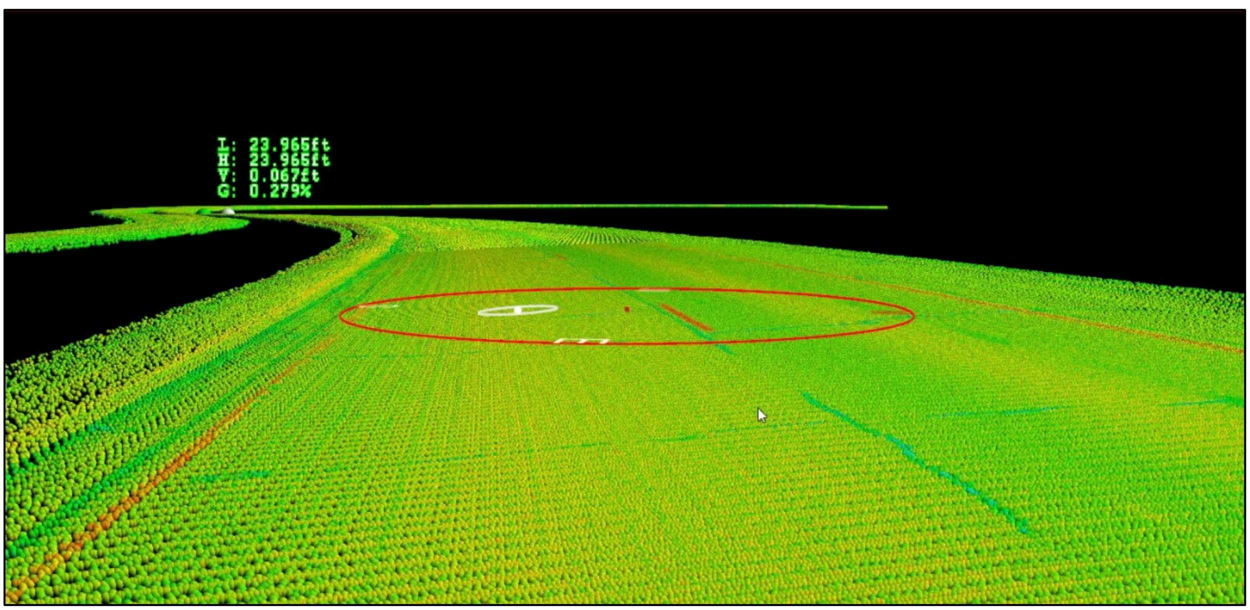

Figure 1.5 Image of effects of using additional scans per lane to clean data.

1.2.2 Topcon Magnet Collage (Mass Data Processing)

The Topcon Magnet Collage software compiles the GPS, IMU and LIDAR files to provide a relative surface of the scanned area. Pavement targets can also be used to tie the LIDAR scans back to the project coordinates within plus or minus 0.01 ft. After compilation of the data files, this software is then used to filter and clean noise from the scanned data. This software contains user definable limits that can be placed for surface clearance and point decimation to remove unwanted points. Additionally, the Topcon Magnet Collage software allows for viewing of the data using varying color intensity and contours. Figures 1.6 through 1.8 show images illustrating how color saturation can be used during review of the scanned data features. As illustrated, color intensity highlights what is present within the scanned data (e.g., cracks, joints, rumble strips, paint stripes, etc.), because each material reflects light differently. In addition, elevation contours help to visualize cracks, flat spots, shoulder breaks, lane breaks, super-elevation changes, etc. Figure 1.9 presents an image illustrating the use of contours during the scanned data review.

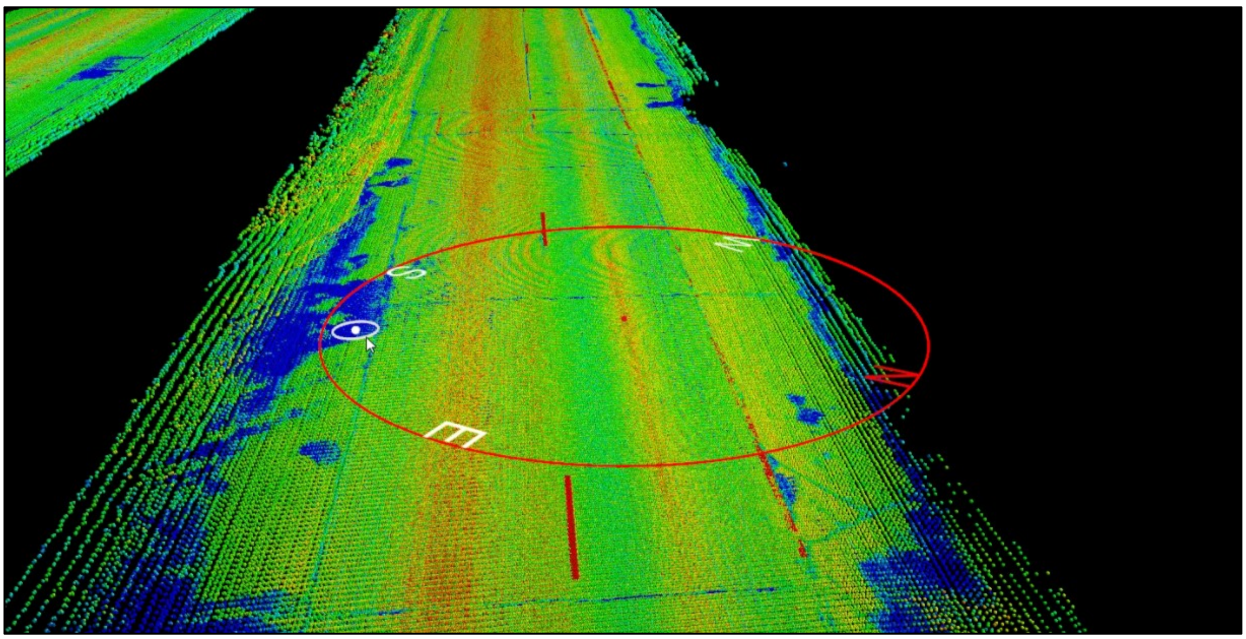

Figure 1.6 Example of surface distresses detected using varying color saturation within Topcon Magnet Collage.

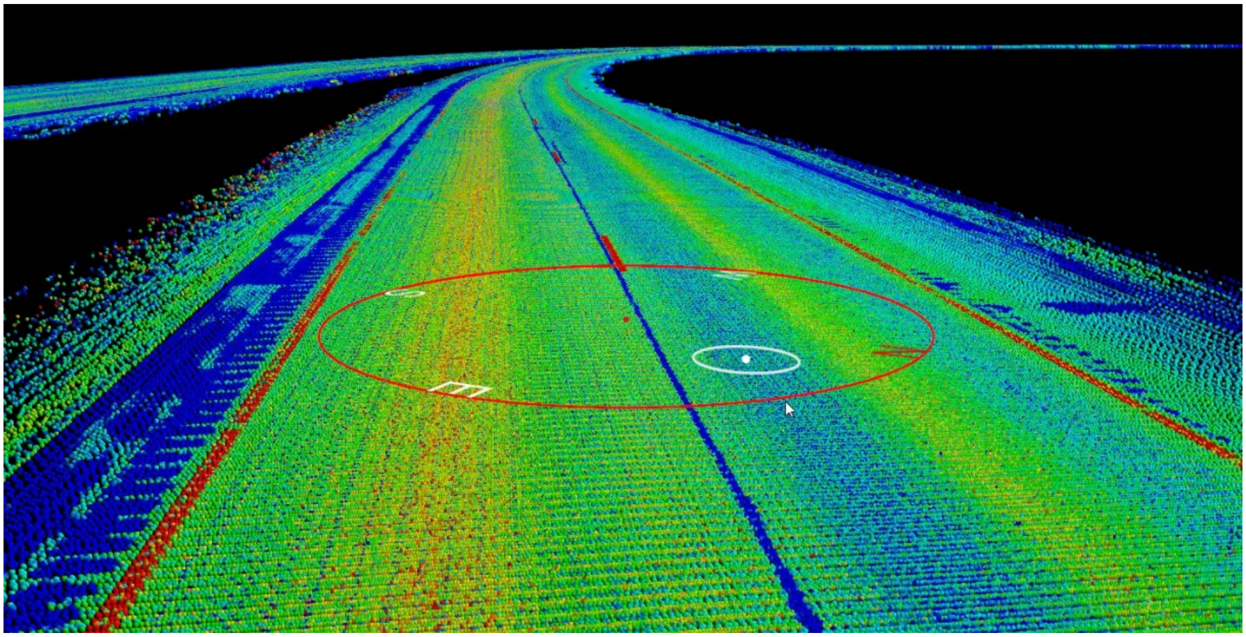

Figure 1.7 Example of rumble strips, longitudinal joints and paint striping detected using varying color saturation within Topcon Magnet Collage.

Figure 1.8 Example of features collected when viewing in black and white within Topcon Magnet Collage.

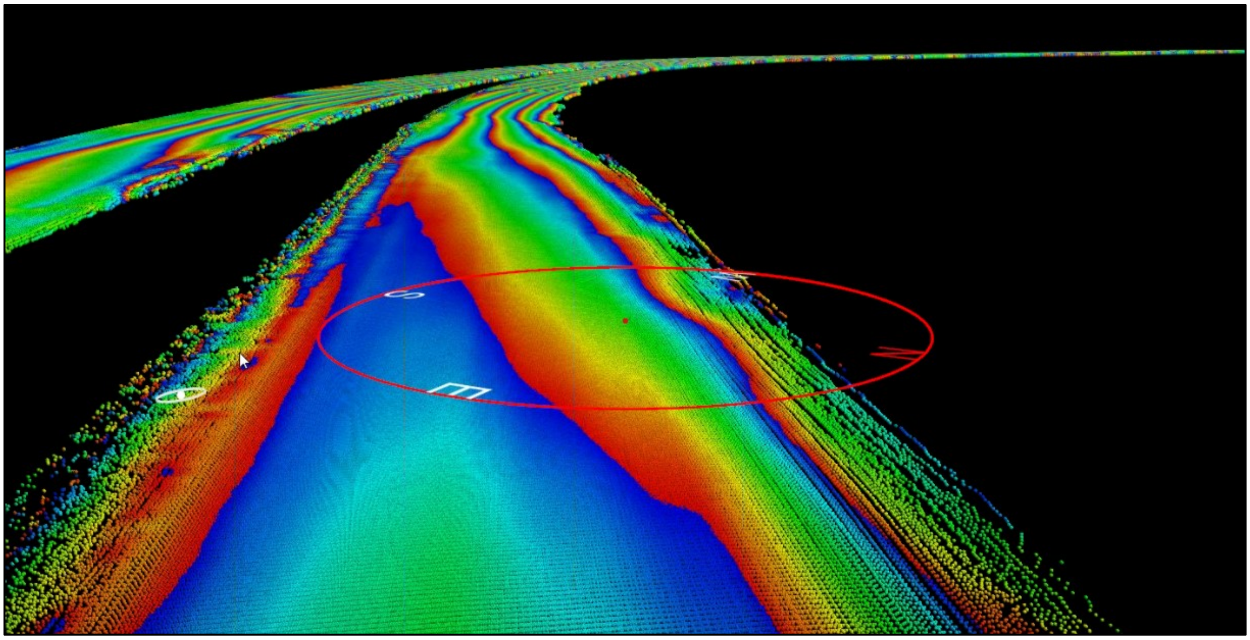

Figure 1.9 Image of use of contour lines to assist with review of data within Topcon Magnet Collage.

The Topcon Magnet Collage software can also create a tin surface from the scanned data at a user defined accuracy. Dense point clouds can be triangulated at shorter ground sample distances. However, care must be taken when determining triangulation sizes as the decreasing sizes will increase the file size of the resulting surface tin. Figure 1.10 presents an image of a surface tin generated using the point cloud.

