Calibration, Certification, and Verification of Transverse Pavement Profile Measurements

Final Report

January 13, 2020

U.S. Department of Transportation
Federal Highway Administration

Foreword

Across the United States, State and local transportation agencies are tasked with collecting transverse profile measurements. Collection of the data is carried out with a variety of systems that operate at the prevailing speed limit. With the wide range of systems used to collect data it is critical that transportation agencies know the system used to collect the data is accurate and the reported results are comparable to other measurement systems. This report summarizes the development of standard practices which should be conducted to calibrate, certify, and verify transverse pavement profiling equipment.

This report will be of interest to pavement engineers, road surface data collection agencies, certification agencies, transverse profiler vendors, and those concerned with the performance of systems collecting transverse profile measurements.

Bernetta L. Collins, Director, National Resource Center

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16. Abstract

Across the United States, state and local transportation agencies are tasked with collecting transverse profile measurements. Collection of the data is carried out with a variety of systems that operate at the prevailing speed limit. With the wide range of systems used to collect data it is critical that transportation agencies know the system used to collect the data is accurate and the reported results are comparable to other measurement systems. This report summarizes the development of standard practices which should be conducted to calibrate, certify, and verify transverse pavement profiling equipment used to collect rut depth, cross-slope, and/or edge/curb detection data. Through implementation of the standard practices and requirement statements presented herein transportation agencies will have the ability to: identify the accuracy and precision of transverse pavement profile measurements, identify if two or more measurement systems are providing results within tolerances, and determine if measurements taken at different times are consistent.

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Metric Conversion Chart

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
In	inches	25.4	millimeters	Mm
Ft	feet	0.305	meters	M
yd	yards	0.914	meters	M
mi	miles	1.61	kilometers	Km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	Ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	Cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	G
lb	pounds	0.454	kilograms	Kg
T	Short tons (2000 lb)	0.907	Megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheidt	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	Lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	In
m	meters	3.28	feet	Ft
m	meters	1.09	yards	Yd
km	kilometers	0.621	miles	Mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yard	yd^2
ha	hectares	2.47	acres	Ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	Gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	Cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	Oz
kg	kilograms	2.202	pounds	Lb
Mg (or "t")	Megagrams (or "metric ton")	1.103	Short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheidt	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	Fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	Fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	Lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS AND SYMBOLS

CAD	Computer-Aided Design
CS	Capability Statement
FHWA	Federal Highway Administration
GRE	Ground Reference Equipment
IQR	Interquartile Range
RS	Requirement Statement
TPP	Transverse Pavement Profiler

EXECUTIVE SUMMARY

Across the United States, state and local transportation agencies are tasked with collecting transverse profile measurements. Collection of the data is carried out with a variety of systems that operate at the prevailing speed limit. With the wide range of systems used to collect data it is critical that transportation agencies know the system used to collect the data is accurate and the reported results are comparable to other measurement systems. This report summarizes the development of standard practices which should be conducted to calibrate, certify, and verify transverse pavement profiling equipment.

The standard practices are designed for equipment collecting transverse pavement profiles for analysis of rut depth, cross slope, and edge/curb detection. To fully evaluate the transverse measurements along the data process flow, five standard practices and a standard practice containing a set of terms and definitions have been developed and are explained herein. Four of the standard practices are developed to assess: the static performance, body motion cancelation capability, navigation drift mitigation, and highway performance capabilities of transverse pavement profiling systems. The fifth standard practice is developed to assess the accuracy and precision of the ground reference data.

During the development of these standard practices two equipment rodeos were conducted. All insights gained and lessons learned from the first equipment rodeo were used to improve the standard practices for the second rodeo. The capabilities of the vendors that attended the two equipment rodeos are provided to provide support for the values in the requirement statement. Through implementation of the standard practices and requirement statements presented herein transportation agencies will have the ability to: identify the accuracy and precision of transverse pavement profile measurements, identify if two or more measurement systems are providing results within tolerances, and determine if measurements taken at different times are consistent.

CHAPTER 1. INTRODUCTION

MOTIVATION

Transportation agencies perform pavement condition surveys in order to assess the performance of the road surface and determine the maintenance and rehabilitation actions necessary to provide a safe, reliable, and functional roadway. One of the most important components of the condition survey is the evaluation of the transverse pavement profile. Transverse profile measurements can be used to:

- Indicate where rutting and shoving of the pavement surface is occurring.
- Locate edge drop-off.
- Quantify rut area and water depth potential in ruts.
- Determine pavement cross slope.
- Evaluate pavement drainage.
- Plan pavement grinding projects.

Transportation agencies conduct pavement condition surveys via agency owned equipment or contracted services. This data collection is carried out with systems that operate at the prevailing speed limit. There is a need for transportation agencies to have practical and efficient methods and procedures to determine the precision and accuracy of transverse profile measurements from agency owned equipment or contractors. The process of verifying these measurements can usually be put into two categories: 1) using a device/method to survey the dimensions of a known object, or 2) performing a transverse profile measurement and comparing the measurements to ground reference measurements. The evaluation of precision and accuracy of a measurement system can be complicated because there may be different points in the flow of the measurement process where calibration, certification, and verification may be performed.

STUDY OBJECTIVES

The objectives of this study are to provide transportation agencies with the information necessary to monitor and evaluate pavement testing programs that include transverse pavement profiles. The methods and procedures developed during this study provide transportation agencies with the ability to:

- Determine the precision and accuracy of (highway speed) transverse pavement profile measurements, and evaluate if the precision and accuracy are within recommended guidelines and reasonable operating parameters.
- Determine if two or more measurement systems are providing results within tolerances (e.g., if multiple pieces of equipment are performing a survey, are they all providing the same results, and how often should the results be compared).
- Determine if measurements taken at different points in time are providing consistent results within tolerances, and how often should the results be evaluated.

SCOPE OF REPORT

This report focuses on the development of standard practices for the assessment of transverse pavement profilers and the requirements transportation agencies can use to monitor and evaluate pavement testing programs. This study focuses on assessment of transverse pavement profilers for three final data requirements: rut depth, cross slope, and edge/curb detection. Prior to the development and presentation of the standard practices and requirements, background information related to collection of transverse measurements and the levels of data which are accessible along the process path is provided.

CHAPTER 2. BACKGROUND

ASSESSMENT OVERVIEW

The objective of this study is to enable transportation agencies to specify, monitor, and evaluate pavement testing programs that include transverse pavement profiles. Specifically, the goal is to match the capabilities of Transverse Pavement Profilers (TPP) with the requirements of various applications. The terms capabilities and requirements imply that clear definitions of precision and accuracy of (highway speed) TPP measurements are needed. However, evaluation of the accuracy and precision of a TPP is complex because there are multiple points in the flow of the measurement process where calibration, certification, and verification may be performed. Figure 1 illustrates the process followed to collect transverse profile measurements from right to left. In generalized terms, for collection of transverse measurements, sensors and systems of sensors work in unison to acquire data which is then processed and analyzed to achieve the final data measurements of interest.

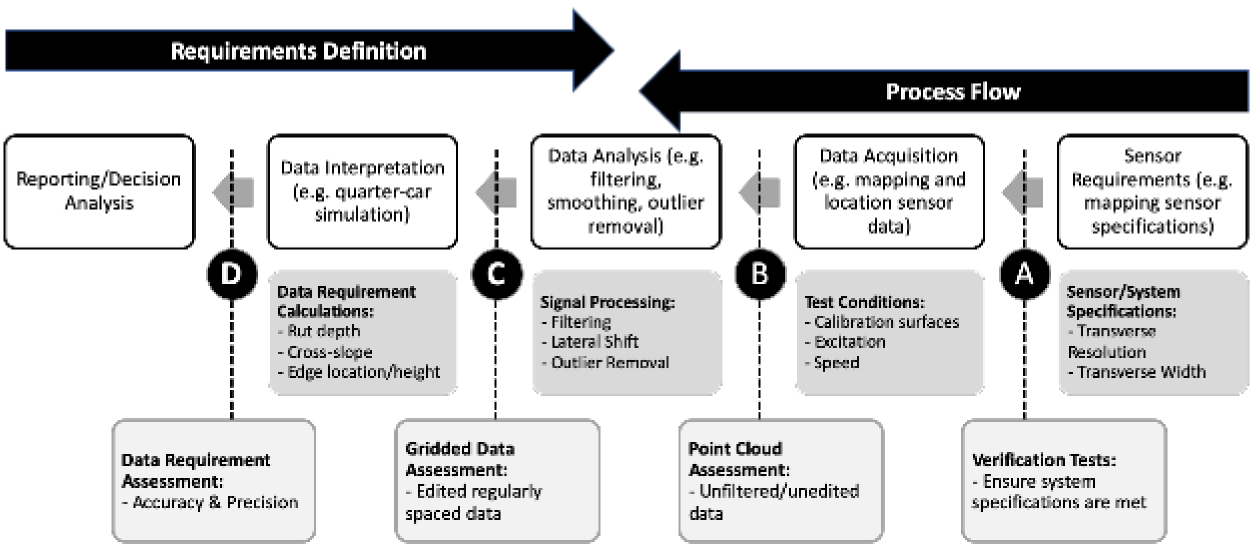

Figure 1. Layers of Assessment for Measurement of Transverse Profiles

In the generalized case for collecting transverse profile measurements there are four primary areas where specific sensors/systems can be assessed and calibration, certification, and verification can be performed. Figure 1 highlights theses four points (A, B, C, and D) and provides the level of assessment which can be performed at each layer. The requirement statements for each layer are defined by the need to achieve the desired accuracy in the final data requirements. Therefore, in figure 1, the requirement definitions must go from left to right to ensure assessments are evaluated on the needs of the final data requirements.

DEFINITION OF DATA LAYERS

In figure 1 the generalized process for acquiring data is presented (from right to left) throughout this process flow, data can be verified and assessed. In this section, four generalized data outputs which can be extracted along the process flow are discussed. These four data outputs are: mapping sensor data, point cloud data, gridded data, and final data requirements.

Mapping Sensor Data

Mapping sensors are any sensors which acquire measurements of the road surface and report the measurements in a local sensor reference frame. Mapping sensors can include, but are not limited to, scanning lasers and cameras. A sensor reference frame is a set of axes fixed in a sensor in which the sensor data are reported. The sensor reference frame is typically defined by the manufacturer of the sensor; see the axes labeled (x_{ms}, y_{ms}, and z_{ms}) in figure 2. Data defined in a sensor reference frame are typically converted (translated and rotated) to a body reference frame (see the axes labeled (x_b, y_b, and z_b) in figure 2) before combining with other sensor measurements that have been similarly converted.

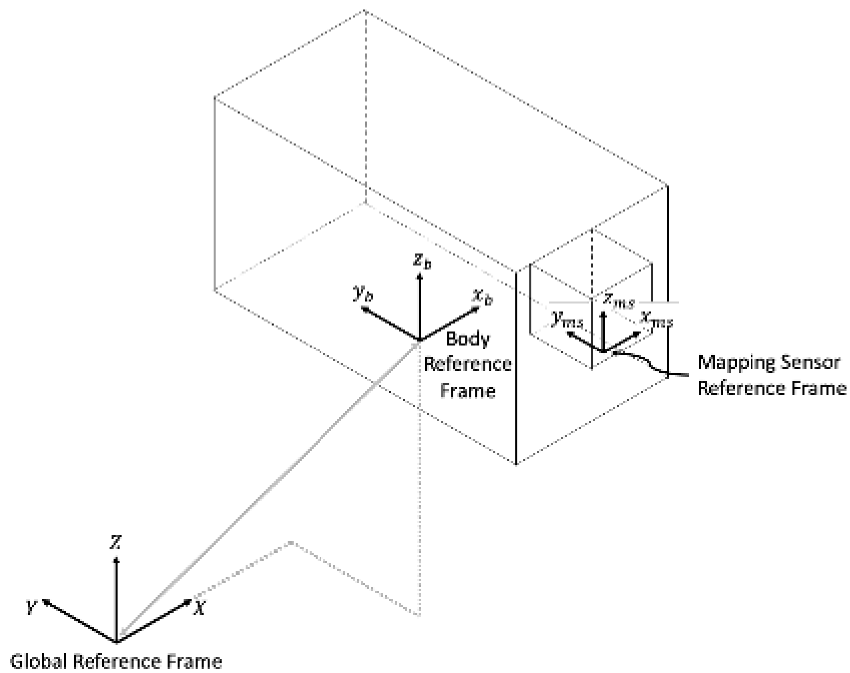

Figure 2. Relationship between global, body, and mapping sensor reference frames.

Mapping sensor data consist of a set of discrete measurements of the road surface. Figure 3 provides a representation of a mapping sensor (gray box) and the set of mapping sensor data measurements of the road surface (black filled circles) within the mapping sensor field of view.

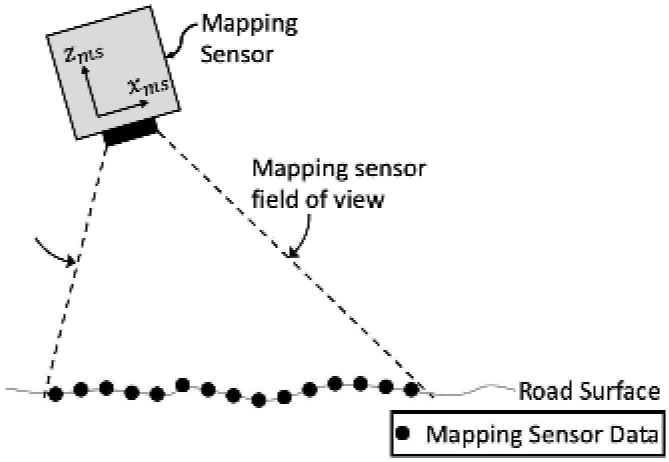

Figure 3. Generalized representation of a mapping sensor and the data collected.

Point Cloud Data

Location sensors are used to acquire the pose (position and orientation) of the sensors, and thereby the vehicle body to which it is attached, in a global reference frame (e.g., units of northing, easting, and elevation). The resulting data from location sensors can be used to form a registration (set of translations and rotations) for the mapping sensor data. Application of the registration to the mapping sensor data results in data defined in a global reference frame instead of a body reference frame. When mapping sensor data is combined with location sensor data the resulting set of measurement points is considered a point cloud. An example point cloud for a road surface is provided in figure 4 by the black spheres.

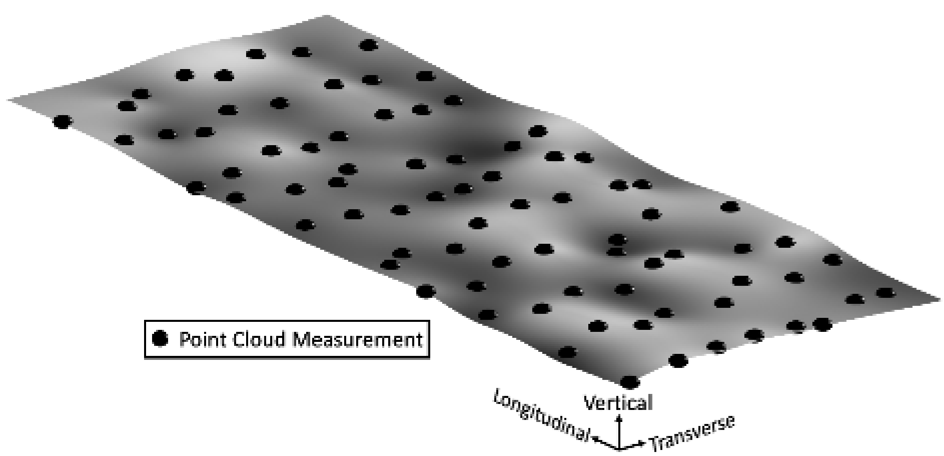

Figure 4. Generalized representation of point cloud measurements from a TPP for a road surface.

Gridded Data

When additional computational post-processing is applied to point cloud data, a gridded data format can be achieved. Gridded data is a set of measurement points which are regularly spaced in the transverse and longitudinal directions. The vertical height of gridded data measurements is achieved through interpolation of point cloud data. Figure 5 provides an example gridded data, where the black spheres are individual gridded data measurements corresponding to the gray scale surface.

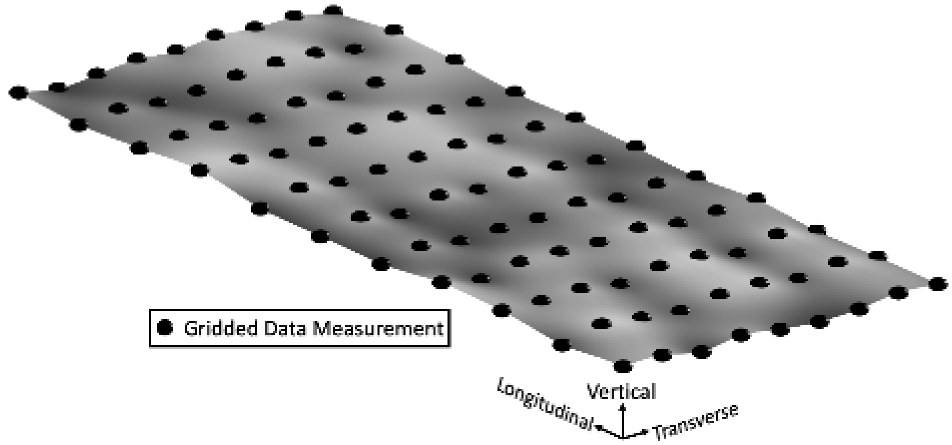

Figure 5. Generalized representation of gridded data measurements from a TPP for a road surface.

For computational efficiency, gridded data can be represented as a matrix where each row is a transverse profile and each column is a longitudinal profile.

Final Data Requirements

Several final data requirements were assessed and presented to the study oversight panel for investigation in this study. The oversight panel selected to pursue three final data requirements: rut depth, cross slope, and edge/curb detection (edge/curb vertical magnitude and edge/curb transverse location). These three final data requirements were selected based on the current needs and data reported by transportation agencies.

GENERAL REQUIREMENT STATEMENT DEFINITION

In this study, TPP capabilities are captured in a Capability Statement (CS) and the application requirements are captured in a Requirements Statement (RS), each containing statements of accuracy and precision in the same format. Some references cite accuracy and precision in terms of standard deviation. This is sometimes done implicitly when 65% and 95% bounds are used as is the case for rut depth requirements in the UK.(1) The issue in using the standard deviation as a measure of the dispersion (variability) in the data is that there is an assumption of symmetry (being 1 standard deviation above the mean is equally likely as being 1 standard deviation below the mean) and an assumption that the estimate of standard deviation is sensitive to extreme values (outliers) in the dataset. Alternatively, the use of the Interquartile Range (IQR) is not affected by extreme values; it is a resistant measure of variability. To capture the variability in the data a larger range is selected: 90% confidence interval. In addition, the median value of the measurement error can be used to establish any bias present.

Using this criteria all accuracy and precision requirements/capabilities can be reported in the form of bias and confidence intervals, where the 50% confidence interval (IQR) and the 90% confidence interval are used. For comparison to referenced documents where precision is given in terms of standard deviation, the 50% and 90% confidence intervals can be established using the assumptions implicit in the use of standard deviations. This means the requirements for the 50% confidence interval are defined as ±0.675 times the standard deviation and the 90% confidence intervals are defined as ±1.65 times the standard deviation.

For this study, the accuracy and precision are identified using non-parametric descriptive statistics. There is no assumption about the underlying distribution of the data (including the symmetry of the errors). Also, the percentiles chosen for evaluation (5^{th}, 25^{th}, 75^{th}, and 95^{th}) are calculated simply from the recorded data. For example, if only 10 data points are sampled and sorted from smallest value to largest, the 1^{st}, 3^{rd}, 8^{th} and 10^{th} values correspond to the 5^{th}, 25^{th}, 75^{th}, and 95^{th} percentiles, from which the 50% and 90% confidence intervals are established.