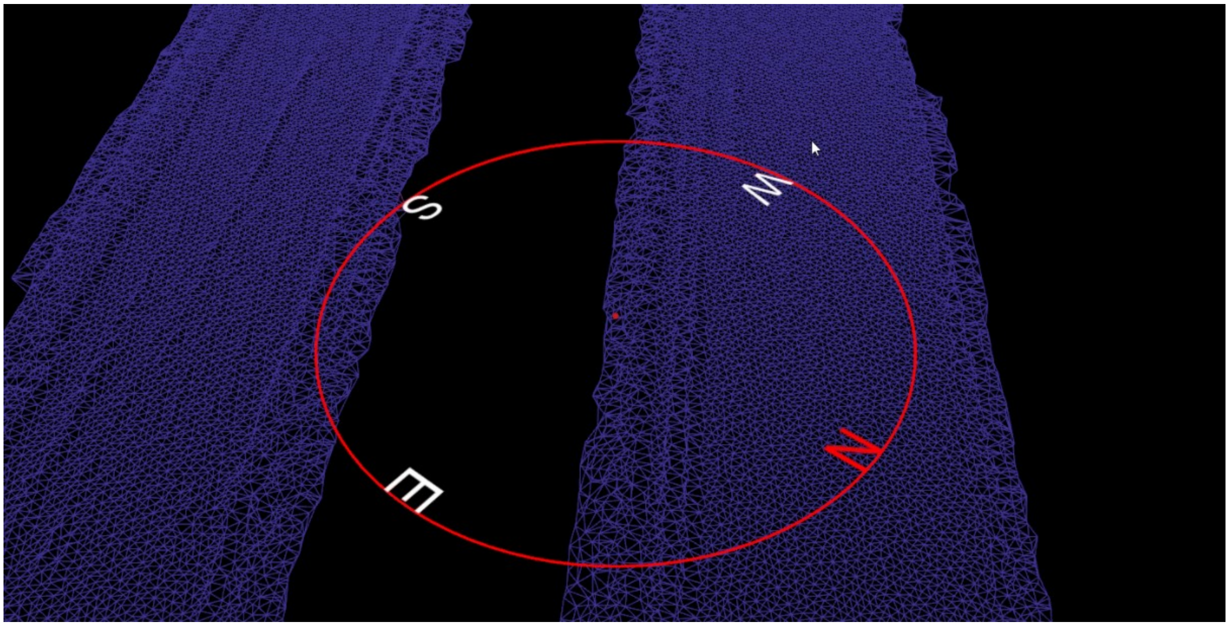

Figure 1.10 Image of a surface tin for the existing surface generated by Topcon Magnet Collage.

1.2.3 Topcon Magnet Resurfacing Software

The Topcon Magnet Resurfacing software interactively assists the user with the creation of 3D models. This software allows the user to select design criteria, which optimizes both lateral and longitudinal smoothness. User defined averaging lengths and cross slope information can be applied over the entire project, or localized areas for a best-fit option. Figure 1.11 presents an image of the set limits screen, which allows the following design criteria to be input based on station limits and profile strings:

- Minimum and maximum milling depths, or paving depths
- Minimum and maximum cross slopes
- Rideability parameters

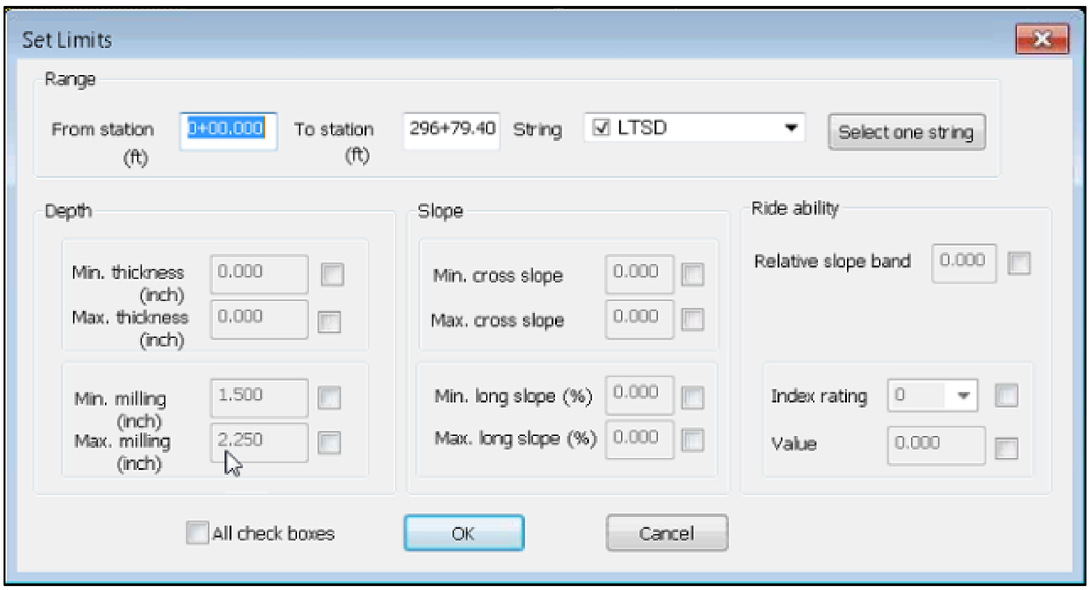

Figure 1.11 Image of a set limits screen for entering design criteria within Topcon Magnet Resurfacing software.

After entering the design criteria and smoothness criteria, the user is then able to identify areas where the design limits are exceeded and determinate modifications that may be needed to the relative surface model and/or to the construction operation. The Topcon Magnet Resurfacing software provides an interactive screen of the following panels to assist the user with this review (see Figure 1.12):

- Top Left Panel – Plan (survey) view map containing the centerline and left and right edges of the pavement.
- Right Panel – Longitudinal profile lines, where each line will reflect a given profile sharing (e.g., centerline).
- Bottom Panel – Cross-section view that updates as the user moves longitudinally along the roadway. The green and red lines represent the existing and design surfaces, respectively.

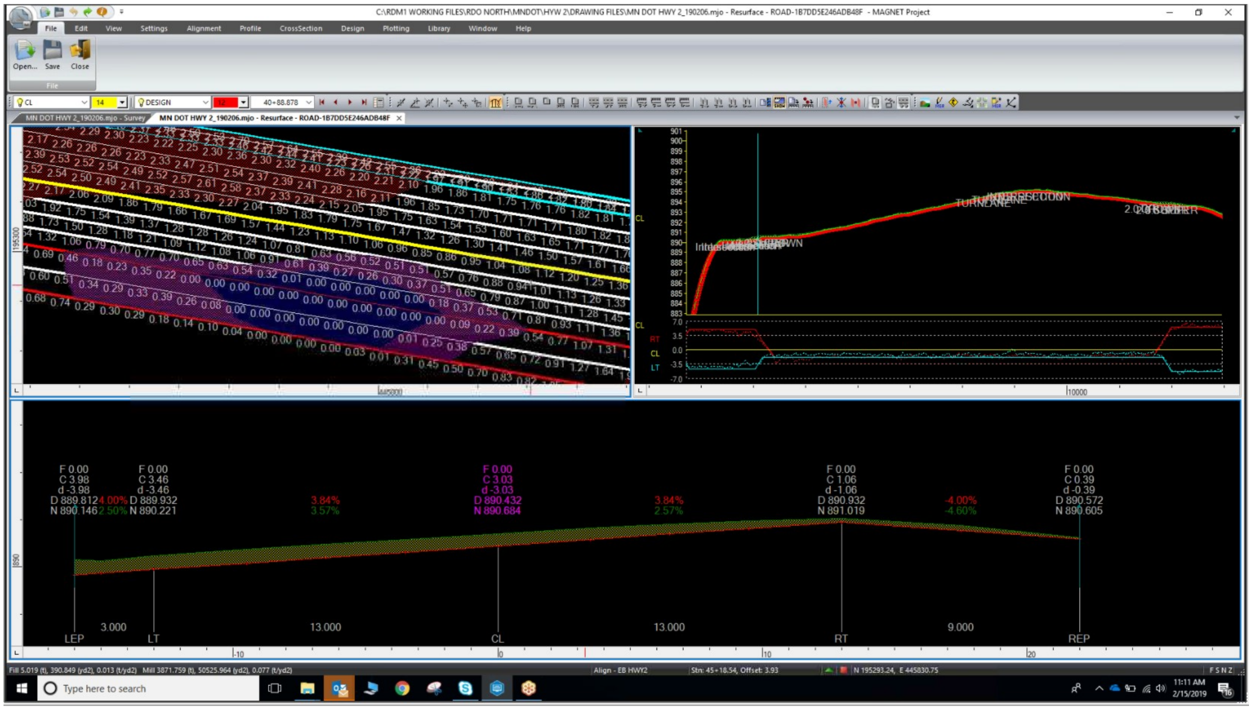

Figure 1.12 Image of plan view, longitudinal profile and cross-section maps in the Topcon Magnet Resurfacing software.

1.2.4 Automated Machine Guided Milling / Paving Solution

The relative surface model generated by the Topcon Magnet Resurfacing software can be exported and uploaded to an AMG, variable depth, milling and/or paving solution. This solution consists of a control box, GPS RTK system, and a 2D machine mounted control system (IE integrated or aftermarket). The Topcon control box uses a patented software to compare the existing, in-place surface (obtained by the RDM1) and the designed smooth model (created by the Topcon Magnet Resurfacing software) to compute cut depths for the mill's cutting-edge position, or conversely the paving heights of the screed during paving.

CHAPTER 2: RDM1 SCAN AND MODEL BUILDING

2.1 RDM1 SCAN ON TH2

The roadway surface of TH2 between reference points 27.71 and 30.30 was scanned using the RDM1 in each direction of travel. Three (3) passes of LIDAR scanning were completed in each travel lane (totaling six (6) passes in each direction of travel). Prior to completing the LIDAR scan, six (6) photo targets were placed on the pavement to tie the model surface to the project's projection in order to verify the system's relative accuracy. One (1) target was placed at each end of the project extents in each direction of travel (totaling four targets), while the remaining two (2) were placed linearly halfway through the project. It took approximately 30 minutes to setup the equipment, photo targets and local base station and about 90 minutes to complete the LIDAR scan on this project.

The Topcon Magnet Collage software was then used to compile the GPS, IMU and LIDAR files to provide a relative surface of the scanned area and to filter noise out of the scanned data. The project team reviewed the surface to verify that it contained an adequate point cloud density for creation of the relative surface models. This entire process (from data collection to review) took approximately eight (8) hours.

In addition to tying the relative scans the project's projection, the photo targets were used to verify that the system was collecting the relative surface accurately. It was found that the measurements were within 3 to 5 mm in the vertical direction. After verifying measurement accuracy, the relative surface was used to identify the magnitude of the roadway movement. It was found that the relative surface measurements adequately identified and documented the vertical roadway movement. Prior to these measurements, roadway movement had only been observed visually, documented using ride measurements and upon receipt of public comments. These measured results are illustrated in the subsequent discussion, which describes the creation of relative surface models for the existing and milled surface.

2.2 CREATION OF RELATIVE SURFACE MODELS

The filtered and cleaned LIDAR data, exported from the Topcon Magnet Collage software, as a surface tin, was imported into the Topcon Magnet Resurfacing software. The desired design typical sections provided by the district were then added as features within this software (i.e., centerline alignment and standard cross-sections) and the information was interpolated at 5-ft intervals to produce relative surface models for both the existing and milled surface.

Initially, the design intent was to bring the pavement back to the original design's cross sections by modeling the pavement lanes and shoulders at 2 and 4 percent cross slopes, respectively. However, after review of the relative milled surface model in relation to the existing relative surface, it was determined that there were a large number of areas where the pavement would have been milled deeper than desired in order to provide a smooth profile. Figure 2.1 provides an example of the plan view map depicting milling depths through numeric numbers and varying color pallets in one section of the eastbound model. The areas shaded in red illustrate the regions where the milling depths would exceed the desired 2-inch maximum depth. Figure 2.2 illustrates an example of the typical cross sections measured for the existing surface along the TH2 roadway. As shown, the existing surface of the roadway deviates significantly from the original design causing the milling depths to exceed the desired maximum of 2 inches in given areas.

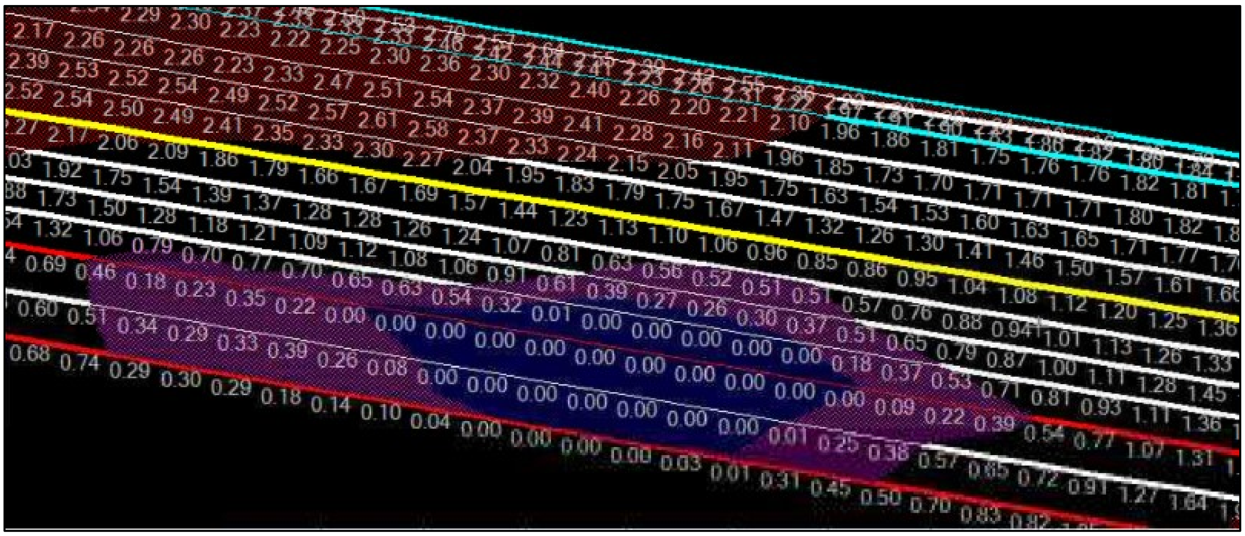

Figure 2.1 Image of milling depths in the Topcon Magnet Resurfacing software.

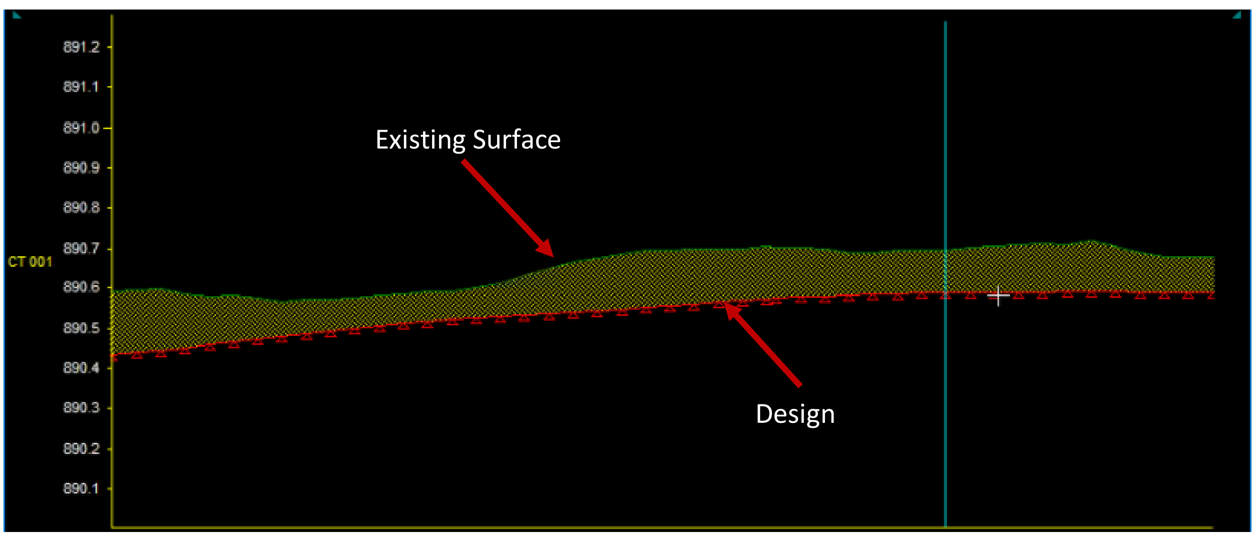

Figure 2.2 Image of the centerline profile in the Topcon Magnet Resurfacing software.

After visual review of the plan view, cross section and profile maps within the Topcon Magnet Resurfacing software, the team noted that the 3-ft wide shoulder had the largest vertical movement, which caused the maximum 2-inch milling depth to be exceeded. Consequently, the team decided to reduce the design slope for the 3-ft wide shoulder to 2 percent, in lieu of the original design intent of 4 percent. This design modification helped to ensure an adequate paving platform still remained and that the milling head would not punch through the shoulder asphalt pavement into the weaker aggregate base. Figures 2.3 through 2.7 illustrate the milling depths for the shoulders and driving lanes for a 13,000-ft stretch of the east bound direction of travel. As illustrated, regardless of the offset location, there is a significant amount of variability in required milling depths in order to construct the roadway back to a smooth profile. The areas of greatest concern were located along the shoulders, where milling depths often exceed the desired 2-inch maximum milling depth and in areas of super-elevations where milling depths exceed the shoulder thickness and would punch into the underlying aggregate base.

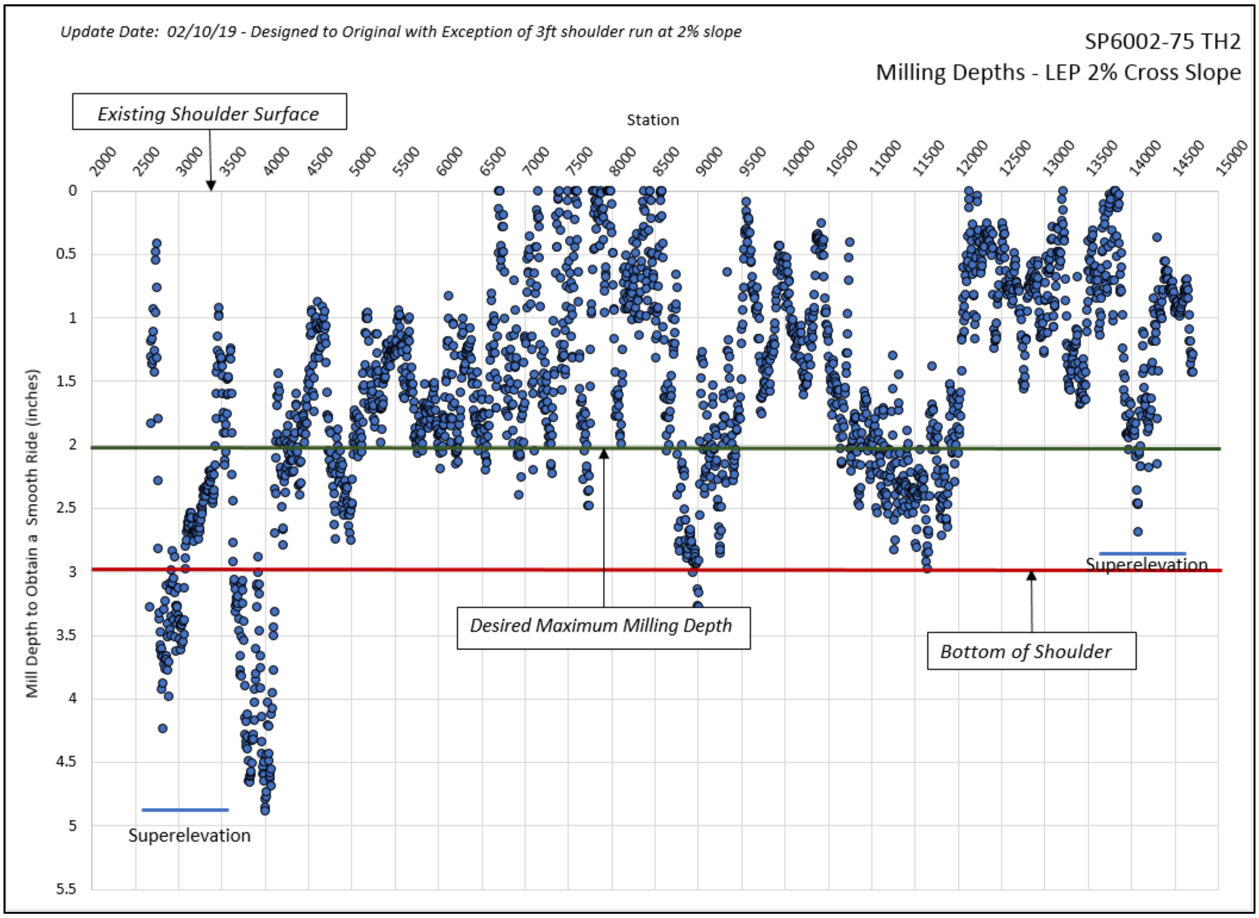

Figure 2.3 Graph of the milling depths required for a smooth profile for the left shoulder (-16 ft offset) using a 2-percent cross slope.

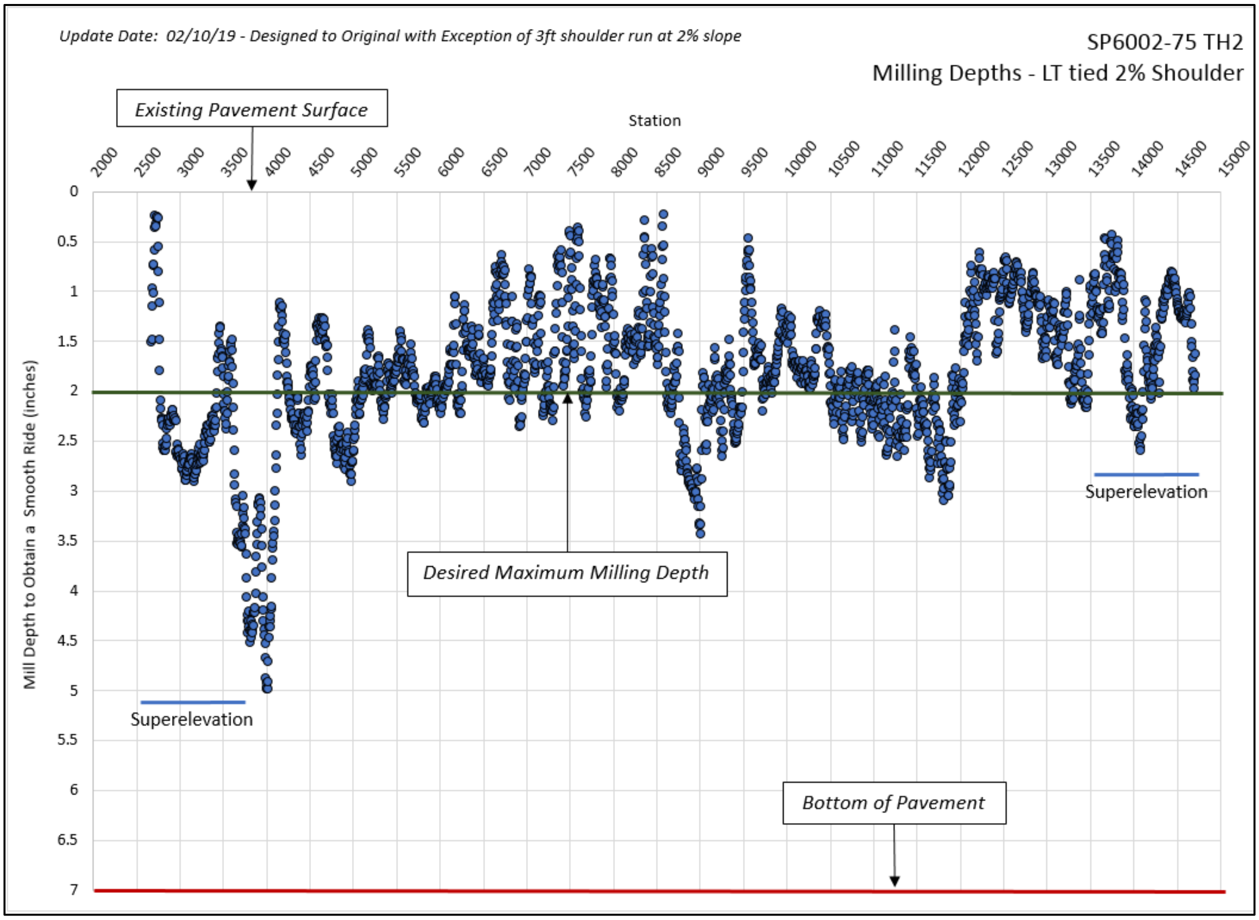

Figure 2.4 Graph of the milling depths required for a smooth profile for the left edge of pavement (-13 ft offset) using a 2-percent cross slope.

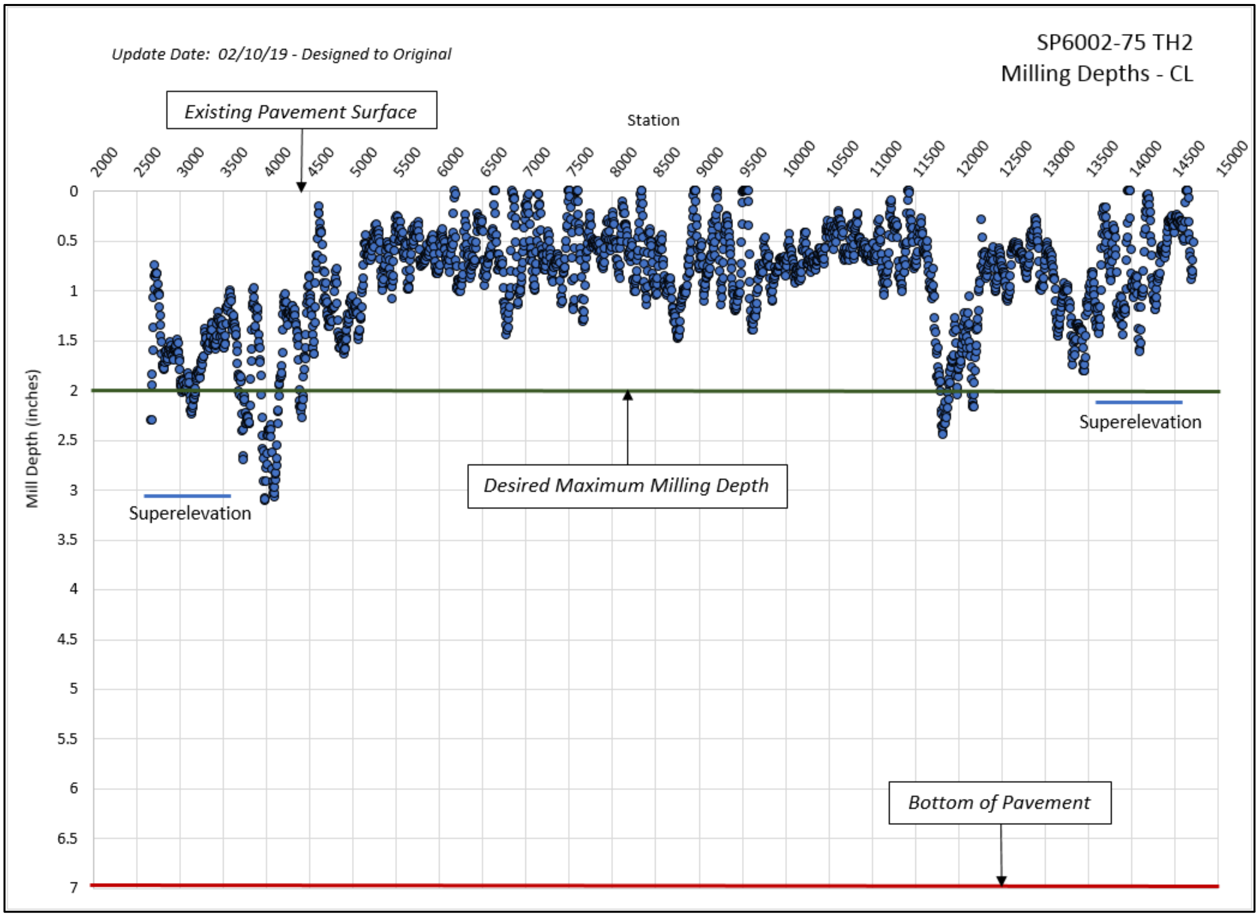

Figure 2.5 Graph of the milling depths required for a smooth profile for the centerline of pavement (0 ft offset) using a 2-percent cross slope.