CHAPTER 3. DEVELOPMENT OF REQUIREMENT STATEMENTS

OVERVIEW

In this chapter the requirement statements for all TPP measurement assessments are presented along with supporting information resulting from analysis of current state agencies' requirements and investigation of established requirements from other (international) agencies. To ensure relevant requirements of the measurements are made along the process flow, the necessary requirements of the final data must first be established; then requirements for measurements assessed along the process flow can be extrapolated from the final data requirements. This ensures that all requirements are established based on the accuracy and precision needs of the final measurements.

This chapter is organized as follows. First, the requirement statements for rut depth, cross slope, and edge/curb detection measurements are developed and summarized in tables. Then, system and sensor requirements are developed, for assessment of prior data layers in the TPP process, to ensure that final data requirements are satisfied.

ASSESSMENT OF RUT DEPTH

State agency requirements for both Network and Project level applications were assessed, and it was found that the differences between Network and Project level accuracy and precision was negligible thus no separate callouts are defined. When investigating the requirements, it was found that the median value was ±1.5 mm, which is consistent with the United Kingdom (UK) recommendations. More specifically, in the UK, a TPP is certified if 65% of the measurements are within ±1.5 mm and 95% are within ±3.0 mm of the true value.[1] When the two percentiles from the UK recommendations are converted to the 50% and 90% confidence intervals, the resulting requirements are equivalent to those provided in table 1. Table 1 provides the requirement statement for the assessment of rut depth in transverse profiles.

Table 1. Requirement statement for rut depth measurements (in millimeters).

Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
90% (5%)	50% (25%)		50% (75%)	90% (95%)
-2.5	-1.0	N/A	1.0	2.5

ASSESSMENT OF CROSS SLOPE

Through analysis of available state agency cross slope requirements it was found that at the Network level an average accuracy of 0.45% was required and at the Project level an average accuracy of 0.26% was required. However, the median accuracy at the Network level was 0.25% and at the Project level a median accuracy of 0.23% was requested. Due to potential outliers in the available accuracy information the median accuracy value was used as guidance for establishing the confidence intervals for the cross slope accuracy and precision. Since the median cross slope error was nearly identical between the Network and Project levels no differential between Network and Project levels is provided in the cross slope requirements. Table 2 provides the resulting cross slope requirement statement containing confidence intervals supported by the median state agency requested cross slope accuracy along with the minimum/maximum requested accuracy.

Table 2. Requirement statement for cross slope measurements (in percent).

Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
90% (5%)	50% (25%)		50% (75%)	90% (95%)
-0.40	-0.15	N/A	0.15	0.40

ASSESSMENT OF EDGE/CURB DETECTION

In the case of edge drop-off, multiple safety studies have been conducted to identify the limit where an edge drop off becomes problematic from a safety perspective. The first study was conducted by Iowa State University, supported by the AAA Foundation for Traffic Safety in Washington, D.C., in cooperation with FHWA, that was published in 2006.(2) The report details research to quantify the contribution of pavement edge drop-off to vehicle crash frequency and severity. The work concludes that the threshold on edge drop off before maintenance is performed is about 50 mm (2.0 in) for most states in the U.S.A.(2) The second study was conducted by the American Association of State Highway and Transportation Officials suggests that no vertical differential greater than about 50 mm (2 in) should occur between lanes.(3) Third, the United States Department of Transportation (DOT) suggests that drop-off with a vertical differential greater than about 75 mm (3 in) or more is problematic from a safety perspective.(4) The distinction between a threshold for maintenance and a suggested threshold for vertical lane differential versus a potential safety condition is about 25 mm. Clearly the accuracy and precision must be defined so that increments within this 25 mm can be distinguished. Table 3 contains the requirement statement for edge/curb transverse location error, defined as a confidence intervals. The requirement statement is defined such that 50% of the error must be less than 25.0 mm and 90% of the measurement error must be less than 50 mm.

The severity of edge drop-offs are typically reported as severity levels and these severity levels are often defined with resolutions of about 3 mm. For example, California defines low severity for an edge drop-off less than 9 mm. Typically, manual measurements allow for 3 mm resolution and the difference of 25 mm represents a significant change from suggested maintenance (or maximum transition between lanes) and a potential safety concern, thus it is recommended that 50% of the measurement error be less than 1.0 mm and 90% of the measurement error be less than 2.5 mm (same as the rut depth requirements), as shown in the bottom row of table 3.

Table 3. Requirement statement for edge/curb detection measurements (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Edge/curb transverse location error	-50	-25	N/A	25	50
Edge/curb vertical magnitude error	-2.5	-1.0	N/A	1.0	2.5

ASSESSMENT OF SENSOR/SYSTEM SPECIFICATIONS

In figures 3, 4, and 5 various forms of TPP measures were presented based on process flow layer being investigated. A range of measurement specifications can be established depending on which TPP data form is analyzed. Common sensor and system specifications are provided below. These specifications include: total transverse width, measurement spacing, and measurement error.

Total Transverse Width

For evaluation of rut depth, AASHTO R88 standard requires that a transverse profile of 4.0 m is collected.[5] In addition, UK quality assurance standards state that transverse profiles between a transverse length of 3.2 m and 4.0 m is required for collection of rut depth. Thus, a lower 5th percentile bounds of 4.0 m is selected for evaluation of rut depth data. For evaluation of cross slope, the collected transverse width does not need to be as wide as that for the transverse profile width for rut depth. Therefore, a lower 5th percentile bounds of 3.8 m was selected and supported by vendor results from Rodeos 1 and 2. For evaluation of edge/curb detection a collected transverse width should be wider than that required for rut depth because of the features of interest are at the transverse extrema of the road surface. AASHTO R88 standard requires a width of 4.25 m for interpretation of edge drop-off. Thus, a lower 5th percentile bounds of 4.25 m is selected for evaluation of edge/curb detection.

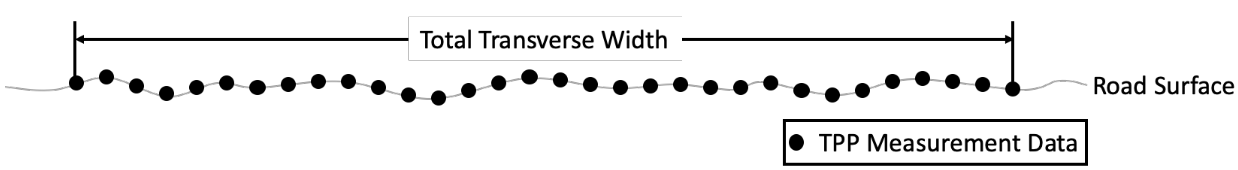

Figure 6. Total transverse width dimension for an individual transverse measurement profile.

Table 4. Requirement statement for total transverse width (in millimeters).

	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
Final Data Requirement of Interest	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Rut depth	4000	N/A	N/A	N/A	N/A
Cross slope	3800	N/A	N/A	N/A	N/A
Edge/curb detection	4250	N/A	N/A	N/A	N/A

Measurement Spacing: Transverse, Longitudinal, and Vertical

Transverse profiles are established using discrete measurements of the road surface, thus there is a given spacing between reported measurements. Depending on the TPP data being analyzed, measurement spacing in at least two out of three directions (transverse, longitudinal, and vertical) can be analyzed. Figure 7 provides an illustration of transverse and longitudinal measurement spacing for a representative point cloud data measurement set. It should be noted that measurement spacing is not always simply the difference between consecutive measurement points, for a more refined method of evaluating measurement spacing see Chapter 4. Vertical measurement spacing is illustrated in figure 8, where the measurement spacing is defined by the vertical deviation of each measurement with respect to a plane fit through the measurement data.

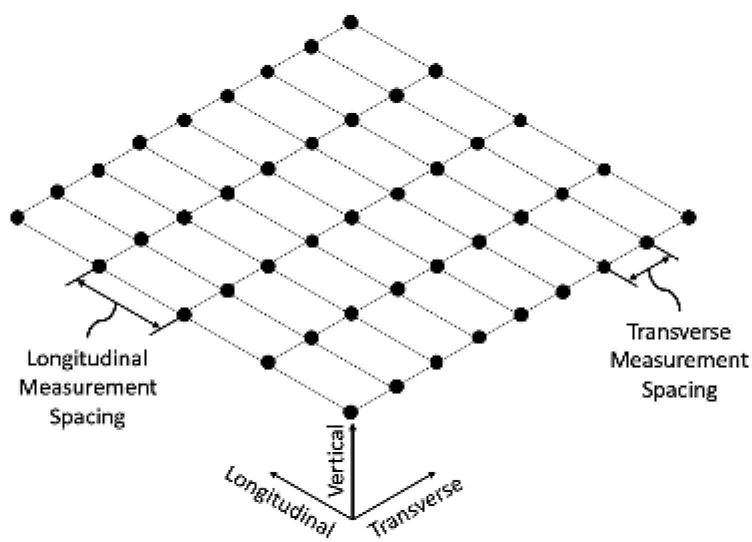

Figure 7. Illustration of transverse and longitudinal measurement spacing for a set of TPP measurements.

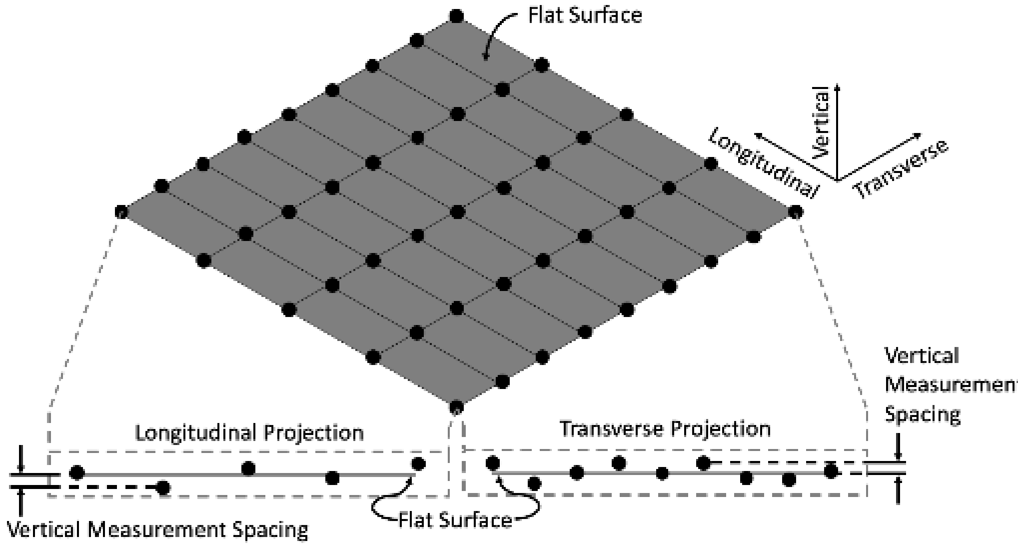

Figure 8. Illustration of vertical measurement spacing for a set of TPP measurements which lie on a flat surface.

Review of standards from the US and international agencies revealed the following. Section 3.4.4 of the 2009 UK Standards recommends applying a moving average filter to a transverse profile and then resampling using a cubic spline with a sampling interval of 25 mm.(6) Section 6.5.2 of Austroads Standard AGAM-T009-16 defines a line laser as a device capable of measuring more than 1000 points per profile and a profile must contain a minimum width of 3 m.(7) This results in a transverse spacing of 3 mm. Lastly, in Section 5.1 of AASHTO R 88, a transverse measurement spacing of 10 mm is specified for collection of rut depth.(5)

For assessment of rut depth, several studies have been conducted on the accuracy of TPP systems and the spacing needed to produce accurate rut depth values. A study conducted by Simpson et al. recommends that a gauge block width between 30 mm and 40 mm be used for manual measurements of rut depth.(8) If a transverse measurement spacing of 10mm is assumed, then 3 to 4 neighboring measurements can be used to estimate the rut depth using a virtual gauge block; allowing for the rut depth to be established by more than one measurement. For TPP systems using multiple point based lasers, one universal conclusion is that neither three-point nor five-point rut bars provide a reliable estimate of rut depth.(9,10,11,12,13)

Some studies have attempted to quantify the underestimation of rut depth, evaluated as measurement error (bias and variation) based on the required transverse resolution. For example, in one study five optical TPP's using line lasers were evaluated and it was found that they underestimate the rut depth with a bias of 1.5 mm (1/16 in) and the error increased with increasing rut depth. When discrete spacing of about 175 mm between sensors is used, the error bias increased by 1.5 mm and if the spacing is about 110 mm the additional error bias drops to 0.8 mm.(14) Similar results show that the improvement in measurement bias is minimal when the transverse spacing is less than about 175 mm and significantly affect the measurement bias when the spacing is greater than about 300 mm. When the transverse spacing is 70 mm the rut depth is underestimated by about 1 mm and for typical devices with a transverse spacing between 140 to 350 mm, the error bias is about 2 to 4 mm.(15) A 3D line laser system operated in the lab has an error bias between 0 and 0.7 mm, while in the field it varies between 0.8 and 2.1 mm.[14] The variation in error is even more dramatic with the standard error in the underestimation of rut depth varying from 1 to 4 mm.[1]

Based on the findings, an upper 95th percentile bounds of 10 mm is selected for evaluation of transverse measurement spacing for rut depth. When measuring road surfaces for cross slope the transverse measurement spacing need not be as fine as for rut depth, thus a less rigorous 95th percentile bounds of 25 mm was selected. This requirement is supported by results from the first and second equipment rodeos. For edge/curb detection, to achieve a transverse position accuracy of 25 mm it is desirable to have a finer spacing between measurements. Thus, the transverse measurement spacing should be equivalent to rut depth; an upper 95th percentile bounds of 10 mm is selected.

Austroads AGAM-T010-16 and Autoroads AGAM-T009-16 are linked together and recommend that laser profilometers should be capable of continuously capturing the transverse profiles at known equal intervals, not greater than 0.25 m (0.8 ft).[7,16] In AASHTO R 88, a longitudinal measurement spacing of 3.0 m is recommended for network level data collection and 0.5 m is recommended for project level.[5] Thus, a longitudinal measurement spacing upper 95th percentile requirement for network level data is 3.0 m and a longitudinal measurement spacing upper 95th percentile requirement for project level data is 0.5 m. Cross slope and edge/curb detection have the same longitudinal measurement spacing requirements as rut depth for network and project levels.

In Section 5.2 of AASHTO R 88, a vertical measurement resolution (spacing) is specified to be less than or equal to 1 mm (0.04 in).[5] However, in Section 3.9.2 of the 2012 UK Standards a resolution of 0.1 mm (0.004 in) is specified for rut depth and hence the vertical measurement spacing for the transverse profile should be less than or equal to 0.1 mm (0.004 in) as specified in section 3.8.2 of the standard.[1] Lastly, Section 8 of Austroads AGAM-T009-16 specifies that rut depth should be reported to the nearest 0.1 mm.[7] Thus, a vertical measurement spacing upper 95th percentile requirement is 0.1 mm for rut depth and edge/curb detection. For cross slope, a vertical measurement spacing upper 95th percentile requirement is 1.0 mm since the error in cross slope is not as affected by error in the vertical spacing.

Table 5. Requirement statement for measurement spacing (in millimeters).

Measurement Spacing Direction	**Final Data Requirement of Interest**	**Lower Bounds (percentiles)**		**Bias**	**Upper Bounds (percentiles)**	
		90% (5%)	50% (25%)		50% (75%)	90% (95%)
Transverse Measurement Spacing	Rut depth	N/A	N/A	N/A	N/A	10
	Cross slope	N/A	N/A	N/A	N/A	25
	Edge/curb detection	N/A	N/A	N/A	N/A	10

Longitudinal Measurement Spacing	Network	N/A	N/A	N/A	N/A	3000
	Project	N/A	N/A	N/A	N/A	500
Vertical Measurement Spacing	Rut depth	N/A	N/A	N/A	N/A	0.1
	Cross slope	N/A	N/A	N/A	N/A	1.0
	Edge/curb detection	N/A	N/A	N/A	N/A	0.1

Measurement Error: Transverse and Vertical

When an object containing certified dimensions is measured by a TPP, the accuracy and precision of the corresponding measurements can be evaluated based on the error between the certified dimension and the resulting dimension from the TPP data. Two directions of interest for evaluation of error in transverse profile measures are: transverse and vertical directions. Both of these errors can be evaluated simultaneously when both width and height of an object are certified. Identification of transverse measurement error for an example TPP measurement data set (black filled circles) is provided in figure 9. Using the same example data set, identification of vertical measurement error is provided in figure 10.

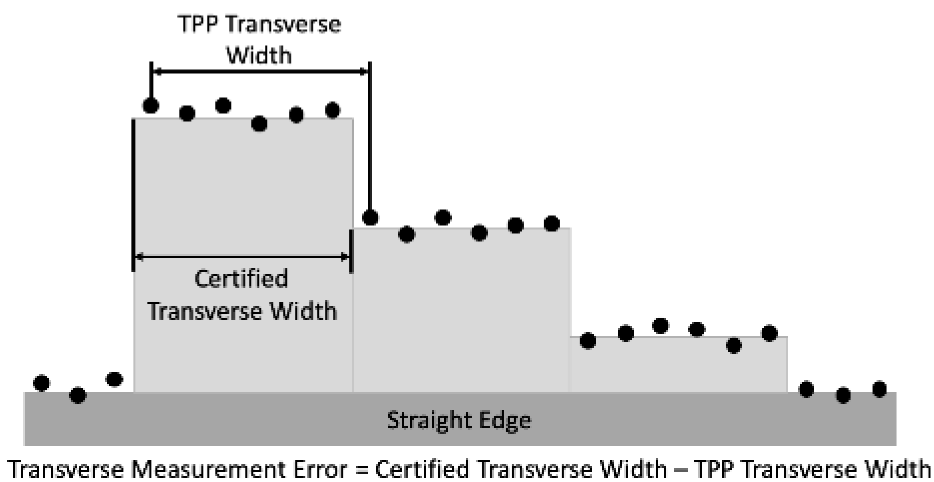

Figure 9. Example transverse measurement error for TPP measurements of a certified gauge block resting on a straight edge.

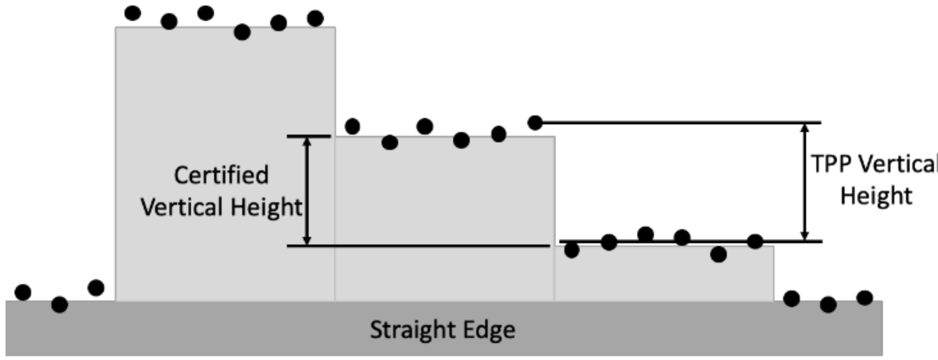

Figure 10. Example vertical measurement error for TPP measurements of a certified gauge block resting on a straight edge.

An estimate on expected accuracy can be defined using the measurement spacing; the lowest expected error is equivalent to half of the measurement spacing. For rut depth and edge/curb detection a transverse measurement spacing of 10 mm is required, thus the lowest expected error is 5 mm. For cross slope a transverse measurement spacing of 25 mm is required, thus the lowest expected error is 12.5 mm. The lowest expected transverse measurement error based on transverse measurement spacing can be used to define the bounds for the 50% confidence interval. For evaluation of rut depth and edge/curb detection the 50% confidence interval is selected to be ±5 mm, and for evaluation of cross slope the 50% confidence interval is selected to be ±12.5 mm, see table 6.