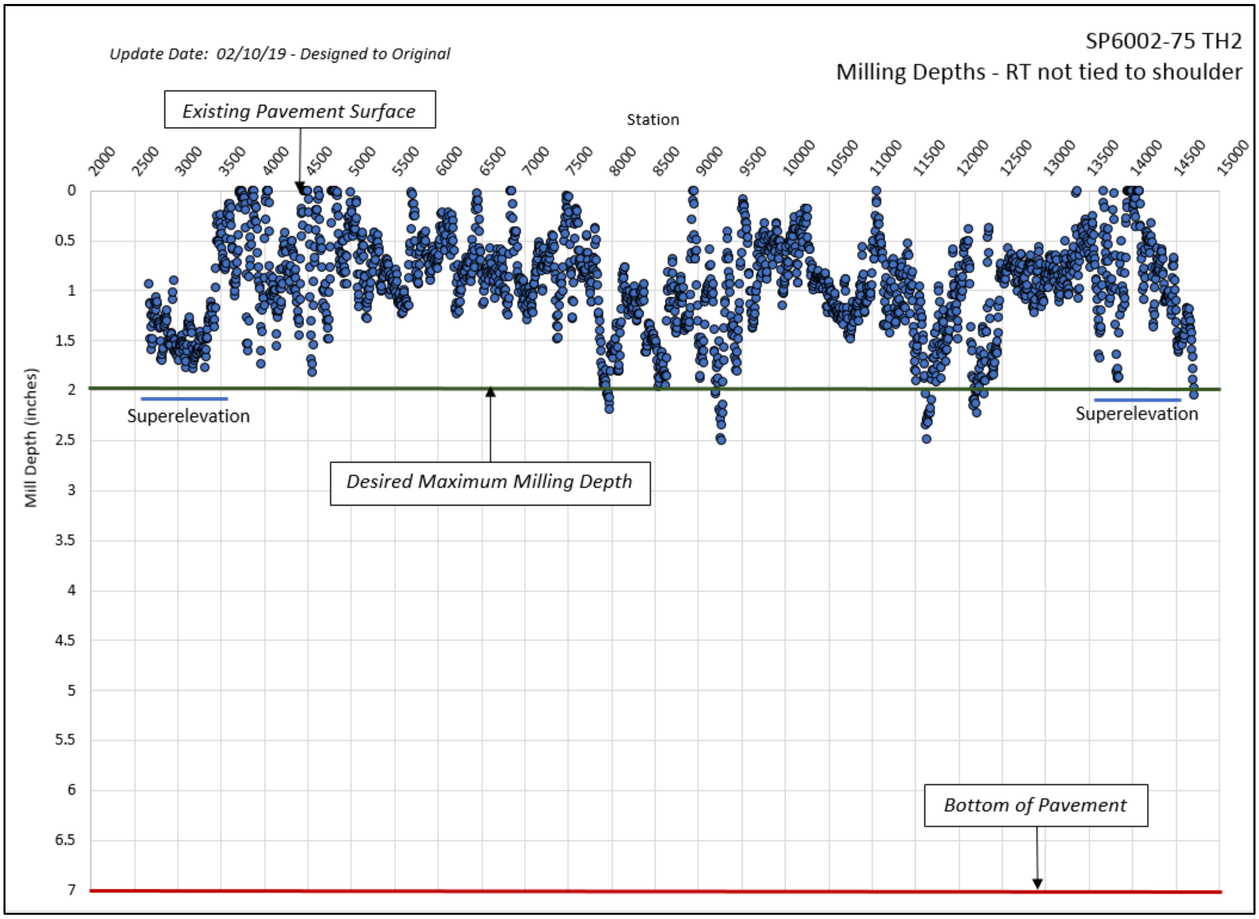

Figure 2.6 Graph of the milling depths required for a smooth profile for the right edge of pavement (13 ft offset) using a 2-percent cross slope.

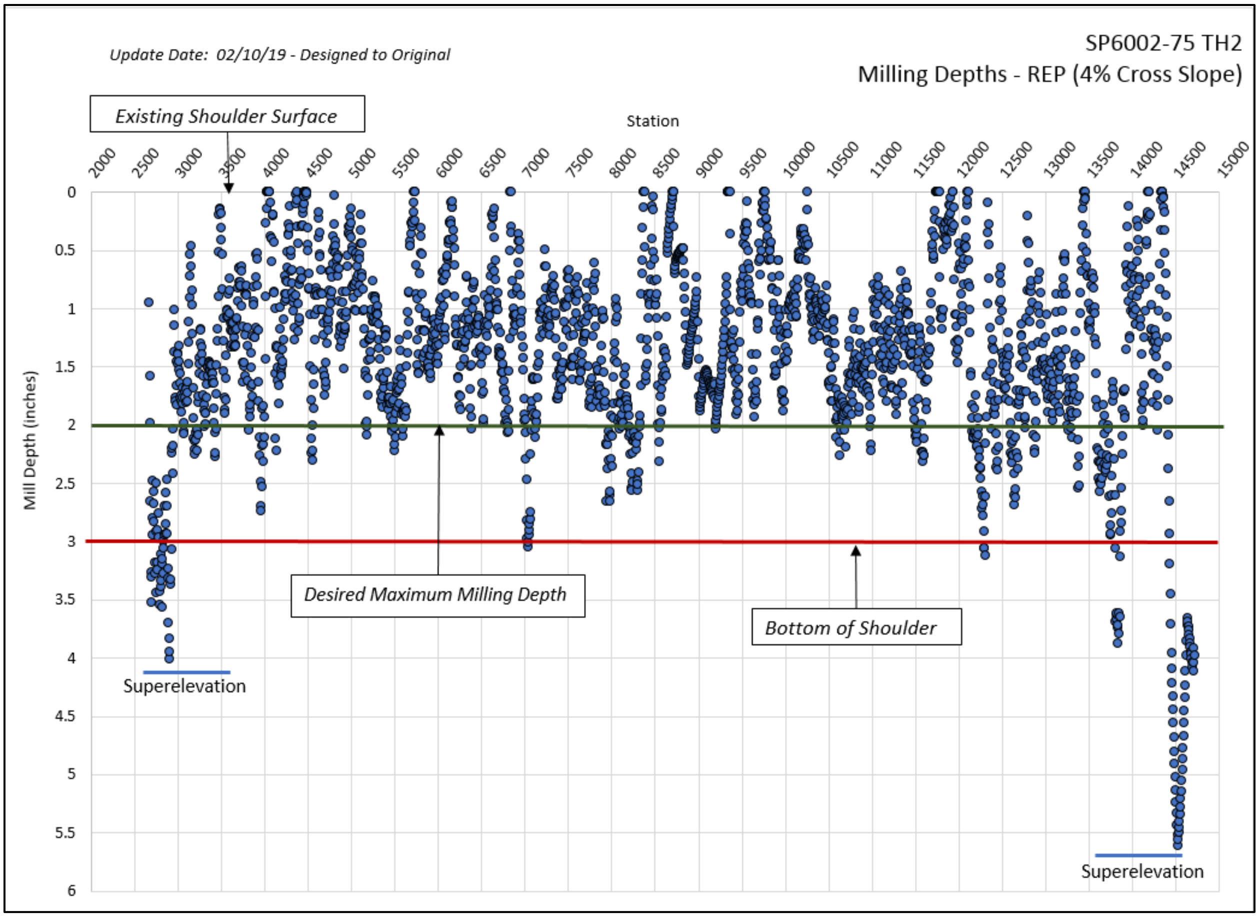

Figure 2.7 Graph of the milling depths required for a smooth profile for the right edge of shoulder (22 ft offset) using a 4-percent cross slope.

To resolve the above issues, it was evident to the project team that a 4 percent cross slope on the outside shoulders would create a design model, which would not meet the desired maximum milling depth. Consequently, the project team decided to create the final relative surface milling depth design model as follows:

- Inside, 3-ft shoulder, designed at 2 percent cross slope with no breakline from the mainline paving.
- Driving lanes, designed at 2 percent cross slopes.
- The outside, 9-ft shoulders originally designed at 4 percent cross slope, were excluded from the model to assist with optimization of smoothness and will be milled using a conventional milling operation with a joint match. Please note, as presented in figure 2.3 and 2.7, the movement of the outside shoulder was not as severe as that of the inside shoulder, whereby it was best to optimize the model by excluding this shoulder.
- Model was not allowed to exceed a maximum milling depth of 2 inches for the mainline and inside shoulders.

- A 75-ft longitudinal average (digital ski) was applied to the centerline, in the Topcon Magnet Resurfacing software, to achieve smoothness and ride. The cross slopes generated from the smoothed centerline profile were then applied to the model.

As discussed earlier, the two relative surface models (existing scanned relative surface and relative surface milling-depth model), along with the alignment file, could now be loaded into the Topcon RDMC system. This would allow for the milling machine to use AMG milling without the need of robotic total stations during the milling operation.

CHAPTER 3: RELATIVE AUTOMATED MACHINE GUIDANCE (AMG) MILLING

3.1 RELATIVE AMG MILLING METHOD SPECIAL PROVISION

The District elected to move forward with requiring relative AMG milling on this project, since creation of the 3D model was considered successful as described in Chapter 2. Consequently, MnDOT included a special provision containing the requirements for relative milling in the contract. The 3D model was included in the contract as reference documentation, since MnDOT does not currently allow the use of digital signatures with these types of models. Consequently, language was included in the special provision to require the Contractor and Engineer to agree upon the model to be used during the milling operation. This model is referred to as the Model of Record. Appendix A, contains the special provision language for “(2232) Mill Pavement Surface – Relative Automated Machine Guidance – Milling Method”.

If desired, contact MnDOT for the latest version, as the version included in this publication will most likely be out of date.

3.2 PRE-CONSTRUCTION ACTIVITIES

Topcon and RDO Construction Equipment and Controls met with the milling Contractor to equip their milling system with the required components needed for the AMG relative milling method and to provide the needed training. As per the requirements of the special provision, the milling Contractor provided a demonstration of the equipment prior to the start of the actual milling operation on TH2 (see Appendix A, section S-1.3.A.2) and shared the Automation Technology Work Plan (see Appendix A, section S-1.3.B.1) with both MnDOT and the paving Contractor. The paving Contractor (prime Contractor on the Contract), was also actively involved in the milling operation (i.e., planning, staging and operation), as these efforts could significantly impact staging, paving operations and the resulting ride. Additionally, per the requirements of the special provision, MnDOT and the Contractor agreed that the model shared during advertisement was appropriate for use as the Model of Record during the milling operation (see Appendix A, section S-1.3.B.2).