Assuming the errors follow a normal distribution, the requirements for the 90% confidence interval is extrapolated to be ±12.5 mm, for rut depth and edge/curb detection. Therefore, 50% of the transverse errors must be ±5 mm or smaller and 90% of the errors must be ±12.5mm or smaller, for evaluation of rut depth or edge/curb detection. Using the same approach for cross slope, the 90% confidence interval is extrapolated to be ±30 mm. Meaning, 50% of the transverse errors must be ±12.5 mm or smaller and 90% of the errors must be ±30 mm or smaller for evaluation of cross slope.

Vertical measurement error for rut depth and edge/curb detection is defined by the requirement for rut depth. Thus, the vertical measurement error requirements for rut depth and edge/curb detection presented in table 6 are equivalent to the rut depth error requirements table 1. Cross slope is less dependent than rut depth on vertical error of the transverse measurements. Accordingly a relaxed set of requirements which is supported by the results from the two equipment rodeos conducted during the study are presented in table 6 for vertical measurement error when evaluating cross slope.

Table 6. Requirement statement for measurement error (in millimeters).

Measurement Error Direction	Final Data Requirement of Interest	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
		90% (5%)	50% (25%)		50% (75%)	90% (95%)

Transverse Measurement Error	Rut depth	-12.5	-5.0	N/A	5.0	12.5
	Cross slope	-30	-12.5	N/A	12.5	30
	Edge/curb detection	-12.5	-5.0	N/A	5.0	12.5
Vertical Measurement Error	Rut depth	-1.5	-1.0	N/A	1.0	1.5
	Cross slope	-2.0	-1.0	N/A	1.0	2.0
	Edge/curb detection	-1.5	-1.0	N/A	1.0	1.5

Straightness Error

When an object containing a certified straightness is measured by a TPP, then the reported straightness of the object can be evaluated. The straightness of the certified object in the reported TPP measurements can be identified by fitting a line to the data and identifying the deviation of the measurements from the linear trend. Figure 11 provides an example TPP measurement data set corresponding to the top surface of a certified straight edge. The deviations from the linear fit to the data points in figure 11 provide a measure of the straightness error for the sensor(s) used to measure the straight edge.

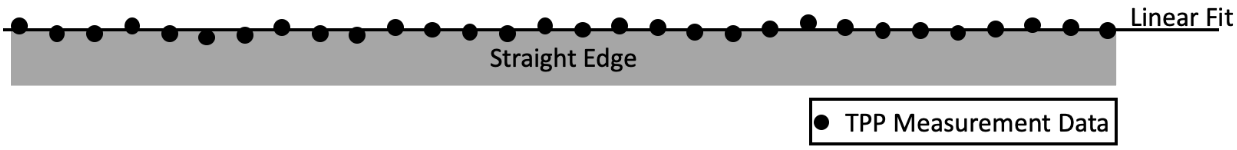

Figure 11. Linear fit to measurement points for determining straightness.

Straightness errors for evaluation of rut depth are equivalent to the requirements for rut depth presented in table 1. This equivalence is due to all measurements being associated with a certified flat surface, meaning no rutting is present in the certified surface. Therefore, any deviations from the linear fit to the TPP data can be considered representative of vertical measurement errors in rut depth. Since the requirement for vertical measurement errors in edge/curb detection is equivalent to the rut depth requirement, the straightness errors for edge/curb detection are equivalent to those for rut depth. The straightness error requirements for rut depth and edge/curb detection are summarized in table 7.

To establish the straightness requirements for cross slope a method of relating cross slope error (in percentage) to straightness error (in distance) is needed. To provide bounds for this relationship a worst case condition for straightness errors when estimating cross slope can be considered; all positive straightness errors are on one half of the data set while all equal magnitude negative straightness errors are located on the other half of the data set. Figure 12 provides an illustration of the worst case condition for straightness errors along with the relationship between the cross slope error and the straightness error. Using the relationship in figure 12 along with the cross slope requirement statement in table 2 a set of confidence intervals for straightness error when measuring cross slope can be established. A straightness error of ± 8 mm is needed to achieve a cross slope error of ±0.4% and a straightness error of ±3 mm is needed to achieve a cross slope error of ±0.15% when an expected total transverse width of 4 m is used. The straightness error requirements for cross slope are summarized in table 7.

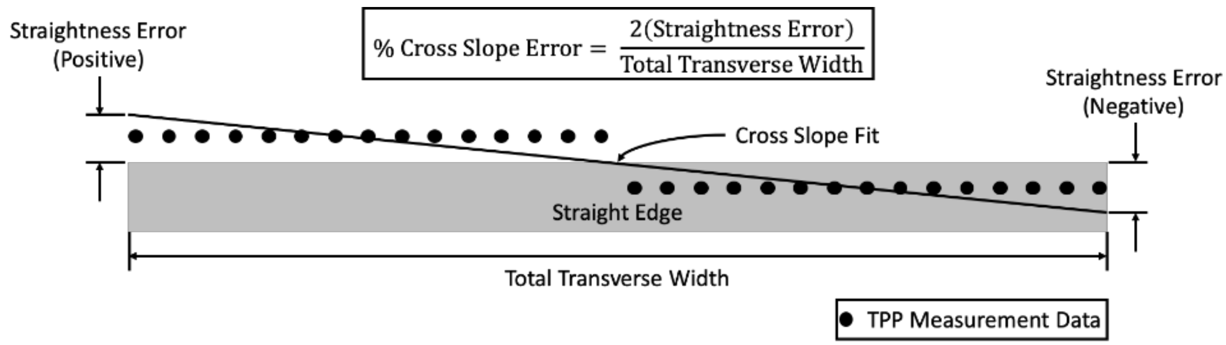

Figure 12. Worst case straightness error stack-up for determining cross slope error.

Table 7. Requirement statement for straightness error (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
Final Data Requirement of Interest	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Rut depth	-2.5	-1.0	N/A	1.0	2.5
Cross slope	-8.0	-3.0	N/A	3.0	8.0
Edge/curb detection	-2.5	-1.0	N/A	1.0	2.5

Body Motion Cancelation Error

When a TPP is collecting road surface measurements the roughness of the road surface results in the movement of the vehicle body. It is important that a TPP system cancels out the motion of the body or the resulting measurements will not correctly represent the road surface. To induce repeatable movement of the TPP vehicle body, a set of excitation boards designed to induce the primary ride and roll characteristics shall be placed on the road surface. When a certified flat surface is measured by a TPP while in operation, the deviation from a plane fit to the measurements of the flat surface shall provide an estimate of the error associated with cancelation of the vehicle body motion. Figure 13 shows nine example TPP measurements and the normal deviation (illustrated by the arrow) from the flat surface.

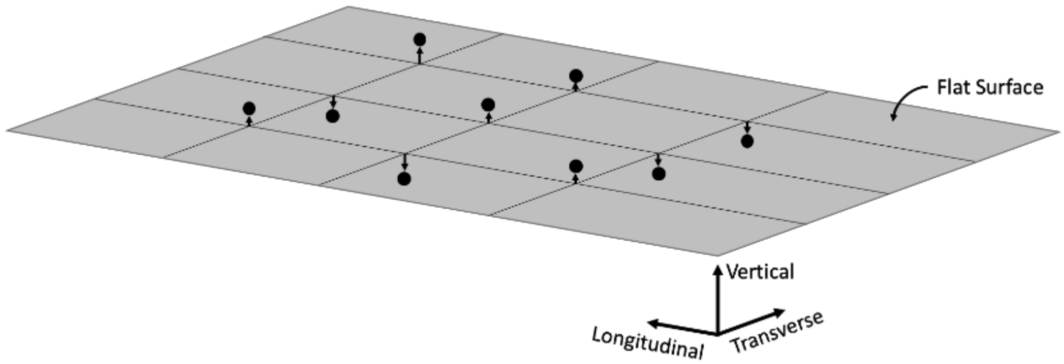

Figure 13. Deviation of vertical measurement heights from a flat surface.

The requirements for rut depth, presented in table 1, state that 90% of the rut depth measurement errors shall be within ±2.5 mm during typical highway operation. Since the TPP is being excited at the primary ride and roll frequencies a more lenient requirement on body motion error is used, where 50% of the vertical error is between ±2.5 mm. Using a normal distribution fit, the 90% confidence interval was selected to be ±4.0 mm. For evaluation of edge/curb detection, the final data requirements for error in vertical magnitude are equivalent to the errors for rut depth measurement. Therefore, the same body motion error requirements as rut depth are used. Body motion error requirements for rut depth and edge/curb detection are summarized in table 8 in the form of confidence intervals.

Cross slope is reported as a percentage instead of a vertical measurement; to establish the required body motion error for cross slope a method of relating cross slope error (in percentage) to vertical error (in distance) is needed. A similar approach to that used for evaluating cross slope straightness error will be used to establish the requirements for body motion error for evaluation of cross slope. Since a flat plate is used to assess the body motion error, the same approach illustrated in figure 12 shall be used. In table 2 the requirements for cross slope are presented. Using these requirements with the worst case vertical measurement error condition results in 90% of the body motion error being between ±8.0 mm and 50% of the body motion error being between ±3.0 mm. Body motion error requirements for cross slope are summarized in table 8 in the form of confidence intervals.

Table 8. Requirement statement for body motion error (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
Final Data Requirement of Interest	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Rut depth	-4.0	-2.5	N/A	2.5	4.0
Cross slope	-8.0	-3.0	N/A	3.0	8.0
Edge/curb detection	-4.0	-2.5	N/A	2.5	4.0

Effective Transverse Width (Transverse Wander)

Positioning of measured data in the transverse direction is a critical issue to address when computing rut depth.[15] Actual errors in transverse positioning could be as much as 570 mm.[11] In a study conducted by Hui et al., the transverse positioning of the profile was varied between 100 mm to 500 mm on both the left and right side of true location and its impact on the quality of rut depth was analyzed.[17] The rut depth computed from the unshifted transverse profile was used as a baseline for comparison. The effect of wander was investigated for rutting of different severity levels and for different rut profile shapes. Figure 14 shows the error in rut depth relative to the magnitude of rut depth as a function of the simulated transverse positioning. The results show relative error increases with the magnitude of transverse positioning offset and it can be as high as 29% for a 500 mm offset.

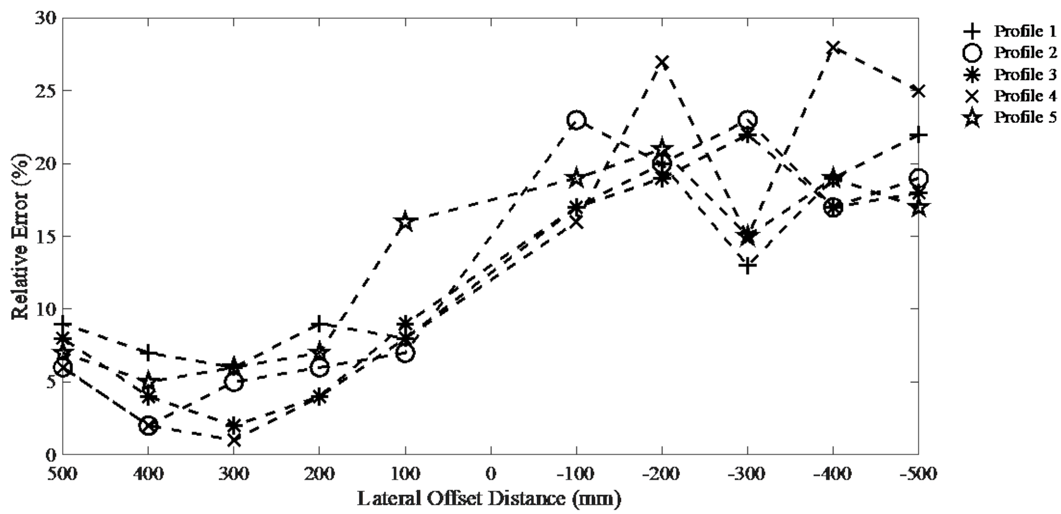

Figure 14. Relative error as a function of lateral offset for a non-symmetrical rut shape.[17]

From this study conducted by Hui et al. it can be seen that the relative error in rut depth can be as high 23% when the transverse localization error is ±100 mm; this relative error corresponds to an absolute error of 4.0 mm.[17] A second study which specifically investigated impact of transverse localization on rut depth measurement overestimation also used ±100 mm as the least value.[18] Thus, the data collected by Hui et al. demonstrates in order to bound rut depth measurement error to less than 1 mm that the lateral offset must be (much) less than ±100mm, but a specific value is not clear. In this study, the effective transverse width is assessed during dynamic operations. The effective transverse width uses reference objects to identify the transverse wander of the TPP and uses the wander to establish the effective transverse width the TPP is accurately capable of measuring.

Navigation Drift Error

During typical operation, a TPP is traveling along a road collecting transverse profile measurements. The location sensors are used to determine the global pose (location and orientation) of the TPP during the measurement process. It is important to know that errors in the global pose are maintained within set bounds to ensure the accuracy of the measurements are maintained. Errors in the global pose can be identified by collecting multiple measurements of a stationary object. When an object with a known global location is repeatedly measured by a TPP, then the error in the TPP reported global location of the object can be identified using the known global location of the object. To illustrate this idea figures 15 and 16 are provided. In figure 15, three example reported locations in the northing and easting direction of a stationary object are illustrated by the black filled circles and the known location of the stationary object is illustrated by the dark gray circle. Arrows are used in figure 15 to highlight the error for each location reported by the TPP. In figure 16, easting and elevation measures are provided to illustrate the elevation repeatability of the three TPP measurements.

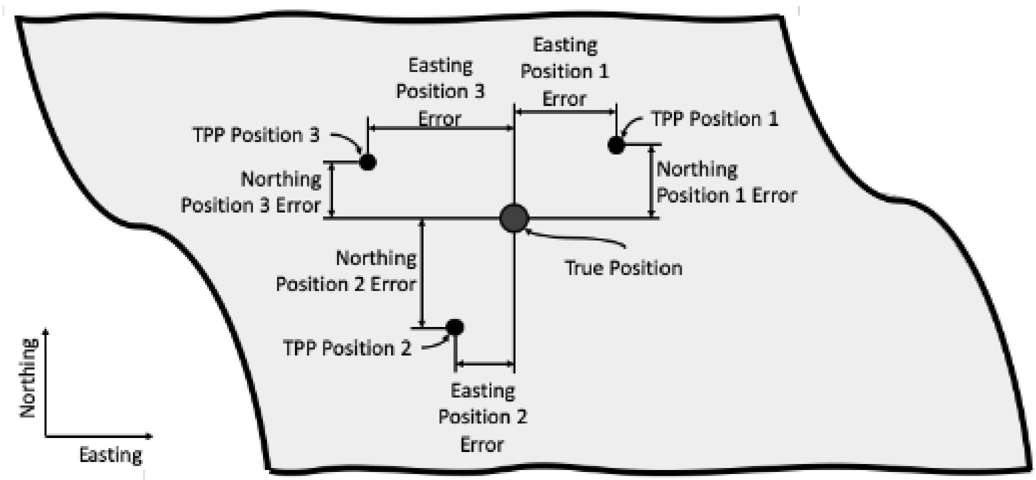

Figure 15. Northing and easting position error for three example TPP reported locations of a stationary object (represented by the true position).

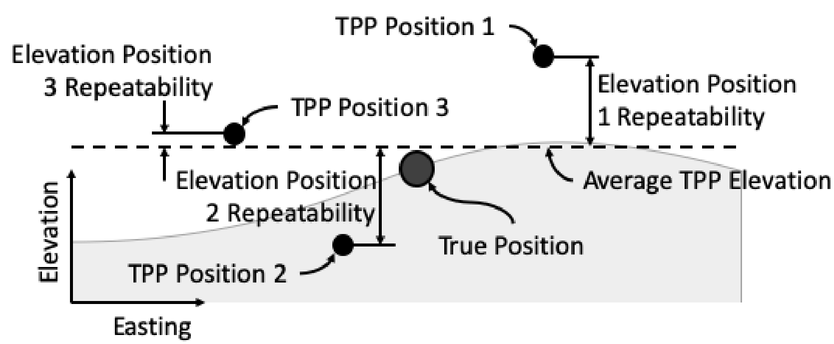

Figure 16. Elevation position repeatability for three example TPP reported locations of a stationary object (represented by the true position).

Calculations to determine the final data requirements (rut depth, cross slope, and edge/curb detection) are not dependent on the global position (northing, easting, and elevation) of the transverse measurement profile. Instead, final data requirements are dependent on the local measurements collected (e.g. relative vertical height change, transverse distance from lane center, etc.). However, for referencing and comparing final data requirements between road sections or between collection intervals it is necessary to know the location along the Earth's surface of the transverse profile measurements. The location along the Earth's surface can be defined in northing and easting terms only, no elevation is required. Using this simplification, only repeatability needs to be assessed for the global elevation, while accuracy and precision assessment are necessary for northing and easting position.

To define the requirement for northing and easting position errors, current state of the practice location sensors were considered. Commercially available GPS (Global Positioning System) receivers are quoted with a position error in the northing and easting directions of ±500 mm CEP (Circular Error Probability)[1] when used in a differential GPS configuration. Since CEP is a measure of the 50% confidence interval global position errors and is specified as a radius, the 50% confidence interval for northing and easting position errors are equivalent to the CEP. The 90% confidence interval northing/easting position errors (±1250 mm) are extrapolated from the 50% confidence interval assuming the errors follow a normal distribution. To define the elevation repeatability, the results from the vendors who attended the second equipment rodeo were used to define the 50% and 90% confidence intervals presented in table 9.

Table 9. Requirement statement for navigation drift error (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Northing position error	-1250	-500	N/A	500	1250
Easting position error	-1250	-500	N/A	500	1250
Vertical position repeatability	-125	-50	N/A	50	125

Probabilistic Comparison of TPP Measurements to Ground Reference Data

When no certified object is present in a set of TPP measurements, then reference measurements are needed to evaluate the accuracy and precision of the TPP measurements. This condition occurs when the TPP measurements being assessed are measurements of the road surface, rather than certified objects. Ground reference data for the same segment of the road surface can be established using higher accuracy and resolution equipment, but it is unlikely that the exact same piece of aggregate in the road surface is measured between the TPP data and the ground reference data. Therefore, a probabilistic evaluation of the TPP measurements must be performed to assess the accuracy and precision of the road surface measurements.

To perform the probabilistic evaluation of the TPP data, a set of randomly selected measurements which lie in the ground reference test section shall be established. For each randomly selected measurement, a reference distribution shall be established using the ground reference data. The reference distribution shall be defined by the vertical heights of the ground reference data which lies in a neighborhood of the TPP measurement. The neighborhood is

[1] CEP (Circular Error Probability) is a measure of the precision of a GPS receiver in the horizontal plane. The magnitude of the CEP quantity is equivalent to the radius of a circle centered at the mean horizontal position includes 50% of the horizontal measurements collected by the receiver.

defined using a rectangle centered about the TPP measurement in the horizontal plane (transverse and longitudinal directions) with edge lengths defined to encompass the range of potential errors in the TPP transverse and longitudinal locations. Figure 17 highlights a single TPP measurement along with a neighborhood around the measurement (black box). The magnified view in figure 17 highlights the discrete ground reference measurements which shall define the reference distribution along with the single TPP measurement. The mean and standard deviation of the vertical heights of the ground reference measurements in the neighborhood of the TPP measurement shall be used to characterize the ground reference distribution. Using the mean and standard deviation of the reference distribution, the number of standard deviations the TPP measurement is away from the mean value of the ground reference distribution shall provide a measure of the accuracy and precision of the TPP measurement. Figure 18 illustrates the relationship between the reference measurements, the reference distribution, and the number of standard deviations the TPP measurement is from the mean ground reference vertical height.

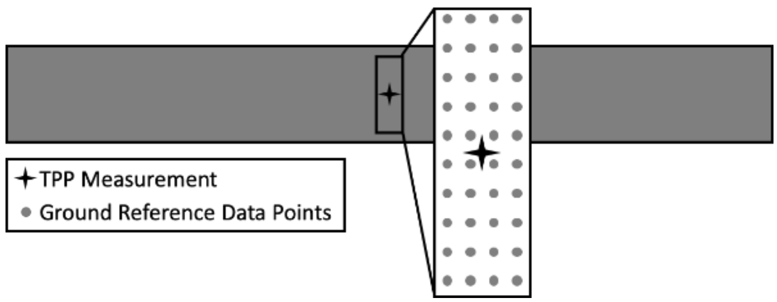

Figure 17. Identification of ground reference data points in the neighborhood of an individual TPP measurement of the road surface.

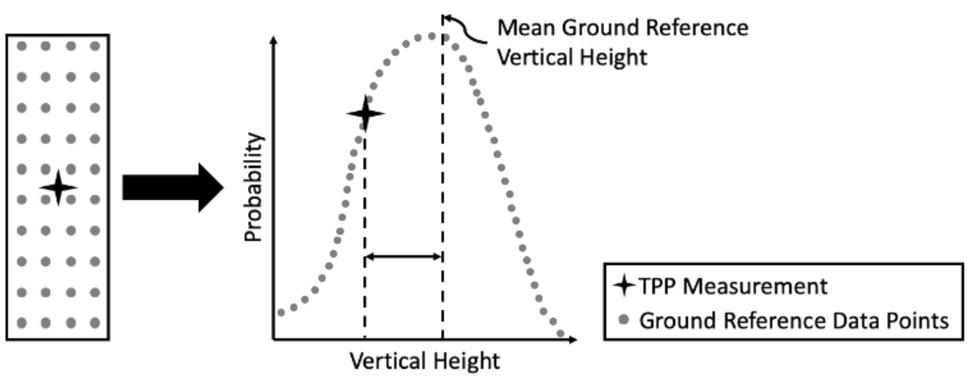

Figure 18. Evaluation of TPP measurement to ground reference distribution.

Depending on the layer of assessment performed, two TPP data types can be assessed with respect to ground reference data: point cloud and gridded data. Table 10 provides the requirement statements for each of these data types. The requirements for gridded data are established utilizing the number of standard deviations associated with the 50% and 90% confidence intervals of a normal distribution. Since point cloud data can contain outliers, less rigorous requirements supported by results from the second rodeo were selected.

Table 10. Requirement statement for evaluation of TPP measurements using ground reference data (in standard deviations).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Point Cloud Vertical Error	-2.5	-1.0	N/A	1.0	2.5
Gridded Data Vertical Error	-1.7	-0.7	N/A	0.7	1.7

CHAPTER 4. DEVELOPMENT OF STANDARD PRACTICES FOR ASSESSMENT OF TRANSVERSE PROFILE MEASUREMENTS

OVERVIEW

In order to fully assess the transverse profile measurements throughout the process flow, five proposed standard practices have been developed. The standard practices are targeted at assessing the measurements in the following areas:

- Static performance
- Body motion cancelation
- Navigation drift mitigation
- Highway performance
- Ground reference data

For each area a standard practice has been developed. In addition, a sixth standard practice was developed to provide definitions for terms used throughout the five proposed standard practices, see Appendix A. The complete standard practice for assessment of: static performance is provided in Appendix B, body motion cancelation is provided in Appendix C, navigation drift mitigation is provided in Appendix D, highway performance is provided in Appendix E, and ground reference data is in Appendix F. These developed standard practices include detailed procedures, step-by-step instructions for performing the data reduction, requirement statements for certification, and processes for performing verification during typical operation.

The remainder of this chapter provides an introduction and overview for first four TPP specific proposed standard practice, and Chapter 5 is centered around the fifth ground reference proposed standard practice. For each standard practice the objectives and scope of the practice are highlighted, a brief overview of the test site setup is provided, an outline of the necessary data reduction is provided, and summarizing requirement statements are provided based on the final data requirement being assessed.

STATIC PERFORMANCE

This standard practice targets assessment of the mapping sensors using certified surfaces (i.e., straight edge and gauge blocks). Data collected while conducting this standard practice shall be used to assess the following: total transverse width, transverse and vertical measurement spacing, transverse and vertical measurement error, and straightness error.

Procedure Overview

For the static performance standard practice, a straight edge is placed below each mapping sensor and care is taken to ensure the top surface of the straight edge is kept in line with the bottom of the TPP wheels. That is, in the test configuration the straightedge is placed a distance equal to, or slightly greater than, the distance from the sensor to the ground when the system is in typical measurement conditions. Figure 19 provides an illustration of the necessary orientation of the straight edge with a mapping sensor. In addition to measuring the straight edge certified surface, certified gauge blocks of varying heights shall be placed on the straight edge at three target locations (centerline of the road, 2.0 m to the left of centerline, and 2.0 m to the right of centerline). The required heights of the gauge blocks along with supporting information for the selection of heights are provided in Appendix G.

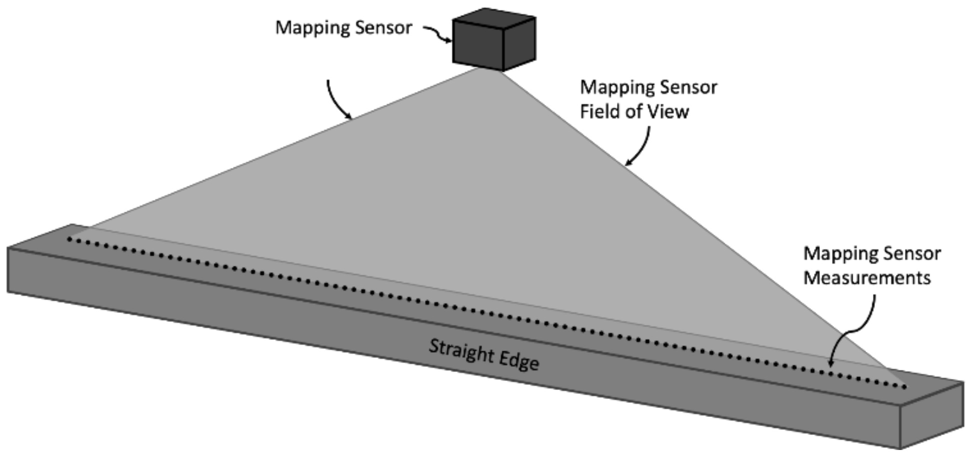

Figure 19. Mapping sensor centered over a leveled straight edge such that the field of view of the sensor is completely on the straight edge surface.

Data Reduction

By conducting the static performance standard practice, each mapping sensor should have a data set corresponding to: measurements of a certified straight edge and measurements of varying gauge block heights in two to three target transverse locations. The comprehensive analysis of the data sets is provided in Appendix B. A brief overview of the necessary analysis is provided in the paragraph below.

Per transverse profile measurement of the straight edge, the difference in the transverse extrema measurements shall be used to establish the total transverse width of the transverse profile. The test setup and measurements collected during the static performance test allow for measurement spacing in the transverse and vertical directions to be assessed. The transverse measurement spacing is determined by finding the absolute difference in the transverse direction between consecutive measurements. Vertical measurement spacing is determined by finding the deviation in the vertical directions for measurements which lie on an individual certified surface (e.g., top surface of a gauge block). Transverse and vertical measurement errors are determined by finding the difference between the certified transverse and vertical dimensions of a gauge block and the TPP reported transverse and vertical dimensions. Lastly, straightness error is determined by fitting a line to the measurements taken of a straight edge and calculating the deviation from the line.

Requirement Statement Based on Final Data Requirement

Requirement statements for the static performance standard practice are provided in tables 11, 12, and 13. The requirements presented in each table are dependent on the final data requirement being assessed (i.e., rut depth, cross slope, or edge/curb detection) and are dependent on the need to achieve the desired accuracy of the respective final data requirement. The requirements presented, per specification, match the required values developed in Chapter 3.

Table 11. Static performance rut depth requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Total transverse width	4000	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	10
Vertical measurement spacing	N/A	N/A	N/A	N/A	0.1
Transverse measurement error	-12.5	-5.0	N/A	5.0	12.5
Vertical measurement error	-1.5	-1.0	N/A	1.0	1.5
Straightness error	-2.5	-1.0	N/A	1.0	2.5

Table 12. Static performance cross slope requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Total transverse width	3800	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	25
Vertical measurement spacing	N/A	N/A	N/A	N/A	1.0
Transverse measurement error	-30	-12.5	N/A	12.5	30
Vertical measurement error	-2.0	-1.0	N/A	1.0	2.0
Straightness error	-8.0	-3.0	N/A	3.0	8.0

Table 13. Static performance edge/curb detection requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)

Total transverse width	4250	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	10
Vertical measurement spacing	N/A	N/A	N/A	N/A	0.1
Transverse measurement error	-12.5	-5.0	N/A	5.0	12.5
Vertical measurement error	-1.5	-1.0	N/A	1.0	1.5
Straightness error	-2.5	-1.0	N/A	1.0	2.5

BODY MOTION CANCELATION

This standard practice evaluates the capability of the TPP to removing motion of the TPP vehicle system when the primary ride and roll characteristics of the vehicle are excited. Data collected while conducting this standard practice shall be used to assess the vertical measurement spacing and body motion error of the TPP.

Procedure Overview

To ensure the primary ride and roll characteristics of the TPP are excited, two excitation boards are placed on the road surface in the wheel paths, as illustrated by the two back and gray rectangles in figure 20. The dimensions and characteristics of the excitation boards are provided in Appendix H. The design of the excitation boards ensure the primary and secondary ride frequencies of the TPP vehicle system are excited, to excite the primary roll frequency the excitation boards are offset in the longitudinal direction. After the excitation boards are placed on the road surface, three flat plates are placed as shown in figure 20. The placement of the flat plate ensures the mapping sensors are measuring the plates while the TPP is experiencing peak excitation.

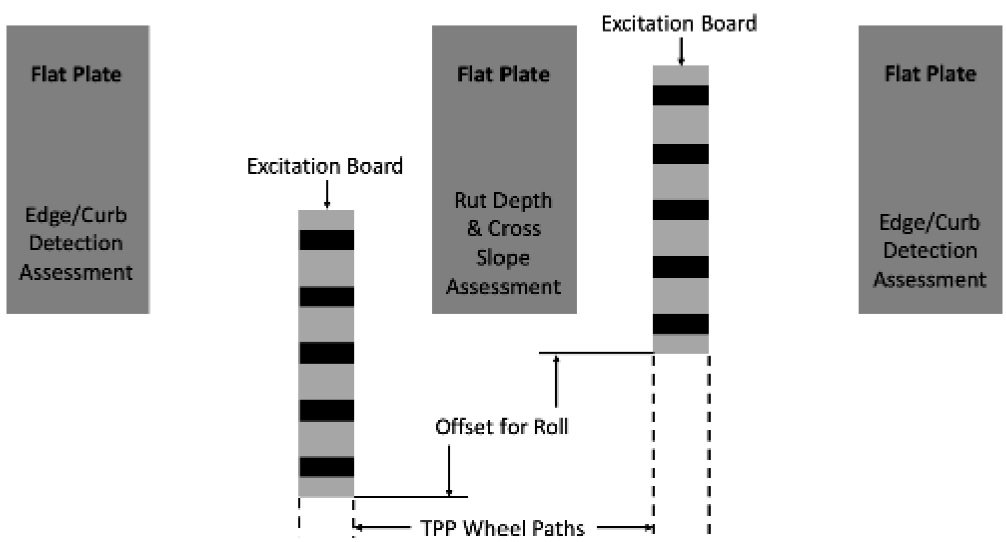

Figure 20. Layout of the two offset excitation boards and flat plates for the body motion cancelation assessment.

Data Reduction

By conducting the body motion cancelation standard practice multiple sets of point cloud data (one for each pass made through the test site) are collected and reported by the TPP. Per point cloud dataset, measurements of the flat plate shall be identified and a least squares error plane shall be fit to the measurements. The deviation of each measurement from the plane shall provide a measure of the body motion error. The difference in deviation between neighboring data points shall provide a measure of the vertical measurement spacing. A comprehensive set of analysis procedures to calculate the body motion error and vertical measurement spacing is provided in the Data Reduction section of Appendix C.

Requirement Statement Based on Final Data Requirement

Requirement statements for the body motion cancelation standard practice are provided in tables 14, 15, and 16. The requirements presented in each table are dependent on the final data requirement being assessed (i.e., rut depth, cross slope, or edge/curb detection) and are dependent on the need to achieve the desired accuracy of the respective final data requirement. The requirements presented, per specification, match the required values developed in Chapter 3.

Table 14. Body motion cancelation rut depth requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Vertical measurement spacing	N/A	N/A	N/A	N/A	0.1
Body motion error	-4.0	-2.5	N/A	2.5	4.0

Table 15. Body motion cancelation cross slope requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Vertical measurement spacing	N/A	N/A	N/A	N/A	1.0
Body motion error	-8.0	-5.0	N/A	5.0	8.0

Table 16. Body motion cancelation edge/curb detection requirement statement (in millimeters).

	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Vertical measurement spacing	N/A	N/A	N/A	N/A	0.1
Body motion error	-4.0	-2.5	N/A	2.5	4.0

NAVIGATION DRIFT

This standard practice evaluates the magnitude of navigation drift (global position error) present in the reported global location of a stationary object when multiple measurements (passes) are made of the stationary object. Data collected while conducting this standard practice shall be used to assess the global position error in the northing and easting directions and the elevation repeatability of the TPP.

Procedure Overview

A figure-eight is laid out in an open area, see Appendix I for the design of the figure-eight. At the center of the figure-eight a reference object is placed on the ground and the global location of the certification object shall be obtained. The certification object shall not move during the test and the TPP will drive over the object in two directions. The TPP will drive through the figure-eight multiple times, each time collecting measurements of the certification object. Figure 21 provides a representation of the figure-eight layout with respect to the reference object.

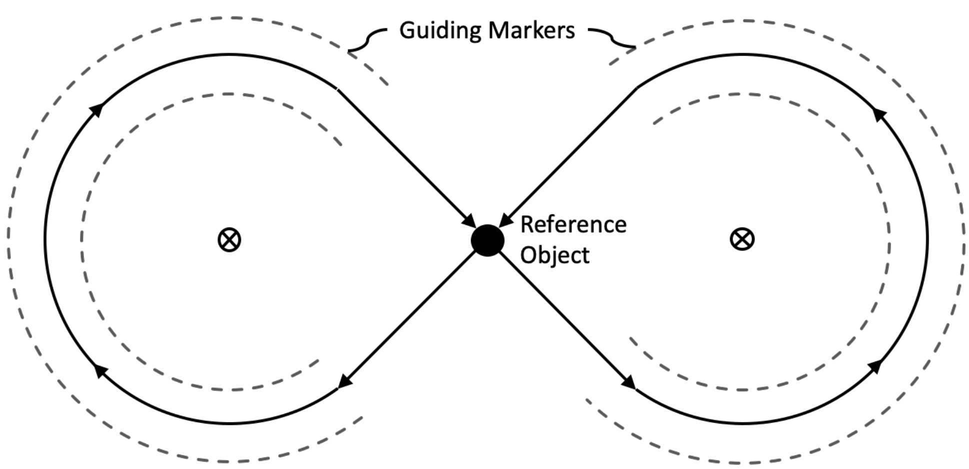

Figure 21. Figure-eight layout with a reference object placed at the center of the figure-eight to assess navigation drift.

Data Reduction

By conducting the navigation drift standard practice multiple sets of point cloud data (one for each pass made over the certification object) are collected by the TPP. For each point cloud the location of the certification object shall be obtained. The difference between the TPP reported location of the certification object and the recorded global location of the certification object in the northing and easting directions shall be calculated to define the northing and easting position errors. The difference between the elevation of the certification object, per pass and the average elevation from all passes shall be calculated to define the elevation repeatability. A comprehensive set of analysis procedures to calculate the global position error/repeatability are provided in the Data Reduction section of Appendix D.

Requirement Statement

Requirement statements for the navigation drift standard practice are provided in table 17. Since the navigation drift test is assessing the global position accuracy and precision of the data, the requirements are independent of the final data requirement being assessed. The requirements presented, per specification, match the required values developed in Chapter 3.

Table 17. Navigation drift requirement statement for all final data requirements (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Easting position error	-1250	-500	N/A	500	1250
Northing position error	-1250	-500	N/A	500	1250
Elevation position repeatability	-125	-50	N/A	50	125

HIGHWAY PERFORMANCE

This standard practice evaluates the TPP during typical highway operations (at speeds from 15 to 105 kph). Data collected while conducting this standard practice shall be used to assess the effective transverse width, transverse and longitudinal spacing, point cloud vertical error, gridded data vertical error, and final data requirements (rut depth, cross slope, and edge/curb detection) errors.

Procedure Overview

A test site is setup along a selected road surface. In the test site, two test sections are set up and defined using bounding beams oriented as shown in figure 22. The dimensions used to orient the bounding beams are provided in Appendix J, along with the comprehensive details regarding the test site road surface selection and setup. Once the test site is setup to reflect the schematic shown in figure 22, ground reference data shall be collected in the ground reference test section. Details regarding collection and verification of ground reference data are covered in Chapter 5.

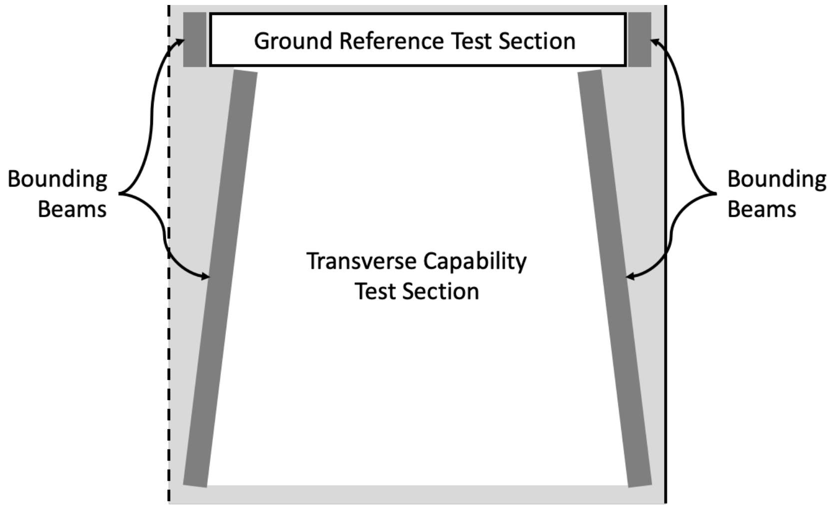

Figure 22. Layout of the transverse capability and ground reference test sections, defined by the bounding beams placed on the road surface.

Data Reduction

By conducting the highway performance test a set of point cloud or gridded data (depending on the layer of TPP assessment performed) per vehicle speed will be known. Per data set, the measurements collected in the transverse capability test section shall be used to establish the transverse spacing, longitudinal spacing, and effective transverse width. The transverse measurement spacing shall be established by calculating the absolute difference in the transverse direction between consecutive transverse data points. The longitudinal measurement spacing shall be determined by finding the absolute difference in the longitudinal direction between consecutive longitudinal data points. The effective transverse width is a collective measure of the total transverse width and the transverse wander of the TPP. The effective transverse width is identified by finding the transverse distance between the TPP center line and the location of the bounding beams. Figure 23 illustrates how TPP wander can reduce the effective transverse width of the TPP.

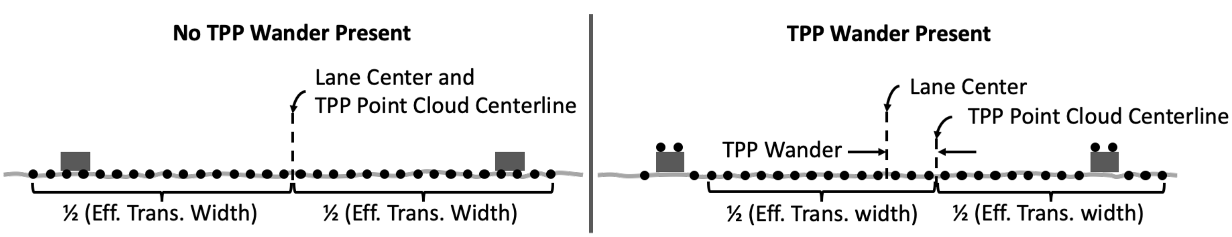

Figure 23. Effect of wander on the effective transverse width of the TPP.