During the preconstruction meeting, the milling Contractor made it known that the AMG relative milling system could not record the as-built milled surface depths during the milling operation as per special provision requirements (see Appendix A, section S-1.3.B.3). It was noted that the system will record this information in the future but could not currently do so. Consequently, MnDOT required the quality control data (including both slope and depth) to be recorded at 1 foot inside of the left and right edge of the milled surface as follows:

- 50-foot linear intervals
- Use of rover for recording of station number
- Use of ruler or level for recording of depth and slope
- Shortening of intervals to 25-feet in areas of super-elevations

3.3 CONSTRUCTION ACTIVITIES

3.3.1 Eastbound Direction of Travel

The eastbound lanes of TH2 were milled on June 2, 2020. Tables 3.1 through 3.3 reflect the as-built delta milling depths at an offset of 12 feet left of centerline (12L), at the centerline (CL) and 12 feet right (12R) of centerline, respectively. Figure 3.1 illustrates a graph of the as-built delta milling depths verses stationing. The special provision designates a hold point, whereby no additional milling (requiring the AMG-milling method) may be completed until corrective action has occurred, or as accepted by the Engineer when 5 percent or more of the as-built delta milling-depth nodes exceed the tolerance of plus or minus 0.02 feet (see Appendix A, section S-1.3.B.4.d). As illustrated below, 10 percent of the as-built delta milling-depth nodes exceeded the tolerance for 12L, CL and 12R. Consequently, MnDOT, the milling Contractor, RDO and Topcon met to discuss potential causes. As shown in Tables 3.1 – 3.3, it was noted that the as-built delta milling-depth nodes would not have exceeded the 5 percent tolerance, if plus or minus 0.03 feet was used as the tolerance for 12L and centerline. However, 12R still exceeded 5 percent, but had significant improvement with a larger tolerance. The team also evaluated the as-built slopes that were measured (see Figure 3.2). As illustrated, the driving lanes averaged around 1.5 percent and should had been milled at 2 percent, while the superelevations were designed at 5 and 5.5 percent. (Please note that the as-built delta slope was unable to be calculated as the Contractor did not extract the Model of Record slopes to allow for these calculations but did so for the westbound direction of travel.) The following items were discussed as possible causes for the out-of-tolerance measurements:

1. The right gate on milling machine appeared to not be set to zero correctly. Therefore, it was recommended that a test strip (with extensive independent verification checks) is completed during the first 250 to 300 feet of the milling operation each day to ensure that both the left and right gates are zeroed correctly. Additionally, it was recommended that quality control be completed to verify the Model of Record milling-depth measurements displayed by the data acquisition system matches that being milled. This would be completed by painting the data acquisition system's Model of Record milling depth on the pavement and then having an individual verify that the as-built milling depth at that location matches that as shown on the data acquisition system.
2. There was insufficient staffing for collection of the quality control points. The individuals were unable to keep up with the milling machine/operation to ensure early identification of out of tolerance measurements, due to wearing of teeth, system setup, or potential system failures (see Appendix A, section S-1.3.B.4.d). Again, this would had been resolved if the machine was able to record the as-built measurements, however, since an individual was manually collecting and recording these measurements, it was recommended that two crews are used to collect measurements (one crew collecting measurements on each side of the cut lane). Additionally, it was recommended that the tablets are pre-loaded with the stationing and Model of Record milling depths and slopes to save on time for collection and verification of measurements.
3. As previously discussed, for troubleshooting purposes, increasing the tolerance from plus or minus 0.02 feet to plus or minus 0.03 feet allowed a significant number of measurements to be

within tolerance. This is indicated that there was difficulty collecting the manual measurements accurately using the ruler and at the rate of the milling operation. Consequently, additional staffing was recommended, along with the use of a carpenter's square to assist with more accurate milling depth measurements. The tolerance requirements were left at plus or minus 0.02 feet, as this tolerance was able to be consistently achieved on other projects using an AMG milling operation with robotic total stations.

4. Due to the amount of manual labor required to accurately collect measurements and continue to keep up with the milling operation, it was recommended that the data collection interval be increased as follows: (1) 100-foot intervals during continuous sections, with data collection measurements decreased down to 50-foot intervals when measurements exceed the tolerance; (2) 50-foot intervals in super-elevations, with data collection measurements decreased down to 25-foot intervals when measurements exceed the tolerance.

Table 3.1 As-built milling depths collected at 12L of centerline for eastbound direction of travel.

	BIN (ft)	Freq-Count	Frequency	Count	Frequency	Frequency
Milled too Deep < -0.02 ft (Fill)	-0.30	0	0	1	1%	0
	-0.20	0	0			
	-0.10	0	0			
	-0.05	0	0			
	-0.04	0	0			
	-0.03	1	1			99
within ±0.02ft Tolerance	-0.02	0	0	86	90%	
	-0.01	0	0			
	0	35	36			
	0.01	26	27			
	0.02	25	26			
Milled too Shallow > 0.02 ft (Cut)	0.03	8	8	9	9%	
	0.04	1	1			1
	0.05	0	0			
	0.10	0	0			
	0.20	0	0			
	0.30	0	0			
	TOTAL:	**96**	**100**	**96**	**100%**	

Table 3.2 As-built milling depths collected at centerline for eastbound direction of travel.

	BIN (ft)	Freq-Count	Frequency	Count	Frequency	Frequency
Milled too Deep < -0.02 ft (Fill)	-0.30	0	0	10	10%	3
	-0.20	0	0			
	-0.10	0	0			
	-0.05	1	1			
	-0.04	2	2			
	-0.03	7	7			97
within ±0.02ft Tolerance	-0.02	13	13	88	90%	
	-0.01	34	35			
	0	41	42			
	0.01	0	0			
	0.02	0	0			
Milled too Shallow > 0.02 ft (Cut)	0.03	0	0	0	0%	
	0.04	0	0			0
	0.05	0	0			
	0.10	0	0			
	0.20	0	0			
	0.30	0	0			
	TOTAL:	**98**	**100**	**98**	**100%**	

Table 3.3 As-built milling depths collected at 12R of centerline for eastbound direction of travel.

	BIN (ft)	Freq-Count	Frequency	Count	Frequency	Frequency
Milled too Deep < -0.02 ft (Fill)	-0.30	0	0	14	15%	8
	-0.20	0	0			
	-0.10	0	0			
	-0.05	5	5			
	-0.04	2	2			
	-0.03	7	8			91
within ±0.02ft Tolerance	-0.02	13	14	78	84%	
	-0.01	19	20			
	0	39	42			
	0.01	5	5			
	0.02	2	2			
Milled too Shallow > 0.02 ft (Cut)	0.03	0	0	1	1%	
	0.04	0	0			1
	0.05	0	0			
	0.10	1	1			
	0.20	0	0			
	0.30	0	0			

TOTAL:	**93**	**100**	**93**	**100%**

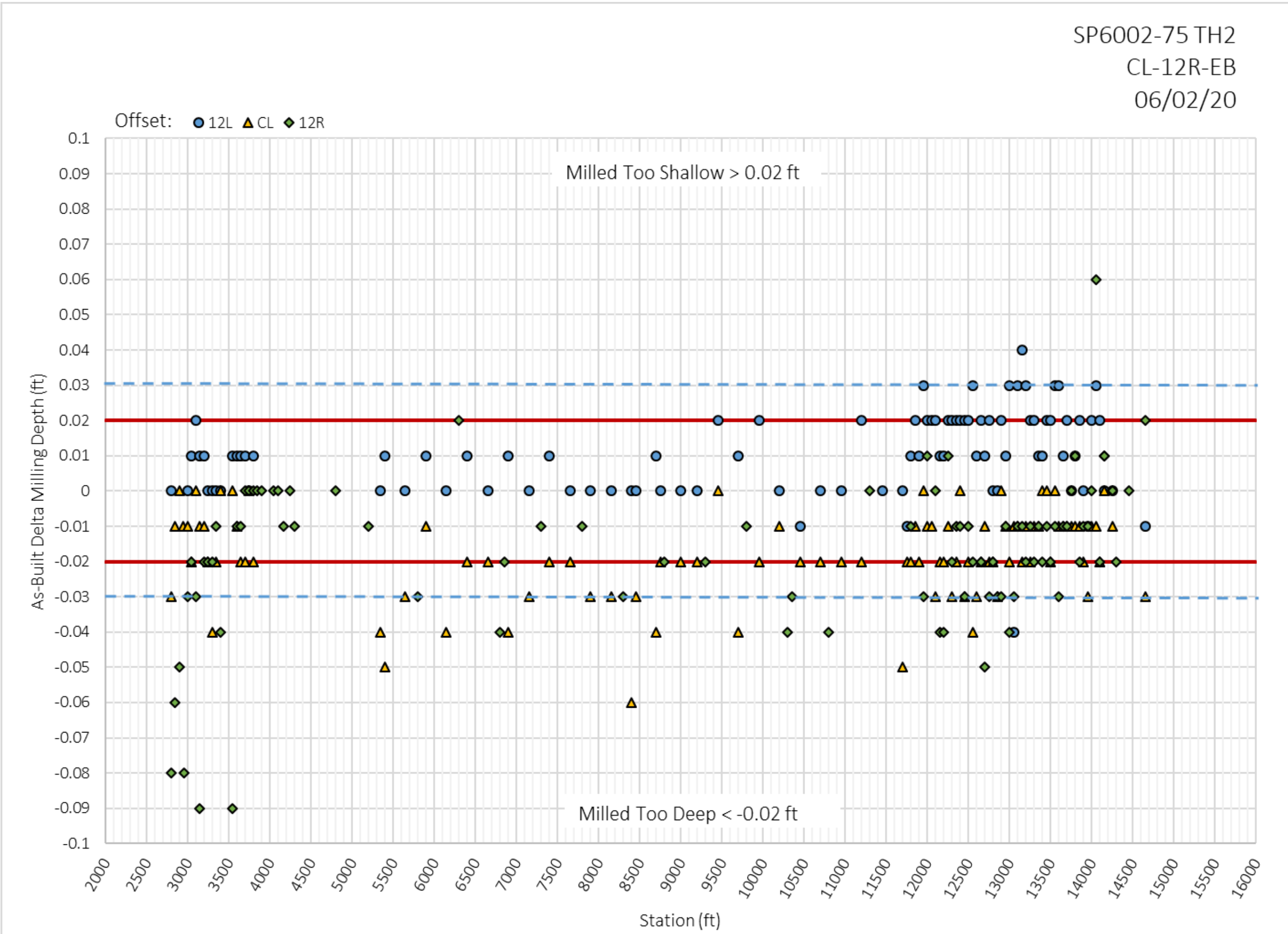

Figure 3.1 As-built delta milling depths with respect to stationing for the eastbound direction of travel.

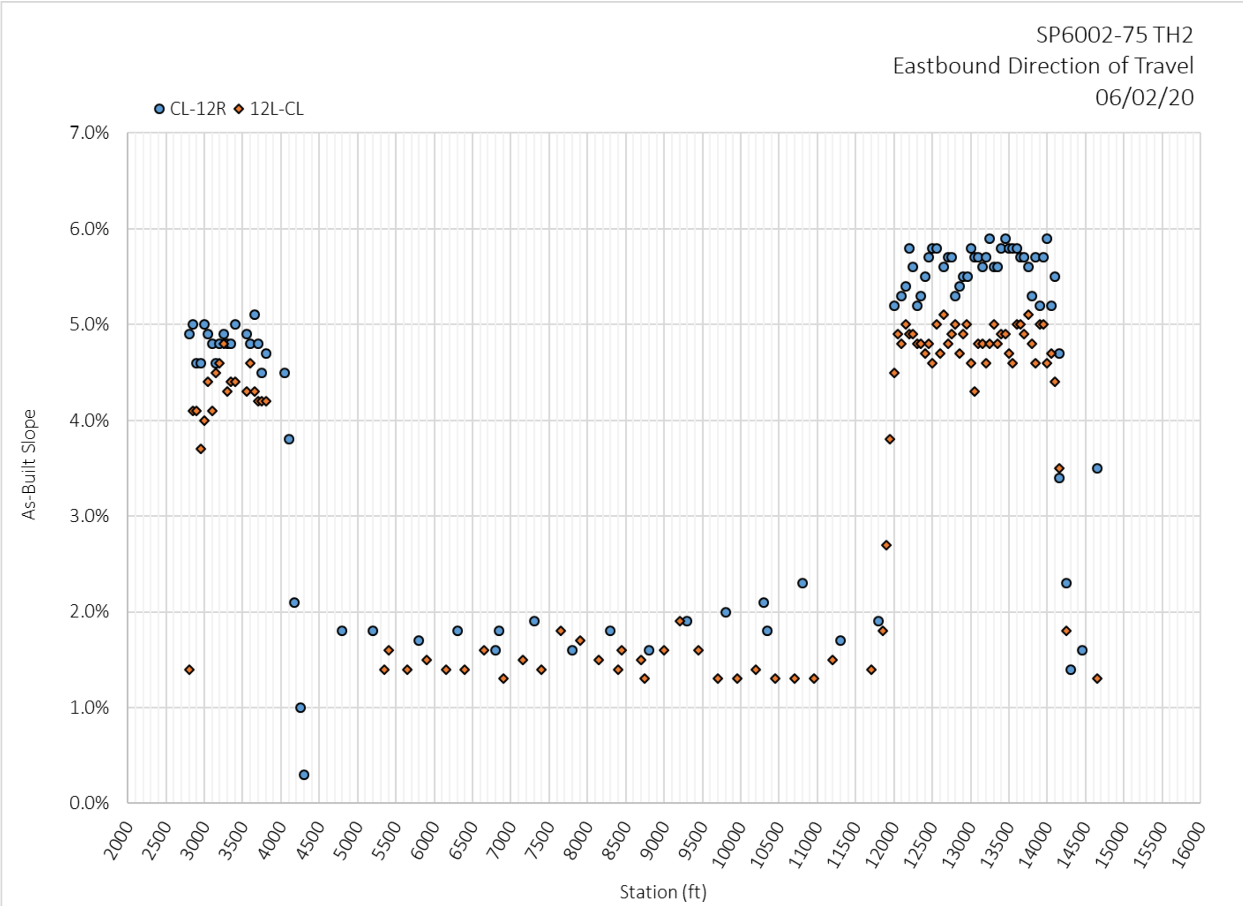

Figure 3.2 As-built slopes with respect to stationing for the eastbound direction of travel.