Per data set, the measurements collected in the ground reference test section can be used to perform the probabilistic evaluation of the TPP data, as presented in Chapter 3. Details regarding the process of determining a reference distribution and calculation of the number of standard deviations from the reference distribution are provided in Appendix E. The results of the probabilistic evaluation of the TPP data set will provide the point cloud vertical error or the gridded data vertical error depending on the TPP data type assessed. Lastly, in the ground reference test section the error in the TPP rut depth, cross slope, vertical edge height, and/or transverse edge location can be evaluated using the ground reference data.

Requirement Statement Based on Final Data Requirement

Requirement statements for the highway performance standard practice are provided in tables 18, 19, and 20. The requirements presented in each table are dependent on the final data requirement being assessed (i.e., rut depth, cross slope, or edge/curb detection) and are dependent on the need to achieve the desired accuracy of the respective final data requirement. The requirements presented, per specification, match the required values developed in Chapter 3.

Table 18. Highway performance rut depth requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Effective transverse width	4000	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	10
Longitudinal measurement spacing - Network	N/A	N/A	N/A	N/A	3000
Longitudinal measurement spacing - Project	N/A	N/A	N/A	N/A	500
Point cloud vertical error	-2.5	-1.0	N/A	1.0	2.5
Gridded data vertical error	-1.7	-0.7	N/A	0.7	1.7
Rut depth error	-2.5	-1.0	N/A	1.0	2.5

Table 19. Highway performance cross slope requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Effective transverse width	3800	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	25

Longitudinal measurement spacing - Network	N/A	N/A	N/A	N/A	3000
Longitudinal measurement spacing - Project	N/A	N/A	N/A	N/A	500
Point cloud vertical error	-2.5	-1.0	N/A	1.0	2.5
Gridded data vertical error	-1.7	-0.7	N/A	0.7	1.7
Cross slope error (as percent)	-0.4	-0.15	N/A	0.15	0.4

Table 20. Highway performance edge/curb detection requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Effective transverse width	4250	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	10
Longitudinal measurement spacing - Network	N/A	N/A	N/A	N/A	3000
Longitudinal measurement spacing - Project	N/A	N/A	N/A	N/A	500
Point cloud vertical error	-2.5	-1.0	N/A	1.0	2.5
Gridded data vertical error	-1.7	-0.7	N/A	0.7	1.7
Edge/curb transverse location error	-50	-25	N/A	25	50
Edge/curb vertical magnitude error	-2.5	-1.0	N/A	1.0	2.5

CHAPTER 5. ESTABLISHING GROUND REFERENCE DATA

OVERVIEW

An important component of assessing TPP data is having a segment of a road surface for which ground reference data is available. This chapter provides the requirements which ground reference data must satisfy in order to be used in the highway performance analysis. The method of collecting ground reference data and performing the necessary analysis on the data is presented. Lastly, two case studies are provided using a commercially available piece of equipment capable of achieving the requirements in table 21.

REQUIREMENTS OF GROUND REFERENCE DATA

To evaluate the accuracy and precision of TPP measurements of the road surface, ground reference data are required. To maintain a chain of traceability, the ground reference data must be of higher accuracy and precision and higher resolution than the TPP data being evaluated. The equipment used to collect the ground reference data must satisfy the requirements presented in table 21 at the time of collection to ensure accuracy and precision of the data collected. All requirements in table 21 are dependent on the requirements developed in Chapter 3. For the ground reference data to be sufficient for use in the highway performance standard practice, the requirements for the reference data must be at least three times finer than the requirements for the TPP.

Table 21. Ground reference data requirement statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Total transverse width	4000	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	2
Longitudinal measurement spacing	N/A	N/A	N/A	N/A	2
Vertical measurement spacing	N/A	N/A	N/A	N/A	0.03
Transverse measurement error	-0.3	-0.15	N/A	0.15	0.3
Longitudinal measurement error	-0.3	-0.15	N/A	0.15	0.3
Vertical measurement error	-0.3	-0.15	N/A	0.15	0.3
Transverse straightness error	-1.0	-0.5	N/A	0.5	1.0
Macrotexture surface error (in standard deviation from a reference	-1.7	-0.7	N/A	0.7	1.7

distribution)					
Planar flatness error	-1.0	-0.5	N/A	0.5	1.0

COLLECTION OF GROUND REFERENCE DATA

When collecting ground reference data, traceable objects shall be introduced into the ground reference test section to verify the accuracy and precision of the ground reference data *in situ*. The traceable objects include: a certified straight edge, gauge blocks, flat plate, and a macrotexture surface. An overview of the complete setup necessary to collect ground reference data is provided in figure 24. For a comprehensive description of the test section setup and collection of ground reference data see the section titled Data Collection and Reporting in Appendix F.

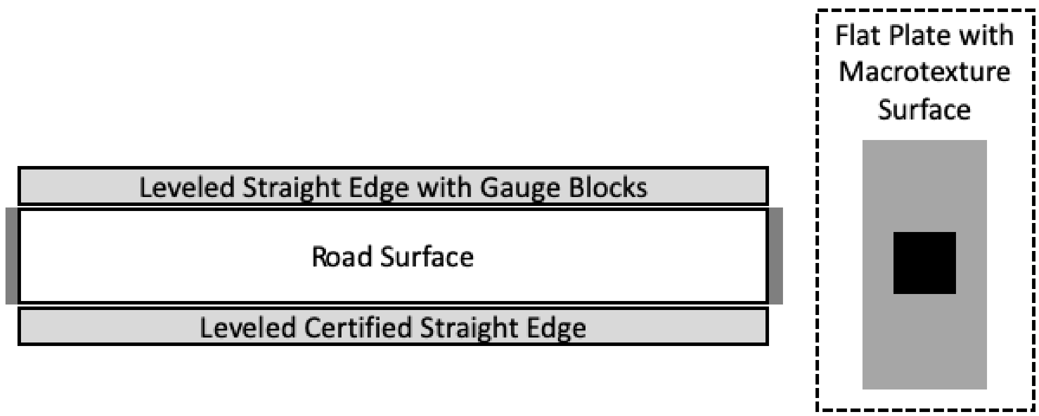

Figure 24. General layout of the ground reference test section.

EVALUATION OF GROUND REFERENCE DATA

By including the traceable objects in the test section when collecting ground reference data all evaluations provided in the ground reference equipment requirement statement, table 18, can be evaluated at the time of data collection. For a comprehensive explanation and set of detailed steps to perform the evaluation of the ground reference data see the Data Reduction section in Appendix F.

Total transverse width can be calculated using the difference in the transverse extrema of the data points on the straight edge. Transverse and longitudinal measurement spacing can be calculated by the absolute difference in transverse/longitudinal distance between nearby neighboring points in the respective direction of interest. All data points which lie on the flat plate shall be used to evaluate the planar flatness error and the vertical measurement spacing. The planar flatness error shall be evaluated by calculating the deviation of each data point from a least squares error plane fit to the data. The difference in deviation between neighboring points shall provide a measure of the vertical measurement spacing. Transverse, Longitudinal, and vertical measurement error shall be determined by calculating the difference in the certified dimensions of the gauge blocks (in the respective direction of interest) with the identical dimension derived from the ground reference data set. Lastly, the macrotexture surface error shall be calculated by performing a probabilistic comparison of the certified dimensions of the macrotexture surface with the ground reference data points corresponding to the macrotexture surface.

GROUND REFERENCE EQUIPMENT EVALUATION

While investigating potential ground reference equipment, the Creaform MetraSCAN was identified as a candidate piece of equipment which would satisfy all requirements presented in table 21. During this study two case studies were performed with the MetraSCAN system. The first study was conducted on the 22nd of March 2019 and was a proof of concept used to identify the capabilities of the system along with determining the general layout and process of collecting ground reference data. The second case study was conducted on the 23rd of May 2019 in conjunction with the second equipment rodeo. In both studies the same equipment was used, however the environment, location, and operator were different and are all factors which can contribute to variations in accuracy and precision.

Test Setup: Case Study 1

To conduct a first assessment of the MetraSCAN system, a loading dock pavement surface was selected. This location contains a worn asphalt surface featuring sharp edges and abrupt changes in the macrotexture. A canopy was setup to shade the road surface of interest and minimize the effect of ambient light on the system. Figure 25 shows the selected test area covered by the canopy on the morning the testing was conducted. It is important to note that the ground surface was damp during the testing as it had rained throughout the night prior. Additionally, temperatures were around 34-36°F and strong winds (~15mph gusts) were present all working together to result in non-ideal conditions.

Figure 25. Setup of a canopy over the test site to reduce the presence of sunlight.

Underneath the canopy a certified straight edge was placed diagonally and a flat beam with gauge blocks was placed 0.5 m away from the straight edge. Thus, the 0.5 m (longitudinal) by 4.0 m (transverse) section of road surface between the two beams was considered the road surface of interest. Outside of the road surface of interest an aluminum plate was placed on the ground and the macrotexture surface was placed on top of the plate. The complete test site can be seen in figure 26 along with a depiction of the technicians calibrating the MetraSCAN system.

Figure 26. Complete test site with Creaform equipment used during the assessment.

After the test site was setup and the system was properly calibrated, the technicians were able to collect measures of the complete test site to provide all necessary measurements for the proposed ground reference standard practice. The complete data acquisition process took roughly 30 to 45 minutes.

Test Setup: Case Study 2

During the second equipment rodeo, for the dynamic standard practice a 4.0 m wide by 0.5 m long segment of road surface in the southbound lane of the VTTI Smart road was selected for the ground reference test site. Figure 27, features the ground reference test site, which was identified by a large white intersection paint marking at the exiting longitudinal end and transversely centered about the center/left lane markings of the southbound lane.

When collecting the ground reference data, the road surface of interest was bounded by a leveled straight edge and an aluminum beam with gauge blocks on the top surface. To maintain correlation between the two test setups the same artifacts (gauge blocks, straight edge, flat plate, and macrotexture surface) were used in both test setups. Similar to the testing performed on March 22nd, a canopy was placed over the test section; the canopy was oriented to provide the best shade coverage over the test section and system to minimize the amount of ambient light. Similar to the March 22nd data collection, once the test site was setup and the MetraSCAN system was calibrated it took approximately 30 to 45 minutes to collect the necessary data.

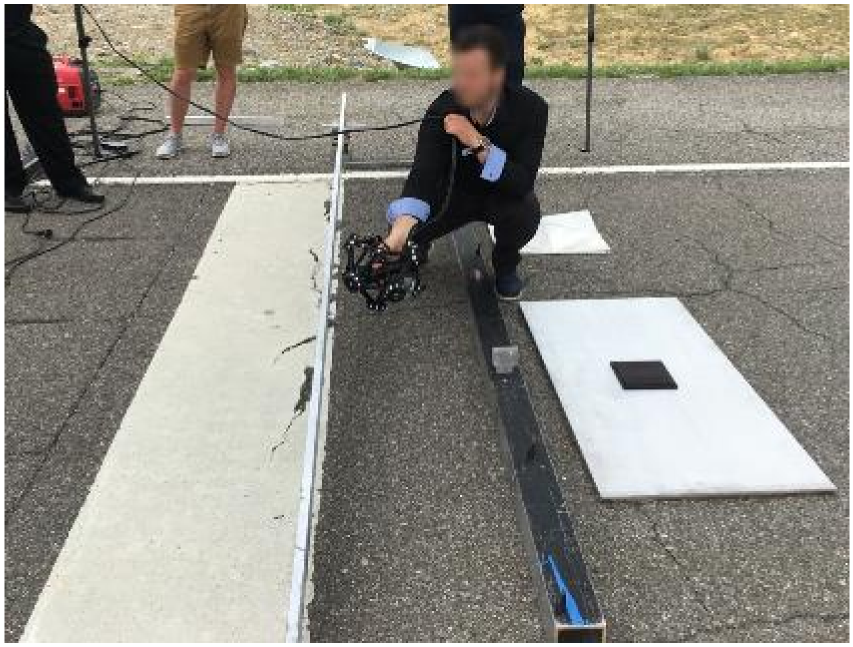

Figure 27. Test site for assessment of ground reference data at the second equipment rodeo.

Analysis of the data collected during both case studies can be found in Appendix K. All requirements, except for vertical measurement spacing were satisfied in the first case. However, it was found that by going slower during data collection and scanning the surface in more than one direction the vertical measurement spacing could be brought into an acceptable range. For the second case study all requirements, except for the transverse straightness error were satisfied. While conducting the second case study the straight edge was simply supported at the ends allowing for excessive deflection of the straight edge. The standard practice was updated to ensure the straight edge is properly supported at 2/9 the length of the straight edge to minimize deflection.

CHAPTER 6. TRANSVERSE PROFILE EQUIPMENT RODEO

OVERVIEW

Two transverse profiler equipment rodeos were conducted throughout the development of this work. Both equipment rodeos were conducted at the Virginia Tech Transportation Institute (VTTI) Smart road facility. During the first equipment rodeo draft standard practices were performed. Based on the results from the rodeo, the standard practices were revised to the resulting standard practices discussed in Chapter 4 and presented in Appendix B through F. During the second equipment rodeo the four TPP standard practices were performed along with the standard practice for collection of ground reference data. All materials used during the equipment rodeos is referenced in Appendix L.

The remainder of this chapter provides an overview of each equipment rodeo, lessons learned from the first equipment rodeo, and the vendor capability statements from each equipment rodeo.

EQUIPMENT RODEO 1

The first equipment rodeo was conducted on the 12th of April 2018 at the Virginia Tech Transportation Institute (VTTI) Smart road facility. A total of four transverse profile vendors participated in the day long testing and successfully completed all proposed standard practices. For the first rodeo, there were two goals: to verify the process by which the proposed standard practices are run and to establish and verify/support the values in the requirement statements.

Insights Gained and Lessons Learned

From the first equipment rodeo two main areas of focus were identified: a continued effort to make the standard practices more efficient and a focus on investigation into defining ground reference for highway speed transverse profile measurements. In addition to these two main areas of focus a couple of smaller issues with the static performance and navigation drift standard practices were identified. For the static performance standard practice it was found that the height of the straight edge must be taken into account so that the proper sensor range is tested. For the navigation drift standard practice it was found that the certification object used was not large enough to be found in the TPP data set, so a slower speed and/or a larger test object was needed.

Vendor Capability Statements

Each of the vendor's data sets is summarized in a capabilities statement provided in Appendix M. Overall, it was found that for all assessments evaluated during the first equipment rodeo at least one of the vendors was able to satisfy the requirements.

EQUIPMENT RODEO 2

The second equipment rodeo was conducted on the 21st of May 2019 at the VTTI Smart road facility. A total of three transverse profile vendors and one ground reference equipment vendor participated in the day long testing. All transverse profile vendors successfully completed all proposed standard practices and the ground reference equipment vendor successfully collected ground reference data for the highway performance assessment. For the second equipment rodeo two objects were manufactured for the rodeo to address lessons learned from the first equipment rodeo. Appendix N provides dimensioned drawings for the two parts.

Vendor Capability Statements

Each of the vendor's data sets is summarized in a capabilities statement provided in Appendix O. Overall, it was found that for the majority of the assessments evaluated during the second equipment rodeo at least one of the vendors was able to satisfy the requirements. The two assessments of concern with lack of vendor supporting requirements are: vertical measurement accuracy and easting position error. For vertical measurement error it is believed that the data was filtered resulting in reduced accuracy of the measurements of the gauge blocks, subsequently resulting in lack of meeting the vertical error requirement. For northing and easting position error, feedback from the road profiling community was asked and it was agreed upon that the requirements set are appropriate.

CHAPTER 7. CONCLUSION

During this study four standard practices for assessing transverse pavement profilers were developed and tested. In addition, a standard practice for collecting and assessing ground reference data was developed to ensure adequate accuracy of the ground reference data for the highway performance standard practice. Complementing these five standard practices, is a standard practice containing terminology and definitions. In conjunction with the developed standard practices, requirement statements were developed containing specifications on accuracy and precision. Through implementation of the standard practices and requirement statements transportation agencies will have the ability to: identify the precision and accuracy of transverse pavement profile measurements, identify if two or more measurement systems are providing results within tolerances, and determine if measurements taken at different times are consistent.

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APPENDIX A. DEFINITION OF TERMS RELATED TO TRANSVERSE PAVEMENT PROFILING SYSTEMS AND GROUND REFERENCE EQUIPMENT

1. SCOPE

1.1. This standard practice is to provide standard definitions for terms used in transverse pavement profiling system specifications, test methods, standard practices, and the various quality assurance procedures.

2. TERMINOLOGY

2.1. Sensors

2.1.1. *mapping sensor*—Any sensor which acquires measurements of a surface (e.g. road, gauge block, etc.) in its sensor reference frame.

2.1.2. *location sensor*—Any sensor which acquires the pose (position and orientation) of the sensor, and thereby the body to which it is attached, in a global reference frame. Data from location sensors are typically used in the rotation and translation of data in a body-fixed reference frame to a global reference frame.

2.1.3. *Ground reference equipment (GRE)*—Any equipment which acquires ground reference data.

2.2. Reference Frames and Directions

2.2.1. *lane*—the traveled surface between the inside edge of the left pavement marking and the outside lane edge or, in the absence of markings, an equivalent portion of the pavement surface.

2.2.2. *outside lane edge*—A line 100 mm (4 in) beyond the outside limit of the edge pavement marking. In the absence of an edge pavement marking, it is a user-defined distance from the left edge marking or pavement centerline.

2.2.3. *lane center*—a location halfway between the inside edges of the pavement edge markings. If no markings are present, a location 22 percent of the total pavement width from the pavement middle on two-lane roads and a location at the middle of the road on one-lane roads.

2.2.4. *transverse direction*—Direction perpendicular to the lane center.

2.2.5. *longitudinal direction*—Direction parallel to the lane center

2.2.6. *vertical direction*—Direction normal to the WGS84 ellipsoid

2.2.7. *sensor reference frame*—A set of axes fixed in a sensor in which the sensor data are reported. The sensor reference frame is typically defined by the manufacturer of the sensor. Data defined in sensor reference frames are typically converted (rotated and translated) to a body reference frame before combining with other sensor measurements that have been similarly converted.

2.2.8. *body reference frame*—A set of three orthogonal axes fixed in a body that is typically assumed to be rigid to which sensors are attached. Data from these sensors are typically converted (rotated and translated) to the body reference frame before being converted to a global reference frame.

2.2.9. *global reference frame*—A set of three orthogonal axes (X-Y-Z) with a known, fixed origin where the X and Y axes are defined by the Universal Transverse Mercator (UTM) conformal projection where X corresponds to Easting (in meters) and Y corresponds to Northing (in meters). The Z axis corresponds to elevation (in meters) as defined by the WGS84 ellipsoid.

2.2.10. *path reference frame*—A set of three orthogonal axes (U-V-Z) with a known, fixed origin where the U and V axes are defined by the path coordinate system where U corresponds to transverse distances (in meters) and V corresponds to longitudinal distances (in meters). The Z axis corresponds to elevation (in meters) as defined by the WGS84 ellipsoid.

2.2.11. *component reference frame*—A set of three orthogonal axes (x'-y'-z') with a known, component fixed origin (typically a unique corner of the part) where the x' and y' axes are defined by edges of the component which are perpendicular to each other and z' is in the normal direction.

2.2.12. See figures 28 and 29 for illustrations of the global reference frame and path reference frame. Figure 28 provides an illustration of the components which are constrained by the UTM surface and Figure 29 provides an illustration of the elevation which is constrained by the WGS84 ellipsoid.

2.3. Data Types

2.3.1. *point cloud data*—A set of irregularly spaced data points in a global or path reference frame, calculated from a combination of mapping and location sensor measurements of the road surface.

2.3.2. *gridded data*—A set of point cloud data whose elevation values have been interpolated to a regularly spaced grid in the horizontal plane (either X-Y or U-V)

2.3.3. *transverse profile*—The vertical deviations of the pavement surface from a horizontal reference perpendicular to the lane direction.

2.3.4. *longitudinal profile*—The perpendicular deviations of the pavement surface from an established reference parallel to the lane direction, usually measured in the wheel tracks.

2.3.5. *mapping sensor measurement*—A set of data points from an individual mapping sensor in a sensor or global reference frame. This measurement may not span the complete lane width and may be oriented at an angle relative to transverse direction.

2.3.6. *system scan*—The combined set of mapping sensor measurements acquired over a single sampling time from all mapping sensors on the TPP.

2.3.7. *ground reference data*—The set of three-dimensional measurements which constitutes reference data for evaluation of point cloud or gridded data and is collected using a GRE.

2.4. Reporting Formats

2.4.1. *point cloud reporting format*—A text file containing three columns of data where each row represents a single point in the initial point cloud and each column represents the projection of that point onto a set of three orthogonal axes in either a global or path reference frame. Initial point cloud data should have no filtering, smoothing or elimination of outliers.

2.4.2. *gridded data reporting format*—A text file containing a matrix of data where each row represents a transverse profile and each column represents a longitudinal profile. The text file shall also contain a central path (typically corresponding to the lane center) defined by coupled transverse-longitudinal data points. Gridded data can have filtering, smoothing, and/or elimination of outliers applied.

2.5. Fabricated Surfaces

2.5.1. *excitation boards*—A manufactured surface which contains consecutive square bumps of specified dimensions to ensure the primary and secondary ride modes of the TPP are excited between a prescribed range of speeds.

2.5.2. *reference object*—An object with a set of verifiable dimensions which has distinguishable features allowing for the global position and orientation of the object to be established from the TPP point cloud.

2.5.3. *macrotexture object*—A manufactured object which has at least one surface (macrotexture surface) with a specified mean profile depth. The macrotexture surface shall contain a set of verifiable dimensions.

2.6. Measurement Analysis Definitions

2.6.1. *measurement spacing*—The smallest distance which can be consistently resolved in a specified direction.

2.6.2. *measurement erro*r—Difference between the measurement of an object or surface made by a sensor, sub-system, or system being assessed and the verifiable dimension. The measurement error must be stated in terms of the accuracy and precision with which the verifiable dimension is known.

2.6.3. *surface distance*—The range between measures for a given surface in a specified direction (e.g. sensor measurement width of a gauge block, transverse width of a road surface, or longitudinal length of a road surface)

2.6.4. *surface-to-surface distance*—The set of distances in a specified direction between data points which lie along a primary surface (e.g. lowest gauge block surface, reference level) and data points which lie along a secondary surface (e.g. highest gauge block surface, road surface).

2.6.5. *point-to-point distance*—The distance in a specified direction between two measurement points.

2.6.6. *point-to-plane distance*—The normal distance from a reference plane to a reported measurement point. The reference plane shall be formed using a least squares error fit to a set of measurements which lie in a single surface.

2.6.7. *point-to-line distance*—The normal distance from a reference line to a reported measurement point from a single system scan.

2.6.8. *transverse wander*—Relative amount of transverse deviation from the physical center of the lane reported in the TPP initial point cloud and the TPP gridded data

2.6.9. *effective transverse width*—The relative lane width a measurement system is capable of measuring based on the relationship between the total transverse width and the transverse wander.

2.6.10. *vehicle body motion error*— Vertical errors present from a least-squares error plane fit to point cloud data on the top surface of a flat plate.

2.7. Ground Reference Equipment (GRE) Measurement Regions

2.7.1. *ground reference*—All GRE point cloud measurements which lie along the road surface bounded by the straight edge, straight edge with gauge blocks, and two transverse bounding beams. All measurements shall be reported in path reference frame.

2.7.2. *transverse straightness*—All GRE point cloud measurements which lie on the top certified surface of the straight edge.

2.7.3. *gauge block*—All GRE point cloud measurements which lie on all visible surfaces (e.g. top and sides) of a given gauge block or set of gauge blocks. If multiple gauge blocks are present in the point cloud, then each should be uniquely identified.

2.7.4. *macrotexture*—All GRE point cloud measurements which lie on the top surface of the macrotexture surface.

2.7.5. *planar flatness*—All GRE point cloud measurements which lie on the top surface of the flat plate upon which the macrotexture surface is placed. Note, the measurements of the macrotexture surface are not included in this region.

2.8. Other Definitions

2.8.1. *certification agency*—The agency/organization that is performing the certification/validation of the TPP.

2.8.2. *transverse pavement profiler (TPP) operator*—The agency/organization that operates the TPP that is being certified/validated.

2.8.3. *verifiable dimension*—A dimension of an object or surface that is traceable to a certification/calibration agency's measurement of that dimension and whose accuracy and precision are known.

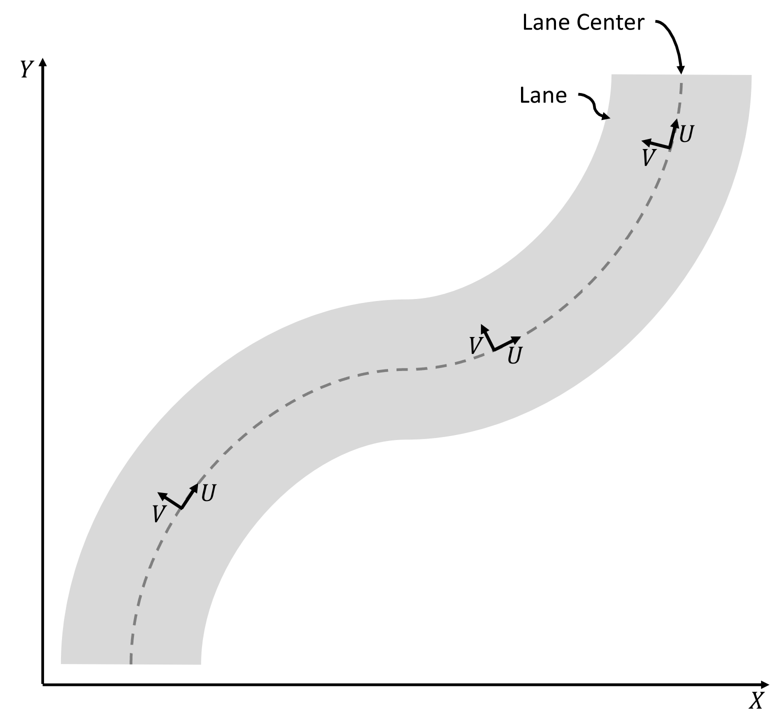

Figure 28. Representation of the reference frame directions which lie along the UTM surface.

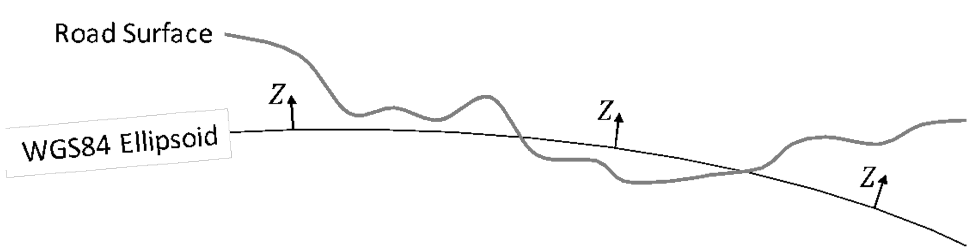

Figure 29. Representation of the vertical direction which is normal to the WGS84 Ellipsoid.

APPENDIX B. ASSESSMENT OF STATIC PERFORMANCE IN TRANSVERSE PAVEMENT PROFILING SYSTEMS

1. SCOPE

1.1. This practice describes the procedure to assess the specifications, accuracy, and precision of the sensor system used on Transverse Pavement Profilers (TPP) in static mode. The particular specifications which will be assessed are: transverse spacing, transverse width, vertical spacing, straightness error, vertical measurement error, and transverse measurement error.

1.2. The minimum requirements stipulated herein are intended to focus on the need for accurate and repeatable transverse measurements for network and project level data collection.

1.3. If any part of this practice is in conflict with referenced documents, such as ASTM Standards, this practice takes precedence for its purposes.

1.4. This standard practice is intended to be conducted in conjunction with three other standard practices to fully assess and certify the TPP in typical operating conditions. For ground reference and transverse width assessment see R### Assessment of Highway Performance in TPP Systems, for body motion assessment see R### Assessment of Body Motion Cancelation in TPP Systems, and for assessment of drift mitigation see R### Assessment of Navigation Drift in TPP Systems.

1.5. This practice does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this practice to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

2. REFERENCED STANDARDS

2.1. AASHTO Standards:

- R010, Definition of Terms Related to Quality and Statistics as Used in Highway Construction
- Certification of Body Motion Cancelation in Transverse Pavement Profiling Systems
- Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment

3. TERMINOLOGY

3.1. See AASHTO R###, Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment, for definition of terms used in this standard practice.

3.2. Table 22 provides the physical parameter definitions, symbols, and default values to be used when administering this standard.

Table 22. Physical parameter definitions and default values.

Physical Parameter	Symbol	Default Value(s)
Minimum length of the straight edge	L_{se}	4.0 m (13 ft)
Minimum width of the straight edge	W_{se}	25 mm (1 in)
Vertical height of the gauge blocks	h_{g1} h_{g2}	75 ± 2 mm (3 ± 0.1 in), 50 ± 1 mm (2 ± 0.05 in), 25 ± 1mm (1 ± 0.05 in), 25 ± 1mm (1 ± 0.05 in), 12 ± 1 mm (0.5 ± 0.05 in), 6 ± 1mm (0.25 ± 0.05 in)
Minimum transverse width of the gauge blocks	w_g	25 mm (1 in)
Transverse distance from the base of the stair-stepped gauge block	d_s	25 mm (1 in)
Number of transverse profiles to be collected per straight edge location.	n_p	10
Distance that the TPP shall be raised in addition to the vertical distance from the road surface to the top of the straight edge	d_v	0 + 25 mm (0 + 1 in)
Desired transverse locations of gauge blocks from the transverse centerline	d_t	2.0 ± 0.05 m (6.5 ± 0.2 ft)

4. SIGNIFICANCE AND USE

4.1. Measured transverse profiles of road surfaces are used to extract pavement deformation parameters such as rut depth, cross-slope, and edge/curb drop off. The accuracy of the estimated pavement deformation parameters depends on the measured transverse profile accurately representing a transverse section of the road surface.

4.2. Requirements on the specifications of mapping sensors ensure that the measured profile accurately represents the road surface. In addition, it is essential that the TPP sensors be able to accurately and precisely measure the height and transverse location of the road surface points.

4.3. This practice outlines standard procedures for assessing the operational accuracy and precision of transverse pavement profilers related to static measurement components. This standard prescribes procedures to evaluate transverse spacing between measurements, total width of measurements, vertical spacing of the measurements, straightness of the transverse measurements, and vertical and transverse measurement accuracy and precision. Because the data are used for subsequent calculations for rut depth, cross slope, and edge/curb drop off, tables of the necessary accuracy and precision are provided in the form of bias and confidence intervals for each use.

5. EQUIPMENT

5.1. Capable of triggering mapping sensors when in a static mode.

5.2. Provide all collected transverse profiles of the test section in electronic text files following the format prescribed by Annex B1.

6. DATA COLLECTION AND REPORTING

6.1. Per mapping sensor, a straight edge of length L_{se} and width W_{se} shall be placed on a road surface directly in the Field of View (FOV) of the mapping sensor and leveled using any desired method. The straight edge shall be oriented such that the complete FOV lies on the top surface of the straight edge. Figure 30 provides examples of orientation of the straight edge with respect to the mapping sensor FOV for four example mapping sensor setups.

6.1.1. The data collection process must be repeated for each mapping sensor. If multiple mapping sensors are oriented such that the field of views lie in a single plane, then the data collection for those sensors can be performed simultaneously by orienting the straightedge such that the complete field of view for all mapping sensors of interest lie on the top surface of the straight edge.

6.2. When conducting the static assessments, the TPP shall be raised an amount equal to the vertical distance from the road surface to the top of the straight edge plus the distance d_v. The intent is to locate the top of the straightedge at, or slightly below, the typical location of the road surface with respect to the TPP when in a typical operating condition. Any method of raising the TPP above the road surface or lowering the straight edge below the road surface can be used to achieve this relative positioning. Independent of the method used to achieve the distance d_v, the general orientation of the TPP shall not be affected (e.g. if the TPP is raised above the road surface the front and rear of the TPP must be raised equally). See figure 31 or a side-view schematic of the straight edge placement with respect to the reference plane.

6.3. At least n_p scans shall be taken, per mapping sensor, of the straight edge with no gauge blocks on the surface. These collected profiles shall be used to analyze the respective mapping sensor's transverse spacing, transverse width, vertical spacing, and straightness error.

6.4. Per mapping sensor, the certification agency shall place a stair stepped gauge block at three transverse locations (transverse centerline of the lane, positive d_t from the centerline of the lane, and negative d_t from the centerline of the lane). If a mapping sensor field of view does not capture one or more of these transverse regions, it shall be noted and the gauge block shall be placed as close to the transverse region as the sensor allows. Figure 30 provides a top view representation of various mapping sensor configurations where gauge blocks were able to be placed at the desired transverse positions and where the field of view of the sensor limited the transverse position. In addition, figure 32 provides a side view showing the gauge blocks placed on the straight edge.

6.5. When placing the gauge blocks on the straight edge, the stair-stepped features shall be oriented to allow for the best collection of data and minimize the potential of missing data. Figure 33 provides a simple illustration of orientation of the stair-stepped gauge block depending on the location of the mapping sensor with respect to the gauge block. For all mapping sensors, the stair stepped gauge block shall be measured in at least two and no more than three transverse locations.

6.6. The TPP operator shall acquire at least n_p transverse profiles of the stair-stepped gauge block in each transverse location.

6.7. To limit the amount of vertical distance between consecutive steps two sets of stair-stepped gauge blocks shall be used having heights h_{g1} and h_{g2}.

6.8. The scans with the gauge blocks will be used to analyze the vertical measurement error and horizontal measurement error of the respective mapping sensor.

6.9. Details regarding the dimensioning, tolerances, surface finish, and material properties of the straight edge and gauge blocks are given in Annex A1 and A2.

6.10. The mapping sensor data from each scan of the straight edge and straight edge with gauge blocks shall be reported in the local sensor coordinate system in a transverse profile as explained in Annex B1.

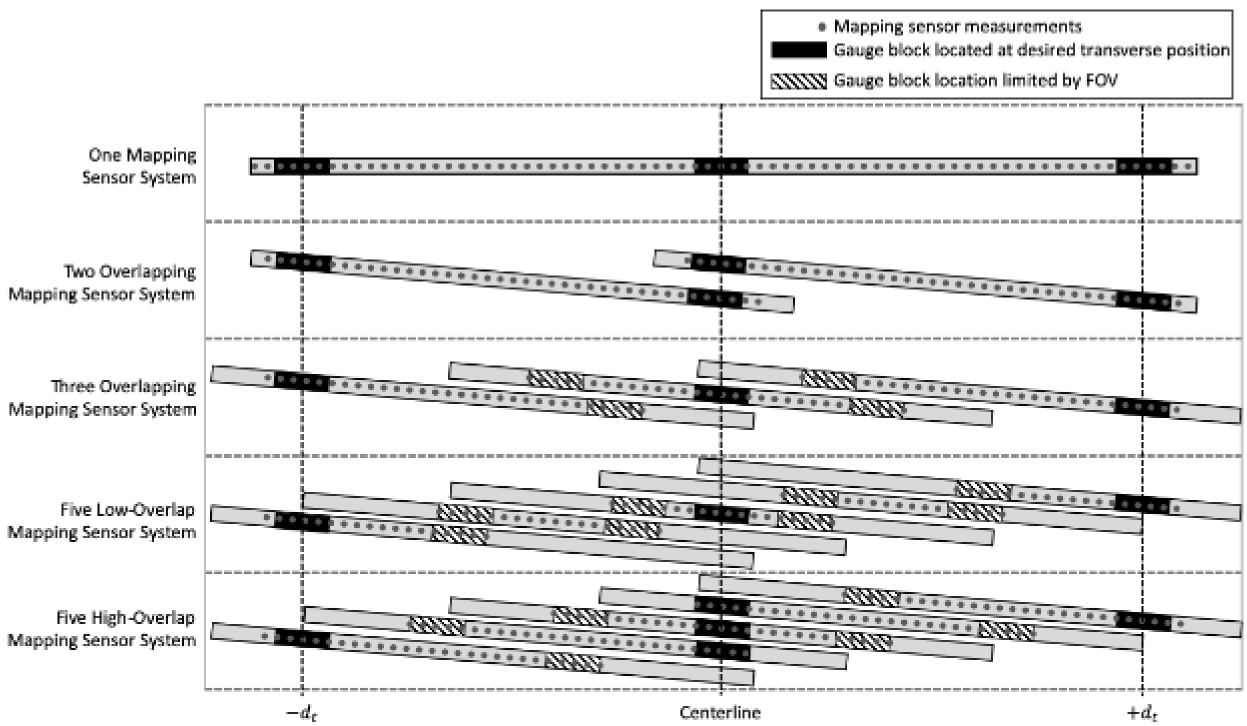

Figure 30. Alignment of the straight edge with the mapping sensor measurement path.

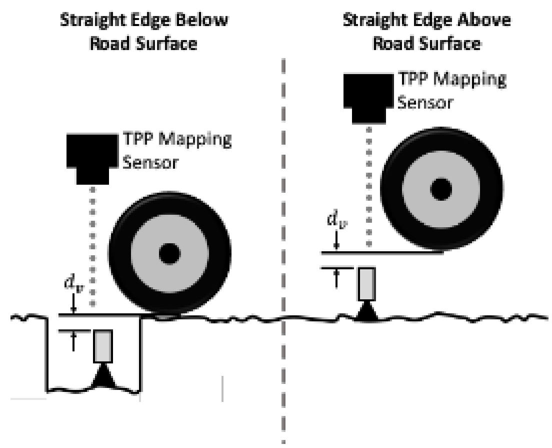

Figure 31. Elevation of the TPP, or depression of the straight edge, to ensure proper vertical positioning of the mapping sensor to the top of the straight edge.

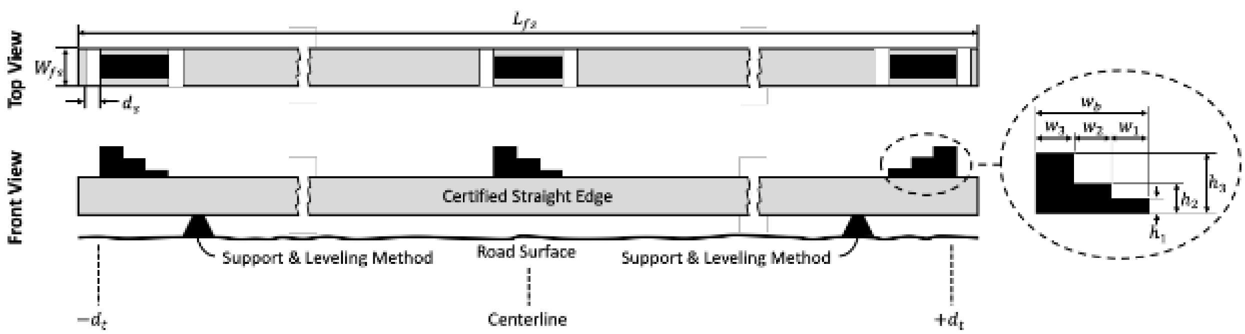

Figure 32. Layout of the stair-stepped gauge blocks at the center, left, and right side of the straight edge.