3.3.2 Westbound Direction of Travel

The westbound lanes of TH2 were milled on June 5, 2020. Tables 3.4 through 3.6 reflect the as-built delta milling depths at an offset of 12 feet left of centerline (12L), at the centerline (CL) and 12 feet right (12R) of centerline, respectively. Figure 3.3 illustrates the as-built delta milling depths verses stationing. As previously discussed, the special provision designates a hold point, whereby no additional milling (requiring the AMG-milling method) may be completed until corrective action has occurred, or as accepted by the Engineer when 5 percent or more of the as-built delta milling-depth nodes exceed the tolerance of plus or minus 0.02 feet (see Appendix A, section S-1.3.B.4.d). As presented below, 100, 99 and 99 percent of the as-built delta milling-depth nodes were within tolerance (within plus or minus 0.02 feet) for the nodes collected at 12L, CL and 12R, respectively. Figure 3.4 illustrates the as-built delta slopes with respect to stationing. The average as-built delta slope and standard deviation was 0.02 and 0.15 percent, respectively. As shown, the recommended changes resulting from the hold-point after milling the eastbound direction of travel were able to resolve the out-of-tolerance issues. Again, these recommendations were to increase quality assurance staffing (two crews), use of a carpenter's square during milling-depth measurements and in-depth verification of the right and left gate zeroing during the first 300 feet of the milling operation.

Table 3.4 As-built milling depths collected at 12L of centerline for westbound direction of travel.

	BIN (ft)	Freq-Count	Frequency	Count	Frequency	Frequency
Milled too Deep < -0.02 ft	-0.30	0	0	0	0%	0
	-0.20	0	0			
	-0.10	0	0			
	-0.05	0	0			
	-0.04	0	0			
	-0.03	0	0			
within ±0.02ft Tolerance	-0.02	0	0	162	100%	100
	-0.01	4	2			
	0.00	107	66			
	0.01	34	21			
	0.02	17	10			
Milled too Shallow > 0.02 ft	0.03	0	0	0	0%	0
	0.04	0	0			
	0.05	0	0			
	0.10	0	0			
	0.20	0	0			
	0.30	0	0			
	TOTAL:	**162**	**100**	**162**	**100%**	**100**

Table 3.5 As-built milling depths collected at centerline for westbound direction of travel.

	BIN (ft)	Freq-Count	Frequency	Count	Frequency	Frequency
Milled too Deep < -0.02 ft	-0.3	0	0	0	0%	0
	-0.2	0	0			
	-0.1	0	0			
	-0.05	0	0			
	-0.04	0	0			
	-0.03	0	0			
within ±0.02ft Tolerance	-0.02	0	0	155	99%	99
	-0.01	6	4			
	0	83	53			
	0.01	42	27			
	0.02	24	15			
Milled too Shallow > 0.02 ft	0.03	0	0	1	1%	1
	0.04	1	1			
	0.05	0	0			
	0.10	0	0			
	0.20	0	0			
	0.30	0	0			
	TOTAL:	**156**	**100**	**156**	**100%**	**100**

Table 3.6 As-built milling depths collected at 12R of centerline for westbound direction of travel.

<table>
<tr><th></th><th>BIN (ft)</th><th>Freq-Count</th><th>Frequency</th><th>Count</th><th>Frequency</th><th>Frequency</th></tr>
<tr><td rowspan="6">Milled too Deep < -0.02 ft</td><td>-0.3</td><td>0</td><td>0</td><td rowspan="6">0</td><td rowspan="6">0%</td><td rowspan="5">0</td></tr>
<tr><td>-0.2</td><td>0</td><td>0</td></tr>
<tr><td>-0.1</td><td>0</td><td>0</td></tr>
<tr><td>-0.05</td><td>0</td><td>0</td></tr>
<tr><td>-0.04</td><td>0</td><td>0</td></tr>
<tr><td>-0.03</td><td>0</td><td>0</td><td rowspan="7">99</td></tr>
<tr><td rowspan="5">within ±0.02ft Tolerance</td><td>-0.02</td><td>0</td><td>0</td><td rowspan="5">158</td><td rowspan="5">99%</td></tr>
<tr><td>-0.01</td><td>13</td><td>8</td></tr>
<tr><td>0</td><td>92</td><td>58</td></tr>
<tr><td>0.01</td><td>37</td><td>23</td></tr>
<tr><td>0.02</td><td>16</td><td>10</td></tr>
<tr><td rowspan="6">Milled too Shallow > 0.02 ft</td><td>0.03</td><td>1</td><td>1</td><td rowspan="6">2</td><td rowspan="6">1%</td></tr>
<tr><td>0.04</td><td>1</td><td>1</td><td rowspan="5">1</td></tr>
<tr><td>0.05</td><td>0</td><td>0</td></tr>
<tr><td>0.10</td><td>0</td><td>0</td></tr>
<tr><td>0.20</td><td>0</td><td>0</td></tr>
<tr><td>0.30</td><td>0</td><td>0</td></tr>
<tr><td></td><td>TOTAL:</td><td>160</td><td>100</td><td>160</td><td>100%</td><td>100</td></tr>
</table>

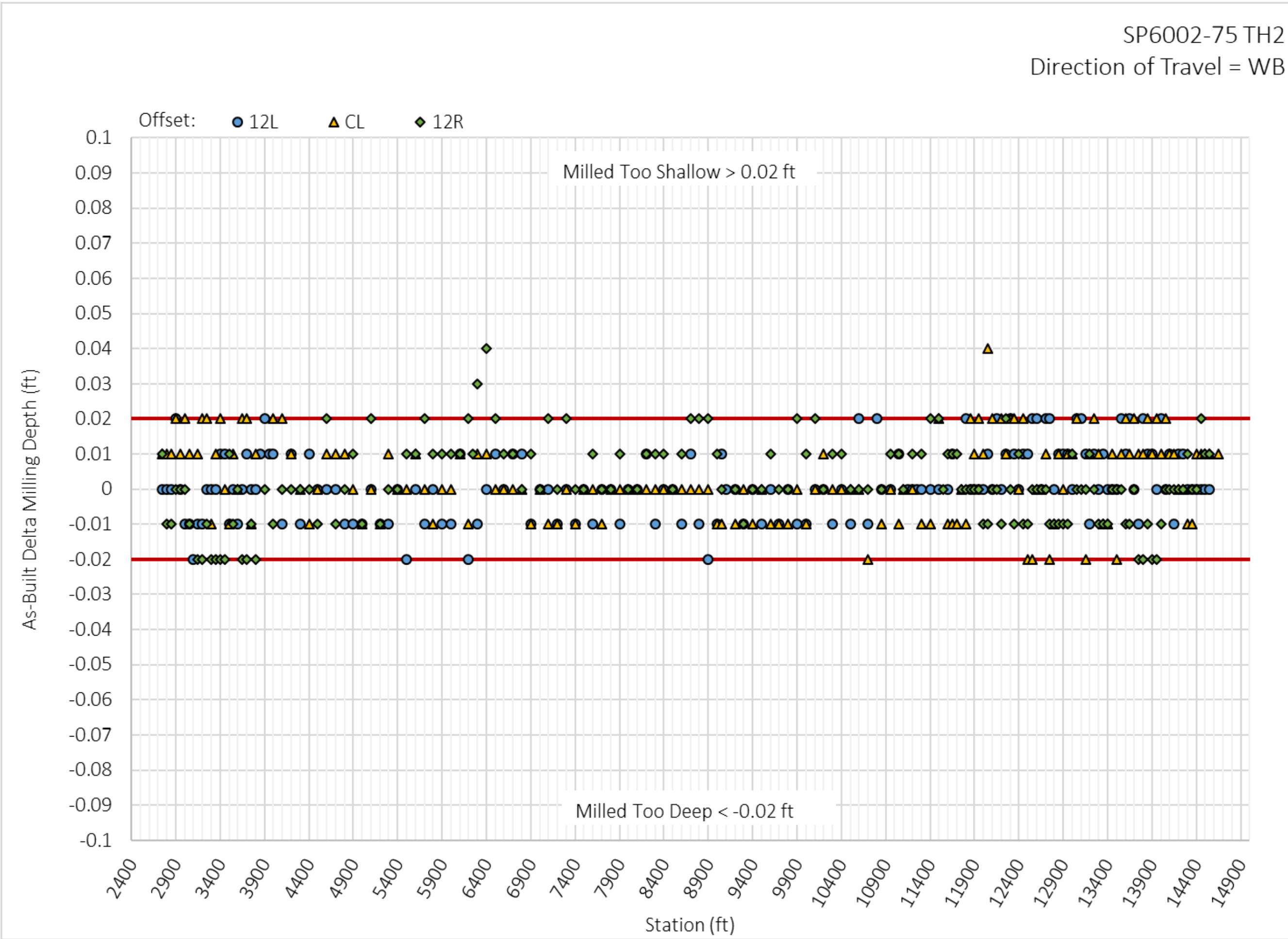

Figure 3.3 As-built delta milling depths with respect to stationing for the westbound direction of travel.

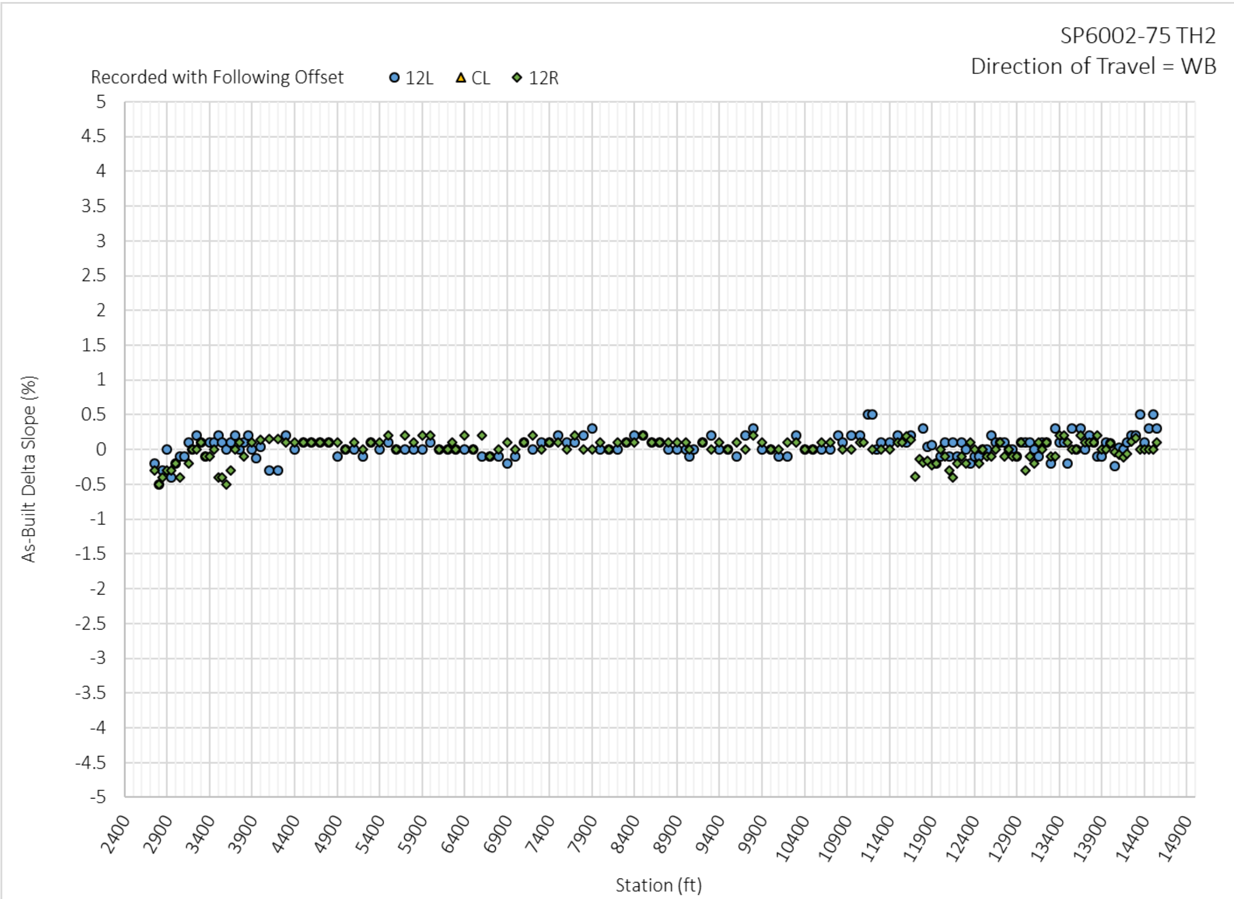

Figure 3.4 As-built delta slopes with respect to stationing for the westbound direction of travel.