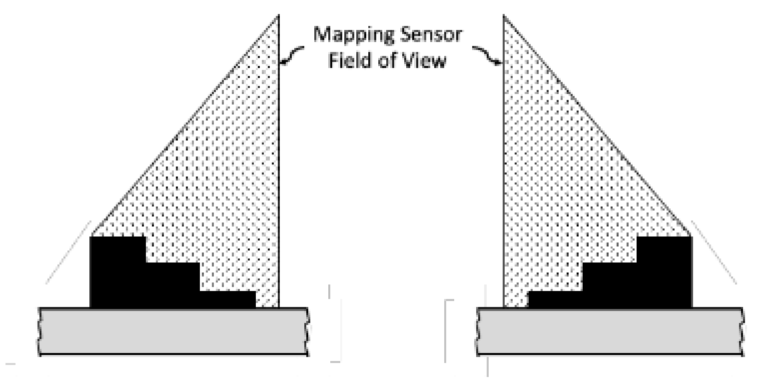

Figure 33. Orientation of a stair-stepped gauge block to best align with the field of view of the mapping sensor.

7. DATA REDUCTION

7.1 Parsing Measurement Data:

7.1.1 Per system scan, all measurements which lie on the top surface of the straight edge shall be defined as the set S_{SE}. This set can have gaps in the transverse direction where gauge blocks are located.

7.1.2 Per system scan with gauge blocks, the top surfaces of the gauge blocks shall be uniquely identified by index i and the set of mapping sensor measurements that lie at the top of the i^{th} surface shall be defined as the set S_i. See Figure 34 for illustration, regarding identification of unique surfaces of a gauge block.

7.1.3 Per system scan, all measurements which do not lie on a certified surface (i.e. top surface of the straight edge or gauge blocks) shall be defined as the set S_{RS}.

7.1.4 The complete set, S_T, of all mapping sensor measurements shall consist of: the set of all mapping sensor measurements which lie on the top surfaces of the straight edge (S_{SE}), individual surfaces of gauge blocks (S_i), and those not on a certified surface (S_{RS}).

7.2 Transverse Measurement Spacing:

7.2.1 The measurements in set S_T shall be sorted based on the measured transverse position. The transverse point-to-point distance shall be calculated between each consecutive measurement point in the set S_T. All calculated point-to-point distances shall be added to the set t_{sys}.

7.2.2 The complete set of t_{sys} values shall serve as a sample from the population of true transverse measurement spacing for the respective mapping sensors which reported the measurements in the set S_T. Analysis of all system scans from each mapping sensor will provide a sample from the population of true transverse measurement spacing for the complete TPP system.

7.3 Total Transverse Width:

7.3.1 The transverse surface distance shall be calculated from the measurements in the set S_T and added to the set w_{sys}. The complete set of w_{sys} values shall serve as a sample from the population of true transverse width of the TPP system.

7.3.2 The complete set of w_{sys} shall include the transverse surface distance from all reported system scans.

7.4 Straightness Error:

7.4.1 Per system scan, the set of measures, S_{SE}, shall be used to identify the straightness error of the mapping sensor(s) used to collect the set of measurements.

7.4.2 A linear trend line shall be fit to set S_{SE} using a least squares error fit.

7.4.3 The point-to-line distance shall be calculated for all measurements in the set S_{SE}, using the linear trend as the reference line.

7.4.4 Each point-to-line distance shall provide an estimate of the straightness error of the TPP system and shall be added to the set e_s. The set of e_s values shall serve as a sample from the population of true straightness error values for the respective mapping sensors used to measure the straight edge.

7.4.5 The complete set of e_s values from all collected mapping sensor measurements shall serve as a sample from the population of true straightness errors for the TPP system.

7.5 Vertical Measurement Spacing:

7.5.1 Per system scan including gauge block surfaces, the vertical measurements from each identified unique surface of a gauge block in the set S_i shall be used to establish an estimate of the vertical measurement spacing of the respective mapping sensor(s) used to collect the measurements.

7.5.2 A base line indicating the horizontal plane of the system scan shall be defined by a least squared error linear trend fit to the set S_{SE}, see figure 35 for illustration of the baseline fit. The slope of the base line shall be used as the corresponding slope of each i^{th} gauge block surface.

7.5.3 Per unique surface, the point-to-line distance shall be calculated for all measurements in each unique surface set, S_i, using the linear trend fit to the set S_{SE} as the reference line.

7.5.4 To establish the vertical measurement spacing, the average point-to-line distance for the set S_i shall be calculated.

7.5.5 For the set S_i, the vertical measurement spacing is equivalent to the absolute difference between the point-to-line distance and the average point-to-line distance. The absolute difference for each point-to-line distance shall be added to the set v_{sys}.

Note 1—Calculation of the absolute difference is comparable to constructing a representative surface which is parallel to the base line and best fits the vertical measurements in the set S_i. Figure 35 provides a representation of a representative surface for a gauge block surface along with the point-to-line distances with respect to the base line. A closer view of the top surface of the gauge block is provided in figure 36 to illustrate the resulting estimate of vertical measurement spacing for each TPP measurement.

7.5.6 The process of calculating the set of point-to-line distances and the corresponding vertical spacing associated with each point-to-line distance shall be repeated for each unique surface in a system scan.

7.5.7 The complete set of v_{sys} values from all S_i sets shall serve as a sample from the population of true vertical measurement spacing of the TPP system.

7.6 Vertical Measurement Error:

7.6.1 Per system scan including gauge block surfaces, a reference surface for each gauge block must be established. This reference surface shall consist of one of the identified S_i set of measurements (e.g. the set of measurements corresponding to the lowest step of a stair-stepped gauge block). A reference line spanning the reference surface is necessary for evaluating the vertical measurement error.

7.6.2 A base line indicating the horizontal plane of the system scan shall be defined by a least squared error linear trend fit to the set S_{SE}. The slope of this linear trend shall be used as the slope of the reference line. Figure 34 provides an illustration of a base line fit to the set S_{SE} and the complementing reference line for the example reference set.

7.6.3 To establish the vertical offset of the reference line from the base line the point-to-line distance for all measurements in the reference surface set shall be calculated with respect to the base line. The vertical offset of the reference line shall be the average of all point-to-line distances. See figure 35 for an example of defining a surface parallel to the base line based on the average point-to-line distance with respect to the base line.

7.6.4 Per gauge block a set of vertical heights with respect to the reference surface shall be calculated per S_i set. The set of the vertical heights between an i^{th} surface of the gauge block and the reference surface shall be established by calculating the point-to-line distance between the measurements in the set S_i and the reference line.

7.6.5 The known certified vertical height of the gauge block corresponding to the point-to-line distance between an i^{th} surface of the gauge block and the reference surface shall be subtracted from the point-to-line distance to provide the vertical measurement error.

7.6.6 The resulting vertical measurement error shall be added to the set e_v. Figure 37 provides an illustration of the identified point-to-line distance for two example measurements.

7.6.7 The complete set of e_v values from all system scans shall serve as a sample from the population of true vertical measurement error for the TPP system.

7.7 Transverse Measurement Error:

7.7.1 Per system scan, each i[th] surface shall be used to identify the transverse measurement error. The transverse surface distance shall be calculated from the measurements in the set S_i and the known certified transverse width of the respective unique surface shall be subtracted from the transverse surface distance to provide the transverse measurement error.

Note 2—If a gauge block contains multiple surfaces, then a comprehensive transverse surface distance of the gauge block can be established by considering all surfaces as one unique surface and determining the resulting comprehensive transverse surface distance.

7.7.2 For each i[th] surface, the transverse measurement error shall be added to the set e_t. Figure 38 provides an illustration of three transverse surface distances for the three unique gauge block surfaces along with the corresponding certified transverse dimensions of the gauge block.

7.7.3 The complete set of e_t values from all i[th] surfaces of all system scans shall serve as a sample from the population of true transverse measurement error for the TPP system.

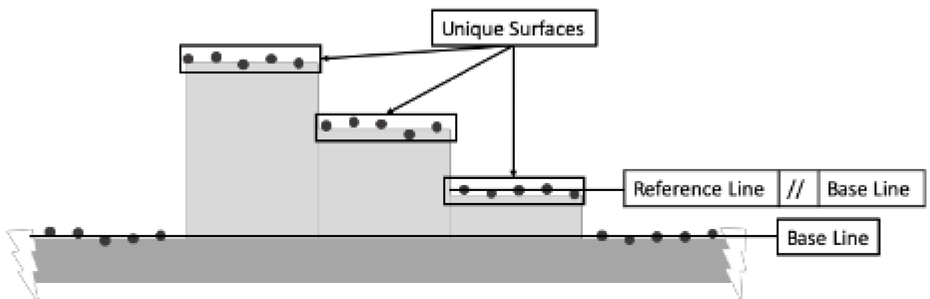

Figure 34. Definition of a base line corresponding to measurements located on the straight edge and a parallel reference line which spans a selected reference set of measurements (e.g. bottom step of the gauge block).

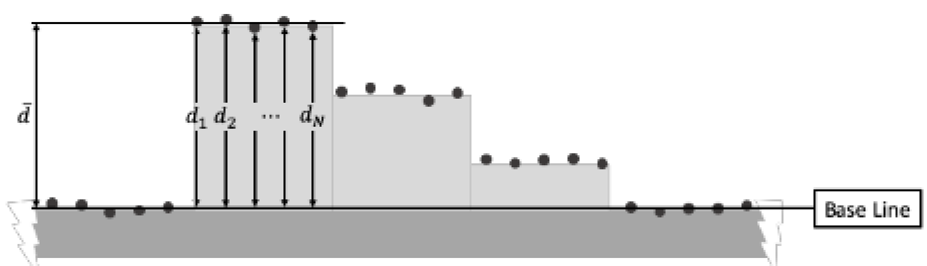

Figure 35. Representation of a nominal surface plane based on the average point-to-line distances for an individual gauge block surface.

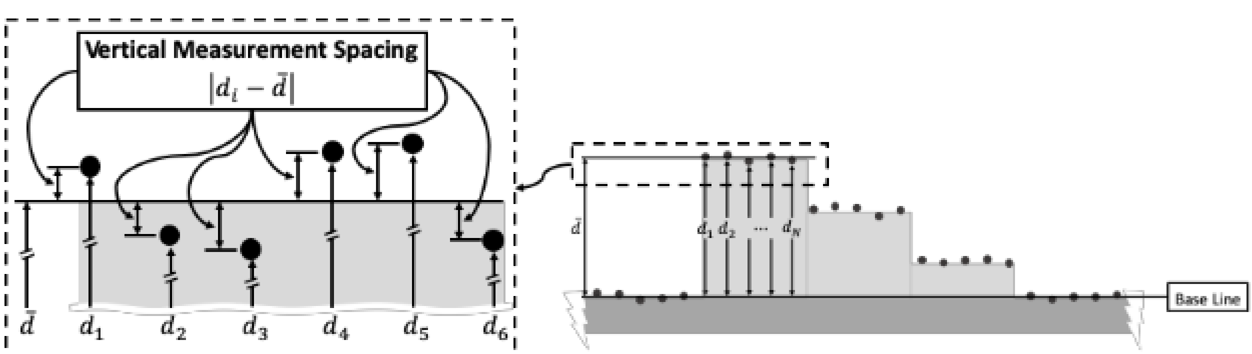

Figure 36. Illustration of vertical measurement spacing based on the absolute difference in the point-to-line distance of each measurement with the average point-to-line distance.

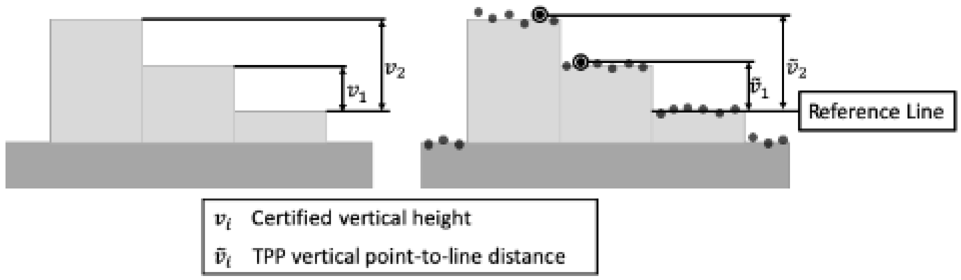

Figure 37. Example vertical point-to-line distance between two horizontal surfaces on a gauge block to provide an estimation of the TPP reported vertical height between gauge block surfaces.

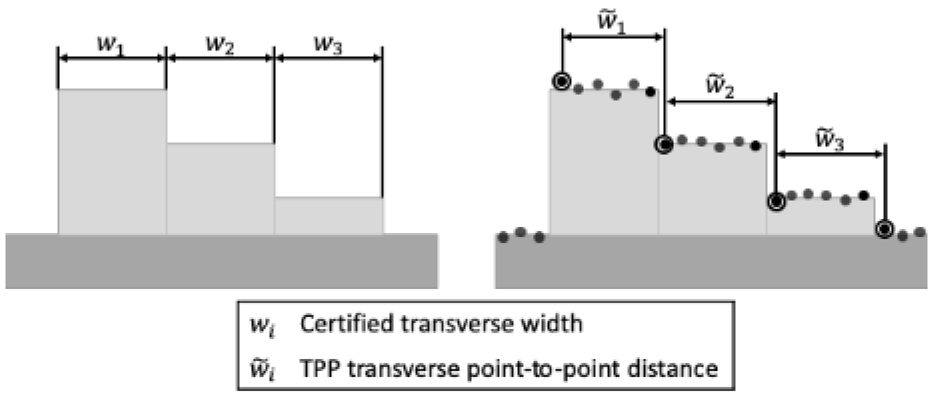

Figure 38. Example transverse point-to-point distances for a given horizontal gauge block surface.

8. REPORTING TEST STATISTICS

8.1 Transverse Measurement Spacing—Report the set of t_{sys} values.
8.2 Total Transverse Width—Report the set of w_{sys} values.
8.3 Vertical Measurement Spacing—Report the set of v_{sys} values.
8.4 Straightness Error—Report the set of e_s values.
8.5 Vertical Measurement Error—Report the estimated distribution of e_v values.
8.6 Transverse Measurement Error—Report the estimated distribution of e_t values.

9. CERTIFICATION REQUIREMENT STATEMENT

9.1 Requirement statements for certification of the static performance of the TPP system is provided in Table 2 for cross-slope, Table 3 for rut depth, and Table 4 for edge/curb drop off.

9.2 Certification shall be based on the final use and the frequency shall be as specified by the Certification agency. The TPP must successfully perform the test procedures outlined in Section 6 and satisfy the requirement statement provided in tables 23, 24, or 25 depending on the final use of the TPP data.

Table 23. Static performance requirement statement for cross-slope.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Transverse Measurement Spacing	NA	NA	NA	NA	25
Transverse Measurement Error	-15.0	-12.5	NA	12.5	15.0
Total Transverse Width	3800	NA	NA	NA	NA
Straightness Error	-8.0	-3.0	NA	3.0	8.0
Vertical Measurement Spacing	NA	NA	NA	NA	1.0
Vertical Measurement Error	-2.0	-1.0	NA	1.0	2.0

Table 24. Static performance requirement statement for rut depth.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Transverse Measurement Spacing	NA	NA	NA	NA	10
Transverse Measurement Error	-7.5	-5.0	NA	5.0	7.5
Total Transverse Width	4000	NA	NA	NA	NA
Straightness Error	-2.5	-1.0	NA	1.0	2.5
Vertical Measurement Spacing	NA	NA	NA	NA	0.1
Vertical Measurement Error	-1.5	-1.0	NA	1.0	1.5

Table 25. Static performance requirement statement for edge/curb drop-off.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Transverse Measurement Spacing	NA	NA	NA	NA	10
Transverse Measurement Error	-7.5	-5.0	NA	5.0	7.5
Total Transverse Width	4250	NA	NA	NA	NA
Straightness Error	-2.5	-1.0	NA	1.0	2.5
Vertical Measurement Spacing	NA	NA	NA	NA	0.1
Vertical Measurement Error	-1.5	-1.0	NA	1.0	1.5

10. SYSTEM CALIBRATION & VERIFICATION

10.1 The process of calibrating and checking the performance of the transverse pavement profiler's mapping sensors is the responsibility of the TPP operator. TPP operators should evaluate and confirm the manufacturer's recommendations for calibrating and verifying performance of mapping sensors.

10.2 In addition to manufacturer recommended verification methods, performance of the mapping sensors should be evaluated on a weekly basis during typical operation. See Section 10 in R###, Assessment of Body Motion Cancelation of the TPP System, for details regarding the verification process to be performed.

ANNEX A – STRAIGHT EDGE AND GAUGE BLOCK PROPERITIES

A.1. Straight Edge

A.1.1. Specified tolerances

A.1.1.1. Straightness/Flatness: ± 0.5 mm

A.1.1.2. Surface Parallelism: ± 0.3 mm

A.1.2. Surface Finish

A.1.2.1. Surface finish is only required on the top edge of the straight edge which will be measured by the TPP.

A.1.2.2. Surface finish shall induce diffuse reflection using any method of coating or media blasting desired while maintain the specified tolerances in Section A1.1.

A.1.2.3. No greater than 5.0% specular reflection is allowed.

A.2. Gauge Block

A.2.1. Specified tolerances

A.2.1.1. Height, width, and length: ± 0.1 mm

A.2.1.2. Flatness/Parallelism: ± 0.05 mm

A.2.2. Surface Finish

A.2.2.1. Surface finish is only required on the top edge of the straight edge which will be measured by the TPP.

A.2.2.2. Surface finish shall induce diffuse reflection using any method of coating or media blasting desired while maintain the specified tolerances in Section A2.1.

A.2.2.3. No greater than 5.0% specular reflection is allowed.

ANNEX B – OUTPUT DATA: TRANSVERSE PROFILE

B.1. Data Output Structure

B.1.1. This is the file format in which the individual mapping sensor profile scans shall be reported by the TPP's operator to the certification agency. The data to be reported in this file includes metadata describing the conditions in which the profile scan was acquired and the measured profile data points.

B.1.2. Metadata:

B.1.2.1. Line 1: TPP vendor name [space] TPP system name/model/make

B.1.2.2. Line 2: Data and timestamp on which profile was acquired in UTC format

B.1.2.2.1. Format: YYYY-MM-DDTHH:MM:SS+OFFH:OFFM

B.1.2.2.2. Example: 2019-10-16T18:11:30+00:00

B.1.2.3. Line 3: Standard practice performed – Mapping sensor tested

B.1.2.3.1. Format: Assessment Title – Mapping sensor # of total mapping sensor count

B.1.2.3.2. Example: Assessment of Static Performance – Mapping sensor 1 of 2

B.1.2.4. Line 4: The number of transverse profiles in the file

B.1.3. Measured profile data

B.1.3.1. Line 5: Transverse (x) corresponding to profile #1 where each measurement is separated by a [space] (meters)

B.1.3.2. Line 6: Vertical (z) data corresponding to profile #1 where each measurement is separated by a [space] (meters)

B.1.3.3. …

B.1.3.4. Line end: Vertical (z) data corresponding to the last profile where each measurement is separated by a [space] (meters)

ANNEX C – ESTIMATION OF MEASUREMENT ERROR

C.1. Vertical Measurement Error

C.1.1. When vertical measurements of a gauge block are collected with a TPP to determine the vertical measurement accuracy, there are four potential sources which contribute to the error in the collected measurements: 1) error in the measured height of the gauge block, 2) error in the measured height of the straight edge, 3) manufactured/calibration error in the height of the gauge block, 4) manufactured/calibration error in the flatness of the straight edge

C.1.2. The vertical measurement accuracy, the error of interest is the combination of the error in the measured height of the gauge block and the measure error in the measured height of the straight edge, together these can be referred to as the error in vertical measurement. In addition, data points along the straight edge are only considered within a distance d_s from the base of the gauge block to ensure that the straight edge can be considered a flat datum and no associated flatness error is needed in the vertical measurement. Thus, as long as d_s is maintained to be sufficiently small the fourth contribution can be considered trivial.