3.3.3 Debriefing Meeting

A debriefing meeting was scheduled on June 24, 2020 between MnDOT, RDO, Topcon and the milling and prime contractor to discuss the relative AMG milling operation. The following highlights the main discussion points:

1. MnDOT, the milling contractor, prime contractor, RDO and Topcon all agreed that the relative AMG system successfully followed the Model of Record and were pleased with the milled surface and final pavement smoothness.
2. MnDOT, the milling contractor, prime contractor, RDO and Topcon would like to see the technology continue to be used on future projects and that a roadmap is developed for deployment of this technology on future projects with asphalt paving – with the goal of full deployment.
3. The milling contractor thought the Model of Record could had been set to mill a little deeper to ensure that the milling operation was out of the wearing course and to reduce daylighting that occurred at the west end of the project. It was discussed that this would had been difficult, as the rapid changes in profile that were being correct prevented this from being done when trying to optimize smoothness and overall maximum and minimum milling depths.

4. There was poor ride on one super-elevation. It was determined that this was due to an error in the Model of Record. Two grade breaks were not addressed in the milling model (see Figure 3.5). The AMG milling system was following the model correctly, however, it was outputting incorrect milling depths due to this error. Consequently, this translated into waves in the exported model that were present in the reference model used by the AMG system (see Figure 3.6). Review of IRI values for the exported model, prior to the milling operation, may had caught this modeling error.

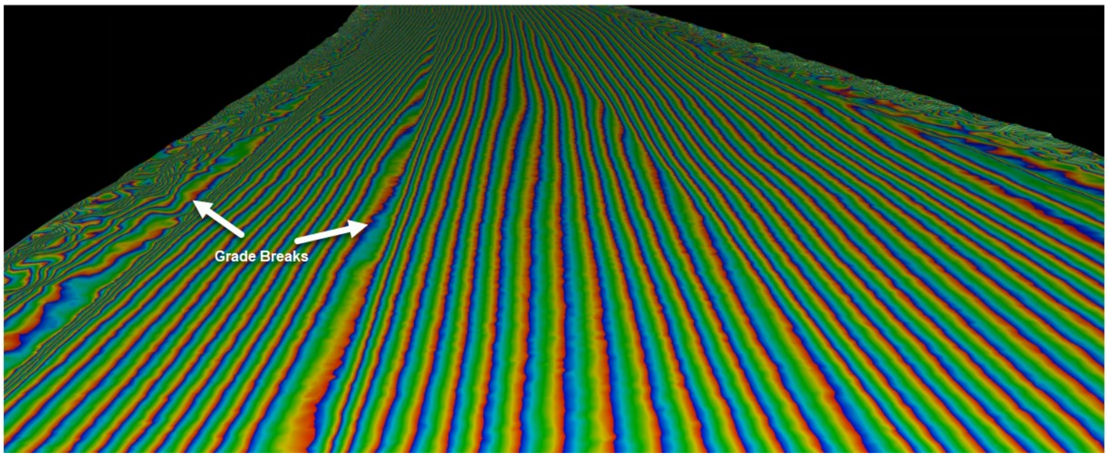

Figure 3.5 Detailed cloud surface of model of record illustrating grade breaks.

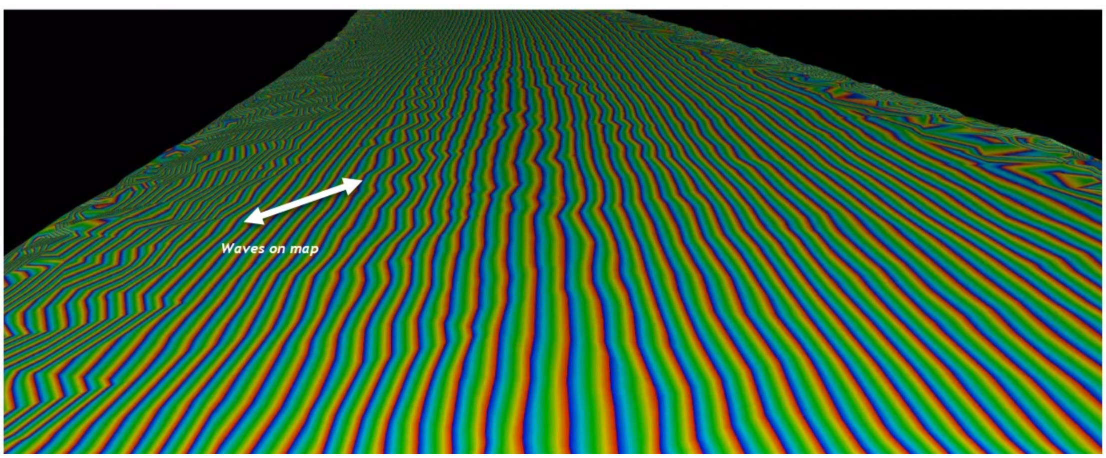

Figure 3.6 Reference surface used by AMG system with waves resulting from missed grade breaks during design process.

3.4 FUTURE ROADMAP

MnDOT plans to continue piloting this technology on other projects and will generate a roadmap with the goal of future, full deployment of this technology. As part of the project selection process, MnDOT recommends the use of this technology when milling an existing asphalt surface for a mill and overlay and when milling the existing asphalt pavement for reclamation projects (i.e., full depth reclamation, stabilized full depth reclamation, cold in place recycling and cold central plant recycling). The technology could potentially be used on concrete surfacing projects, however, the precision of vertical measurements still requires detailed evaluation.

Ground penetrating radar and core measurements will be required for determination of asphalt pavement thicknesses in both the inner and outer wheel paths of each lane to capture any crown corrections prior to building the 3D models. Model vertices will be established at 5-foot intervals in all tangents and 1-foot intervals in curves. Additionally, the 3D models will be reviewed for smoothness to ensure that there are not significant irregularities present within the model to cause bumps in the resulting as-built milled surface. These irregularities are typically located at design templated drops, station equations and super elevations. An inertial ride index (IRI) of 15 inches/mile, or less, is required for the wheel paths extracted from the milled surface model (e.g., 3L, 9L, 3R and 9R of centerline). Smoothness analyses would be run at 1-foot intervals.

As part of the roadmap development, the entity to scan the existing roadway and create the 3D models will need to be determined (i.e., as to whether it would be MnDOT, a consultant, and/or through the construction contract). Design software currently used by state agencies and consultants should be evaluated to determine as to whether these platforms can be used as the preliminary design software, as designers are already experienced with given software applications and pre-made template drops, etc. are already available for use in these applications.

CHAPTER 4: RECOMMENDATIONS AND CONCLUSIONS

4.1 CONCLUSIONS

4.1.1 Relative Milled Surface Model Creation

The following summarizes the conclusions resulting from scanning the existing surface and creation of the relative milled surface model:

- The accuracy of the relative surface scan measurements was within 3 to 5 mm in the vertical direction.
- It required approximately 8 hours to collect, clean and review the relative surface measurements.
- The relative surface (RDM1) LIDAR scan adequately identified and documented the magnitude of the vertical roadway movement and could be used to assist with the correction of irregular roadway profiles.
- The Topcon Magnet Resurfacing software allowed designers to iteratively modify cross slopes and milling depths to optimize smoothness, while maintaining maximum and minimum milling-depth criteria.
- The relative surface measurements can be used for creation of the relative existing surface and milling-depth models.
- The relative surface solution will help address safety concerns associated with conventional survey methods for establishment of digital terrain models and/or the use of string-lines to allow for profile milling operations.

4.1.2 Relative AMG Milling Method

The following summarizes the conclusions resulting from use of the relative AMG milling system during the milling operation on TH2:

- MnDOT, the milling contractor, prime contractor, RDO and Topcon all agreed that the relative AMG system successfully followed the model of record and were pleased with the milled surface and final pavement smoothness.
- MnDOT, the milling contractor, prime contractor, RDO and Topcon would like to see the technology continue to be used on future projects and the development of a roadmap for deployment of this technology on future projects with asphalt paving – with the goal of full deployment.
- The milling contractor thought the model of record could have been set to milling a little deeper to ensure that the milling operation was out of the wearing course and to reduce the daylighting that occurred at the west end of the project. It was discussed that this would have been difficult, because the rapid changes in profile that were being corrected prevented this from being done when trying to optimize smoothness and overall maximum and minimum milling depths.

- There was poor ride on one super-elevation. It was determined that this was due to an error in the model of record. Two grade breaks were not addressed in the milling model. While the AMG was following the model correctly, it was outputting incorrect milling depths due to this error. Review of IRI values for the exported model, prior to the milling operation, may had caught this modeling error.
- Two crews are needed to adequately capture milling depths for detailed as-built measurements when AMG milling systems are unable to record the as-built milling measurements. This allows the crew to keep up with the milling machine to capture more accurate measurements. Additionally, a carpenter's square is needed for increased accuracy in milling-depth measurements.
- A tolerance of plus or minus 0.02 feet was achievable and will continue to be used for requirements on future projects.

4.2 RECOMMENDATIONS

The following summarizes recommendations resulting from scanning the existing surface, creation of the relative milled surface model and use of a relative AMG milling system:

- A project selection criterion should be developed to outline when the relative surface solution should be used and on which applications.
- The relative surface solution is recommended for use during the milling operation on asphalt overlay projects with significantly irregular profiles.
- Additional verification should be completed by MnDOT to increase comfort level with respect to the vertical accuracy of the relative solution for use on unbonded concrete overlays and whitetopping projects.
- It is recommended that the relative surface solution be used on reclamation projects. Reclamation projects often run into problems due to the non-uniform pavement thicknesses present on roadways. Conventional, variable depth milling is not cost effective on these projects, and therefore designers often have to split the project into sections with set milling depths for use with conventional milling operations. This often results in varying amounts of recycled asphalt pavements (RAP) being ground into the existing base materials on full-depth reclamation and stabilized full-depth reclamation projects and variable amounts of RAP (thereby affecting the mix designs) in cold in-place recycling and cold central plant recycling projects. This cost-effective solution will allow for more uniform and stable reclaimed materials, thereby significantly improving long-term performance of the roadways.
- Design software currently used by state agencies and consultants should be evaluated to determine whether these platforms can be used as the preliminary design software, because designers are already experienced with these software applications and pre-made template drops, etc. are already available for use in these applications.
- Ground penetrating radar and core measurements should be collected for determination of asphalt pavement thicknesses in both the inner and outer wheel paths of each lane to capture any crown corrections prior to building the 3D models.

- Model vertices should be established at 5-foot intervals in all tangents and 1-foot intervals in curves.
- 3D models should be reviewed for smoothness to ensure that there are not significant irregularities present within the model to cause bumps in the resulting as-built milled surface. These irregularities are typically located at design templated drops, station equations and super elevations. An inertial ride index (IRI) of 15 inches/mile, or less, is recommended for the wheel paths extracted from the milled surface model (e.g., 3L, 9L, 3R and 9R of centerline). Smoothness analyses should be run at 1-foot intervals.
- Relative AMG milling requirements should include a 250- to 300-foot control/test strip, with highly densified independent verification checks completed at the start of the milling operation each day to ensure that the left and right gates are zeroed correctly.
- Relative AMG milling systems are recommended to record the as-built milled surface at intervals of 10 feet or less. Independent quality-control measurements should continue to be continuously collected behind the milling machine. However, the measurements collected by the AMG system would provide a more densified DTM for verification of the system.

APPENDIX A: (2232) MILL PAVEMENT SURFACE – RELATIVE AUTOMATED MACHINE GUIDANCE – MILLING METHOD (VERSION 12/16/20)

DESIGNER NOTES

Only use this provision if District requests the use of automated machine guidance during the milling operation. This provision is recommended for use when milling an existing asphalt surface for a mill and overlay and when milling the existing asphalt pavement for reclamation projects (i.e., full depth reclamation, stabilized full depth reclamation, cold in place recycling, cold-central plant recycling).

Collect GPR and core measurements for determination of asphalt pavement thicknesses in the inner and outer wheel paths of each lane to capture any crown corrections prior to building 3D models.

Ensure that the final design model vertices are follows:

5 ft in tangents

1 ft in curves

It is recommended that the milled surface model is reviewed for smoothness to ensure that there are not significant irregularities present within the model to cause bumps in the resulting as-built milled surface. These irregularities are typically located at design template drops, station equations and super elevations. An IRI of 15 in/mile, or less, is recommended for the wheel paths extracted from the milled surface model (e.g., 3L, 9L, 3R and 9R of centerline). Run smoothness analyses at 1-ft intervals.

Since the surface models cannot be included with the contract and are instead provided as a 1205 (or RID) document, add a note to the SEQ to the Mill Bituminous Surface Special pay item to assist with more accurate bidding: "X percent < A inches, A inches ≤ Y percent ≤ B inches; Z percent > B inches".

When producing the LandXML outputs of surfaces, it is important to include both triangles and features in the surface definition. Without these features, the software will re-triangulate the surface, which may not match the design intent.

Provide a Provision for 1205 (or supplement project information) with a link to the location of the digital data. It is recommended to provide a list of the files and the associated metadata and can also include a list of expectations and authorized uses (e.g., the digital data was developed only for use with the automated machine guidance – milling method).

Ensure that the following digital data is provided to the bidders:

(1) LandXML file with centerline and final profile.

(2) The following surface model files from shoulder PI to shoulder PI using a maximum node spacing of 5-ft vertices or less:

(2a) LandXML Relative Surface Models and 3D Breaklines for:

(i) Existing Pavement

(ii) Milled Surface

(2b) 2D Line-Work

(3) The milling depths (within ± 0.01 feet) at 25 foot linear-intervals (exported in *.csv or *.xlsm format) for the following nodes (include fill areas [pre-fill areas]):

(3a) Edges of pavement and centerlines.

(3b) Edge of shoulder (when AMG-Milling is required on shoulders)

(4) Geodetic and Control Points

MnDOT 2232 Mill Pavement Surface is modified with the following:

S-1.1 DESCRIPTION

This work consists of using a relative automated machine guidance system when removing existing pavement by cold milling. The steering functions of the milling machine are operated by a contractor personnel, however, the milling operation is controlled by an onboard data acquisition system which automatically follows a Milling Surface Model (Model of Record) to control variable depth milling relative to the existing pavement surface.

A Definitions

As-Built Surface Model

Model of the milled surface recorded by the Relative AMG-milling system during the milling operation.

Delta Milling Depth

Difference in depth between Model of Record and As-Built Surface Model. Negative values indicate regions that were milled too deep (fill regions). Positive values indicate regions milled too shallow (cut regions).

Model of Record

Contains a variety of digital data that defines the design intent, and therefore, is not a single file. This includes horizontal and vertical alignments, existing relative pavement surface models, relative milled surface model, and 3D line strings (e.g., edges of pavement, break points, etc.).

Relative Automated Machine Guidance (AMG) – Milling System

A grade control system attached to milling equipment that uses the existing pavement surface to follow the Model of Record.

Surface

A surface, in the context of 3D engineered models, represents an element of design such as existing ground, final grading, milling, or pavement in a 3D workspace. All elements of surface are spatially oriented to one another.

3D Breaklines

Lines in a file that reflect a distinct change in surface type or slope.

S-1.2 MATERIALS – (BLANK)

S-1.3 CONSTRUCTION REQUIREMENTS

Replace 2232.3.A Equipment with the following:

A Equipment

Mill existing pavement with a self-propelled cold milling machine capable of removing concrete and bituminous materials to the profile, cross-slope, grade and depth uniformly across the pavement surface as provided in the Model of Record. Use automatic controls to control depth, grade, cross-slope and profile.

A.1 AMG-Milling System Requirements

Instrument all milling machines used in locations requiring the relative AMG-milling method with a relative AMG-milling system calibrated according to Manufacturer's recommendations and meeting requirements of this provision. The Engineer has the right to wave use of the relative AMG-milling method on secondary passes that are less than 3 feet in width. The relative AMG-milling system must reference the Model of Record to within plus or minus 0.02 feet in the vertical direction along each edge of the cutting edge of the mill.

Additionally, the system must meet the following:

(1) Import surface models that include station-based alignment data.

(2) Contains an onboard data acquisition system that displays current milling depths and milling depths from the Model of Record for the cutting edge of mill.

(3) Uses a relative system for vertical positioning.

(4) Uses the entire surface of the Model of Record during the milling operation in lieu of profile strings.

(5) Ability to view the following from the onboard data acquisition system and/or remotely from cloud computing within 15-minute intervals when adequate data cellular coverage is available:

(a) As-Built Milling and Model of Record Surface Models, and/or

(b) Delta Milling Depths.

(6) Displays reference line on the onboard data acquisition system to assist with lateral positioning of milling head.

Mark reference line on pavement surface for systems that cannot display reference line on the onboard data acquisition system.

Provide Engineer with access to cloud storage and cloud computing prior to start of milling efforts requiring the relative AMG-milling method. Cloud storage data is accessible until 90 days after final acceptance of all work per MnDOT 1516.2.

A.2. Training and Equipment Demonstration

Demonstrate relative AMG-milling system meets requirements of this provision no later than 2 weeks prior to production.

Provide demonstration location and date to Engineer no later than 7-working days in advance to demonstration.

A documented, successfully, completed project from Contractor’s current, or previous, construction season will meet requirements of equipment demonstration. Provide documentation to support that system met tolerance requirements.

Add the following to 2232.3 Construction Requirements:

B Operations

B.1 Automation Technology Work Plan

Develop an Automation Technology Work Plan and provide it to Engineer no later than 7 days prior to preconstruction meeting. Work Plan will include the items listed in Table 2232-1.

Submit Automation Technology Work Plan modifications to Engineer (for review and approval) no later than 7 days after preconstruction meeting, or no later than 7 days prior to start of operations requiring the relative AMG milling method, whichever comes first.

Table 2232-1
Required Documentation in the Automation Technology Work Plan

Item	Description
Roles and Responsibilities	• List roles and responsibilities of individual(s) assisting with tolerance verifications, Model of Record and relative AMG milling method.
Model of Record (see S-1.3.3.B.2)	• Proposed changes to digital data in Model of Record. • Schedule for agreeing on Model of Record.
AMG System / Milling Operation	• General information about relative AMG system. • Process for daily calibration checks on relative AMG system(s). • Process for verification of tolerances. • Details pertaining to training and equipment demonstration, including proposed time and location and how equipment will be demonstrated. • Proposed milling operation staging. • Potential challenging conditions.

B.2 Model of Record

The Department providing the digital data does not relieve the Contractor from the responsibility of making an investigation of conditions to be encountered, including but not limited to site visits, and basing the bid on information obtained from these investigations and professional interpretations and judgment. The Contractor assumes the risk of error if the information is used for any purposes for which the information was not intended. Assumptions the Contractor makes from this electronic information or manipulation of the electronic information is at their risk.

Convert and densify the Department provided Relative Milled Surface Model, as needed, for use with the relative AMG-Milling system. Document all model modifications, if any, and provide this information to the Engineer for approval. The Engineer is allowed 5 working days to review model modifications and/or to update files with Department approved changes requested by the Contractor. The Contractor and Engineer must agree on a single set of data that constitutes the Model of Record.

Final approved digital data is considered the Model of Record. Document file name(s) and associated date and time stamps of Model of Record.

Use Model of Record during all milling operations requiring the relative AMG-milling method.

B.3 Relative AMG Milling Operations

Verify relative AMG-milling system is calibrated according to Manufacturer’s recommendations.

Complete <u>continuous quality control</u> measurements of milling depths at right and left of the cutting edge of the mill to allow for adjustments for teeth wear and to ensure milling depths are reflective of the Model of Record.

Use the relative AMG-milling system to real-time, record the milled surface depths during the milling operation at a maximum spacing of 10-foot intervals. Provide Engineer with summary of the relative AMG-milling operations per the requirements of Table 2232-2.

Table 2232-2
AMG-Milling Operation Summary Requirements

Description	Format	Submittal to Engineer
As-Built Milled Surface Model *	LandXML, or format as approved by the Engineer	• Submit **daily** prior to start of the subsequent day's milling operation requiring the Relative AMG-Milling Method.
As-Built Cut / Fill Volumes and Surface Map ‖	Volume Report & LandXML, or format as approved by the Engineer	• Submit **daily** prior to start of the subsequent day's milling operation requiring the Relative AMG-Milling Method.
As-Built Delta Milling Depth Report Using Form AMG-103 †	*.xls, or *.xlsm	• Create **daily** during the first 2 production days or first 5 lane miles, whichever is greater, after mobilization or re-mobilization of the equipment during a given construction season. Submit prior to the end of the next working day. • Create a **weekly** as-built delta milling depth report containing the delta milling depths for any day(s) in production that week. Submit prior to the end of the next working day. • Create a **final** as-built delta milling depth report for the entire milling operation upon completion of milling requiring the AMG-Milling Method. Submit within 14 working days of completion of work requiring the AMG milling method.

* Model of the milled surface recorded by the relative AMG-milling system during the milling operation.

‖ Create a color-coded surface map and calculate the cut/fill volumes by comparing the Model of Record to the As-Built Milled Surface Model. Ensure the cut/fill surface map indicates the cut (milled too shallow [>0.02 feet]) and fill (milled too deep [< -0.02 feet]) regions.

† Created by comparing the Model of Record to the As-Built Milled Surface Model. This report contains the following information:

(1) Export of the As-Built Delta Milling Depths at 10 foot intervals for the following nodes located 1-foot inside of the left and right edge of the milled surface (e.g., 8-foot milling head, left side of milling head adjacent to the centerline, nodes would be extracted at offsets of 1- and 7-feet right of centerline).

As-Built Delta Milling Depth is defined as follows:

As-Built Delta Milling Depth (ft) = "As-Built Milled Surface Model" – "Model of Record"

(2) A minimum of the following statistics for the As-Built Delta Milling Depth: Sample Size, Minimum, Maximum and Average

(3) Calculation of the percent of nodes that were:

(3a) milled too shallow, "cut" (> 0.02 feet),

	(3b)	milled within tolerance (±0.02 feet) and
	(3c)	milled too deep, “fill” (< -0.02 feet).
(4)	Histogram plotting the Frequency vs. As-Built Delta Milling Depth (feet)	
(5)	Graph of As-Built Delta Milling Depth vs. Station for each node.	

The Engineer will verify that the relative AMG-milling system is milling to the required Model of Record milling depths per Table 2232-3. The Engineer will ensure that milling depths are within ±0.02 feet of the Model of Record and verify the measurements provided in form AMG-103.

Table 2232-3
Milling Depth Verification Locations * ‖

Description	Description	Measurement Location
First Day of Production, or after mobilization of the AMG-milling system ‖	Minimum of every 500 feet	Verify depth and cross slope.
First Super-Elevation after mobilization of the AMG-milling system †	Verify cross-slope is correct throughout super-elevation	
Daily Verification	Minimum of 12 Random Measurements	
* Verify milling depth and cross slope. Verify cross slopes with a robotic total station, or smart level. Verify milling depths with a tape measure, or robotic total station. ‖ Randomly verify that the milling machine is meeting the requirements of this provision. † Take measurements starting at the beginning of the super-elevation transition, through the full super-elevation curve and continuing through the ending super-elevation transition to verify that the AMG controls are calibrated and milling to the cross slope of the Model of Record.		

B.4 Hold Point

B.4.a Automation Technology Work Plan

Review and approval of the Automation Technology Work Plan by the Engineer is considered a hold point – do not begin milling using the relative AMG-milling method until the Engineer has approved the plan. All milling (requiring the relative AMG-milling method) completed before approval of the Automation Technology Work Plan, or acceptance by the Engineer, constitutes Unauthorized Work per 1512.2.

B.4.b Equipment Demonstration

Equipment demonstration not meeting the requirements of this provision is considered a hold point – do not begin milling using the relative AMG-milling method until approval by Engineer.

B.4.c Model of Record

Review and approval of the Model of Record by both the Contractor and Engineer is considered a hold point – do not begin milling using the relative AMG-milling method until the Contractor and Engineer have approved the model. All milling (requiring the relative AMG-milling method) completed before approval of the Model of Record constitutes Unauthorized Work per 1512.2.

B.4.d AMG – Milling System Failure

AMG-milling system failure occurs when:

(1) relative AMG-milling system does not mill per requirements of this provision,

(2) 5 percent or more of the as-built delta milling depth nodes exceed the tolerance of ± 0.02 feet as calculated in form AMG-103 for a given daily report,

(3) 50 percent or more of the independent verification measurements completed by Engineer exceed the tolerance of ±0.02 feet within 1,000 feet of milling production (with verifications spaced no more than 100 feet apart), or

(4) the milling machine becomes inoperable.

AMG-milling System Failure is designated as a hold point, whereby no additional milling (requiring the relative AMG-milling method) may be completed until corrective action has occurred, or as accepted by Engineer. All additional milling (requiring the relative AMG-milling method) completed before corrective action, or acceptance by the Engineer, constitutes Unauthorized Work per 1512.2.

Replace 2232.5 Basis of Pavement with the following:

S-1.4 BASIS OF PAYMENT

Interruptions in availability of satellite signals used with the relative AMG milling system will not result in any adjustments to the “Basis of Payment” for any construction items or to Contract time.

The square yard price for Mill Bituminous Pavement (Special) includes the cost of cleanup, disposal operations, equipment demonstration of the relative AMG system, efforts put towards finalizing the digital data as the Model of Record, splitting models into smaller file sizes for use during the milling operation, site calibrations, system setup, system monitoring, remote server data storage, cloud-based software, data package plans and creation of submittals. The cost of constructing a temporary milled taper and providing, placing, and removing temporary bituminous tapers is included in the contract unit price for other relevant contract items.

The Department will pay for square yard item 2232.604 Mill Bituminous Pavement (Special) on the basis of the following schedule:

Item No.	Item	Unit
2232.604	Mill Bituminous Pavement (Special)	Square Yard