C.1.3. When these simplifications and bounds are placed on the establishments of the TPP's vertical height measurement, then the actual vertical height of the specified ith surface can be defined as the sum of the nominal vertical height of the surface and the uncertainty in the vertical height of the ith surface of the gauge block.

$$H_i = h + U_i$$

C.1.4. Similarly, we can consider that several measurements (several samples index by j) of the actual height of the ith surface of the gauge block is defined as the sum of the actual height of the ith surface and the jth measurement error.

$$\delta_{i,j} = H_i + E_{i,j}$$

C.1.5. Therefore, the measurement error for the jth measurement of the ith surface can be calculated from the two above equations. This particular sample of the vertical measurement error is the sum of the deterministic term (the measured height minus the nominal vertical height of the surface) and a random variable (the uncertainty in the height of the ith surface of the gauge block).

$$E_{i,j} = (\delta_{i,j} - h) - U_i$$

C.1.6. The uncertainty in this particular sample of measurement error is then just the uncertainty with which the actual height of the gauge block surface is known. While the uncertainty in the vertical height of the ith surface of the gauge block, U_i, may not be perfectly known, the gauge block can be certified such that a bound on the uncertainty can be established. This is typically stated as a tolerance on the manufacturing process, such that the uncertainty is above some minimum tolerance, u_{min}, and below some maximum tolerance, u_{max}, for all gauge block surfaces (including those in the particular sample).

$$u_{min} < U_i < u_{max}$$

C.1.7. The measurement error for the jth measurement of the ith surface is then bounded by these minimum and maximum bounds on the uncertainty.

$$(\delta_{i,j} - h) - u_{max} < E_{i,j} < (\delta_{i,j} - h) - u_{min}$$

C.1.8. To illustrate how the error in the TPP's measurement of vertical height of the gauge block surface can be isolated from the manufactured/certified error in the height of the gauge blocks, a simple example is provided.

C.1.8.1. Example: A TPP is used to collect measurements of a gauge block surface and the surface of a straight edge. Using these measurements a set of vertical height measurements are identified. The nominal height of the gauge block then subtracted from the vertical heights resulting in a distribution of error values. Four error values are selected from this distribution to represented the requirement statement:

5% — -0.261 mm
25% — -0.115 mm
75% — 0.107 mm
95% — 0.232 mm

C.1.8.2. It is known that the gauge block surface has a vertical height certified to ±0.05 mm. Therefore, the true requirement statement for the TPP vertical measurement error are:

5% — -0.261-0.05 = -0.311 mm
25% — -0.115-0.05 = -0.165 mm
75% — 0.107-(-0.05) = 0.157 mm
95% — 0.232-(-0.05) = 0.282 mm

C.2. Transverse Measurement Error

C.2.1. When measurements of the horizontal width of the gauge block are collected with a TPP to determine the transverse measurement accuracy, there are two potential sources which contribute to the error in the collected measurements: 1) error in the measured width of the gauge block, 2) manufactured/calibration error in the width of the transverse surface.

C.2.2. When collecting data, several samples can be taken a TPP to identify a horizontal width of a specified surface of a gauge block. However, for each sample taken with the TPP both errors are connected so a method for identifying the TPP's horizontal measurements capabilities is needed.

C.2.3. The actual transverse width of the specified i^{th} surface can be defined as the sum of the nominal transverse width of the surface and the uncertainty in the transverse width of the i^{th} surface of the gauge block.

$$W_i = w + U_i$$

C.2.4. Similarly, we can consider that several measurements (several samples index by j) of the actual width of the i^{th} surface of the gauge block is defined as the sum of the actual width of the i^{th} surface and the j^{th} measurement error.

$$\delta_{i,j} = W_i + E_{i,j}$$

C.2.5. Therefore, the measurement error for the j^{th} measurement of the i^{th} surface can be calculated from the two above equations. This particular sample of the transverse measurement error is the sum of the deterministic term (the measured width minus the nominal transverse width of the surface) and a random variable (the uncertainty in the width of the ith surface of the gauge block).

$$E_{i,j} = (\delta_{i,j} - w) - U_i$$

C.2.6. The uncertainty in this particular sample of measurement error is then just the uncertainty with which the actual width of the gauge block surface is known. While the uncertainty in the transverse width of the ith surface of the gauge block, U_i, may not be perfectly known, the gauge block can be certified such that a bound on the uncertainty can be established. This is typically stated as a tolerance on the manufacturing process, such that the uncertainty is above some minimum tolerance, u_{min}, and below some maximum tolerance, u_{max}, for all gauge block surfaces (including those in the particular sample).

$$u_{min} < U_i < u_{max}$$

C.2.7. The measurement error for the jth measurement of the ith surface is then bounded by these minimum and maximum bounds on the uncertainty.

$$(\delta_{i,j} - w) - u_{max} < E_{i,j} < (\delta_{i,j} - w) - u_{min}$$

C.2.8. To illustrate how the error in the TPP's measurement of transverse width of the gauge block surface can be isolated from the manufactured/certified error in the width of the gauge blocks, a simple example is provided.

C.2.8.1. Example: A TPP is used to collect measurements of a gauge block surface and the surface of a straight edge. Using these measurements a set of transverse width measurements are identified. The nominal width of the gauge block then subtracted from the transverse width resulting in a distribution of error values. Four error values are selected from this distribution to represented the requirement statement:

5% — -0.261 mm
25% — -0.115 mm
75% — 0.107 mm
95% — 0.232 mm

C.2.8.2. It is known that the gauge block surface has a transverse width certified to ±0.05 mm. Therefore, the true requirement statement for the TPP transverse measurement error are:

5% — -0.261-0.05 = -0.311 mm
25% — -0.115-0.05 = -0.165 mm
75% — 0.107-(-0.05) = 0.157 mm
95% — 0.232-(-0.05) = 0.282 mm

APPENDIX C. ASSESSMENT OF BODY MOTION CANCELATION IN TRANSVERSE PAVEMENT PROFILING SYSTEMS

1. SCOPE

1.1. This practice describes the procedure to assess the accuracy and precision of the Transverse Pavement Profiler (TPP) when the system is excited at the primary ride and wheel hop excitation frequencies. The particular specifications which will be assessed are: vehicle body motion error.

1.2. The minimum requirements focus on the need for accurate and repeatable transverse measurements for network and project level data collection.

1.3. If any part of this practice is in conflict with referenced documents, such as ASTM Standards, this practice takes precedence for its purposes.

1.4. This standard practice is intended to be conducted in conjunction with three other standard practices to fully assess and certify the TPP in typical operating conditions. For static assessment see R### Assessment of Static Performance of TPP Systems, for ground reference and transverse width assessment see R### Assessment of Highway Performance in TPP Systems, and for assessment of drift mitigation see R### Assessment of Navigation Drift in TPP Systems.

1.5. This practice does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this practice to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

2. REFERENCED STANDARDS

2.1. AASHTO Standards:

- R010, Definition of Terms Related to Quality and Statistics as Used in Highway Construction
- Assessment of Static Performance in Transverse Pavement Profiling Systems
- Assessment of Highway Performance in Transverse Pavement Profiling Systems
- Assessment of Navigation Drift in Transverse Pavement Profiling Systems
- Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment

3. TERMINOLOGY

3.1. See AASHTO R###, Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment, for definition of terms used in this standard practice.

3.2. Table 26 provides the physical parameter definitions, symbols, and default values to be used when administering this standard.

Table 26. Physical parameter definitions and default values.

Physical Parameter	Symbol	Default Value(s)
Excitation board length	L_e	1.28 ± 0.05 m (4.2 ± 0.2 ft)
Excitation board cleat spacing	a	256.0 ± 5.0 mm (10.0 ± 0.2 in)
Excitation board cleat width	w	90.0 ± 5.0 mm (3.5 ± 0.2 in)
TPP Operating speed	v	9.0 ± 2.0 kph (5 ± 2 mph), 13.0 ± 2.0 kph (8 ± 2.0 mph), 18.5 ± 2.0 kph (12 ± 2 mph)
Minimum flat plate length	l_p	1.2 m (4.0 ft)
Minimum flat plate width	w_p	0.6 m (2.0 ft)
Minimum flat plate thickness	t_p	10.0 mm (0.4 in)
Flat plate offset from front center of excitation board	d_p	TPP dependent
TPP track width of the nearest wheelset	w_t	TPP dependent
Minimum number of passes through the test section at each speed	n_p	2
Number of measurements to randomly select	N_r	50

4. SIGNIFICANCE AND USE

4.1. Measured transverse profiles of road surfaces are used to extract pavement deformation parameters such as rut depth, cross-slope, and edge/curb drop off. The accuracy of the estimated pavement deformation parameters depends on the collected data accurately representing the transverse section of the road surface.

4.2. Requirements on the cancelation of vehicle body motion ensure that the TPP is effectively canceling out the motion of the vehicle body and the resulting collected data accurately represents the road surface.

4.3. This practice outlines standard procedures for assessing the expected operational accuracy and precision of transverse pavement profilers when driving over rough road surfaces. The standard prescribes a procedure to evaluate the ability of the system to accurately represent a planar surface through multiple transverse profile measurements (a single point cloud) captured while the vehicle is subject to primary ride and roll excitations at a set range of speeds. Because the data are used for subsequent calculations for rut depth, cross slope, and edge/curb drop off, tables of the necessary accuracy and precision for certification are provided in the form of bias and confidence intervals for each use.

5. EQUIPMENT

5.1. The TPP must be able to collect transverse profiles at a minimum sampling rate of 30 complete transverse profile scans per second.

5.2. Provide all collected transverse profiles of the test section in electronic text files following the format prescribed by Annex B1.

6. DATA COLLECTION AND REPORTING

6.1. A test site which has ample space for a TPP to safely achieve the maximum operating speed in the set of operating speeds, v, and safely slow down afterwards shall be selected.

6.2. Two reference lines (e.g. chalk lines) shall be marked on the road surface to ensure that the excitation boards and reference objects of longitudinal length L_e and transverse width w_p are aligned appropriately. The first reference line, a central primary reference line shall be placed in the longitudinal direction of the test site. A secondary reference line shall be placed in the transverse direction.

6.3. To excite both the primary ride and primary roll characteristics of the TPP simultaneously, the certification agency shall offset both excitation boards in the longitudinal direction by a quarter of the excitation board length ($L_e/4$) in opposing directions about the secondary reference (e.g. one board shall be shifted closer to the start of the test site and one board shall be shifted further from the start of the test site).
Note 1—The excitation boards are designed to excite the primary ride and wheel-hop natural frequencies of the TPP when the TPP travels at a speed of over the excitation boards. The provided default values are designed around a typical passenger vehicle. If the TPP being assessed is not a passenger vehicle see (Smith and Ferris, 2010) for the general design of an excitation board based on the two primary ride frequencies.
Note 2—The offset of the excitation boards (quarter of the excitation board length) is designed around the primary roll frequency of a typical passenger vehicle. If the TPP being assessed is not a passenger vehicle, then the primary roll frequency should be used to identify the target excitation board offset to excite the primary roll frequency.

6.4. Using the primary reference line the excitation boards shall be moved in the transverse direction to ensure they are equally spaced about the primary reference line and the distance between the excitation boards is equivalent to the track width, w_t, of the TPP. Figure 39, provides an illustration of the excitation boards setup to excite the primary ride and roll characteristics.

6.5. The central reference object of longitudinal length L_e, transverse width w_p, and vertical thickness t_p conforming to the specifications provided in Annex A1 shall be centered transversely along the primary reference line. The offset, d_p, of the object in the longitudinal direction from the secondary reference line shall be dependent on the nominal offset of the mapping sensors from the nearest TPP wheelset. Figure 40 provides a side view representation of the longitudinal offset of the mapping sensor which is proceeding or following the nearest wheelset.

6.5.1. The longitudinal offset, d_p, will vary between TPP systems. However, this varying distance is needed to ensure that mapping sensors are collecting data when the TPP is experiencing peak ride/roll disturbances.

6.6. Two additional transversely offset reference objects of longitudinal length L_e, transverse width w_p, and vertical thickness t_p conforming to the specifications provided in Annex A1 shall be placed outside the excitation boards/wheel path of the TPP. Each reference object shall be placed on opposite sides of the test site and placed such that the furthest transverse edges are a distance $W_{TS}/2$ from the primary reference line. Both reference objects shall be offset in the longitudinal direction by a distance d_p from the secondary reference line.

6.7. Figure 39 provides a schematic of the test site and shows the orientation of all three reference objects with respect to the primary and secondary reference lines. For data reduction, the central reference object shall be used for rut depth and cross slope analysis, while the two transversely offset reference objects shall be used for edge/curb detection analysis.

6.8. The TPP operator shall drive the TPP system over the excitation boards for a total of n_p times per target speed.

6.9. All collected data of the reference object shall be reported in a global reference frame with a structure conforming to the point cloud format in Annex B1.

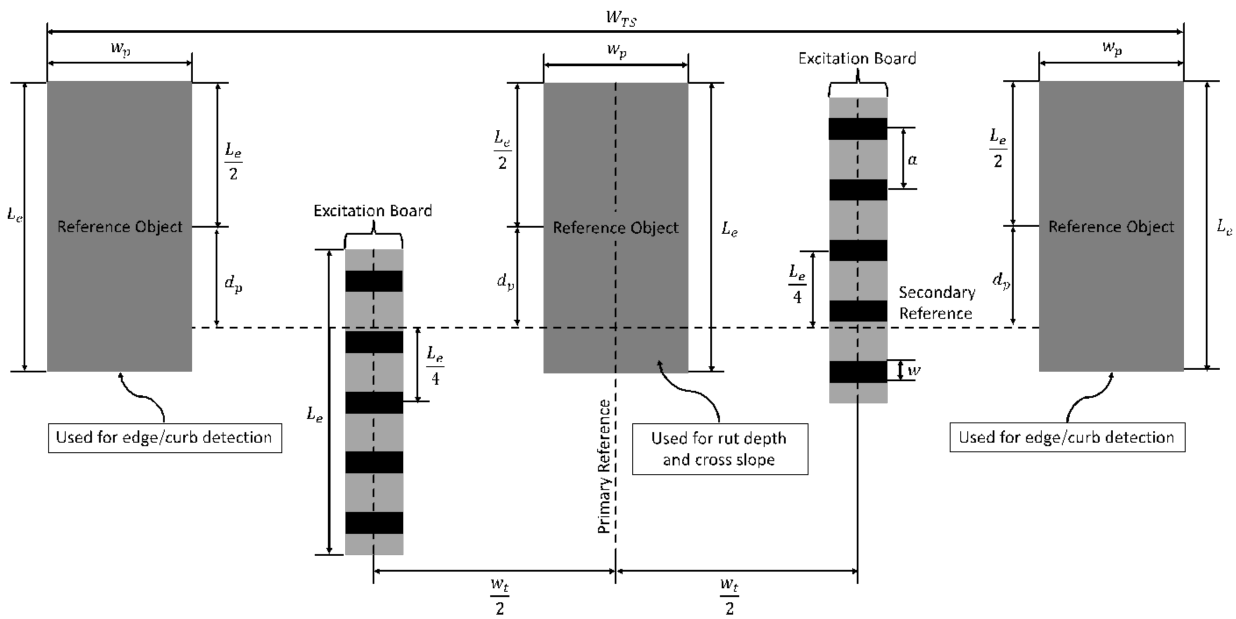

Figure 39. Vehicle motion compensation setup to induce primary ride and roll TPP harmonic.

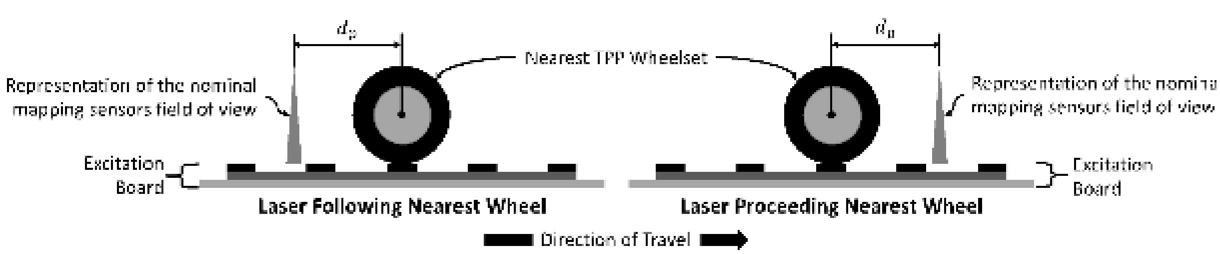

Figure 40. Determination of the plate offset based on the nominal mapping sensor offset from the nearest wheelset of the TPP.

7. DATA REDUCTION

7.1 Vehicle Body Motion Error

7.1.1 Per point cloud, all measured points on the top surface of a reference object shall be identified, by utilizing the discrete changes in height in comparison to the road surface, and added to the set S_p.

7.1.1.1 Vehicle body motion error analysis shall be performed on each reference object separately. All error results from the central reference object shall be used for rut depth and cross slope requirements while all error results from the two transversely offset reference objects shall be used for edge/curb detection requirements.

7.1.2 A least squares error plane fit shall be applied to the measurements in set S_p and the point-to-plane distance between each measurement in the set S_p and the plane fit to the measurements shall be calculated and stored in the set e_{bm}. The set e_{bm} will be used to evaluate the body motion error present in the TPP point cloud.

7.1.3 The process of fitting a plane to point cloud measurements of a reference object shall be repeated for each provided point cloud and each reference object present in the point cloud.

7.1.4 The complete set of e_{bm} values derived from the central reference object for all reported point clouds at all operating speeds shall serve as a sample from the population of true vehicle body motion error when performing rut depth and cross slope analysis.

7.1.5 The complete set of e_{bm} values derived from the two transversely offset reference objects for all reported point clouds at all operating speeds shall serve as a sample from the population of true vehicle body motion error when performing edge/curb detection.

7.2 Vertical Measurement Spacing

7.2.1 Per point cloud, all measured points on the top surface of a reference object shall be identified, by utilizing the discrete changes in height in comparison to the road surface, and added to the set S_p.

7.2.1.1 Vertical measurement spacing analysis shall be performed on each reference object separately. All spacing results from the central reference object shall be used for rut depth and cross slope requirements while all spacing results from the two transversely offset reference objects shall be used for edge/curb detection requirements.

7.2.2 The vertical height of each measurement in the set S_p shall be defined by the point-to-plane distance between the reported TPP measurement and a least squares error plane fit to the measurements (i.e. vertical body motion error associated with a measurement shall be representative of the vertical height).

7.2.3 From the set S_p, N_r measurements shall be randomly chosen and added to the set S_r. These N_r measurements shall be used to estimate the vertical measurement spacing of the TPP reported data.

7.2.4 For each measurement in the set S_r, the nearest neighboring point in each of four quadrants shall be identified (1 neighboring point per quadrant). The nearest neighboring measurement per quadrant shall be identified as the measurement point which is located in the quadrant of interest and has the shortest three-dimensional Euclidian distance. The quadrants shall be defined by a set of two dimensional orthogonal axes oriented at a 45° angle with respect to the transverse-longitudinal axes of the path coordinate system. See figure 41, for an example of the quadrants for a selected point and the identification of the nearest neighboring point per quadrant.

7.2.5 The vertical point-to-point distance between the respective measurement in the set S_r and each of the four nearest neighboring points shall provide four estimates of the vertical spacing. The four calculated point-to-point distances shall be added to the set v_{prof}.

7.2.6 The complete set of v_{prof} values derived from the central reference object for all reported point clouds at all operating speeds shall serve as a sample from the population of true vertical measurement spacing when performing rut depth and cross slope analysis.

7.2.7 The complete set of v_{prof} values derived from the two transversely offset reference objects for all reported point clouds at all operating speeds shall serve as a sample from the population of true vertical measurement spacing when performing edge/curb detection.

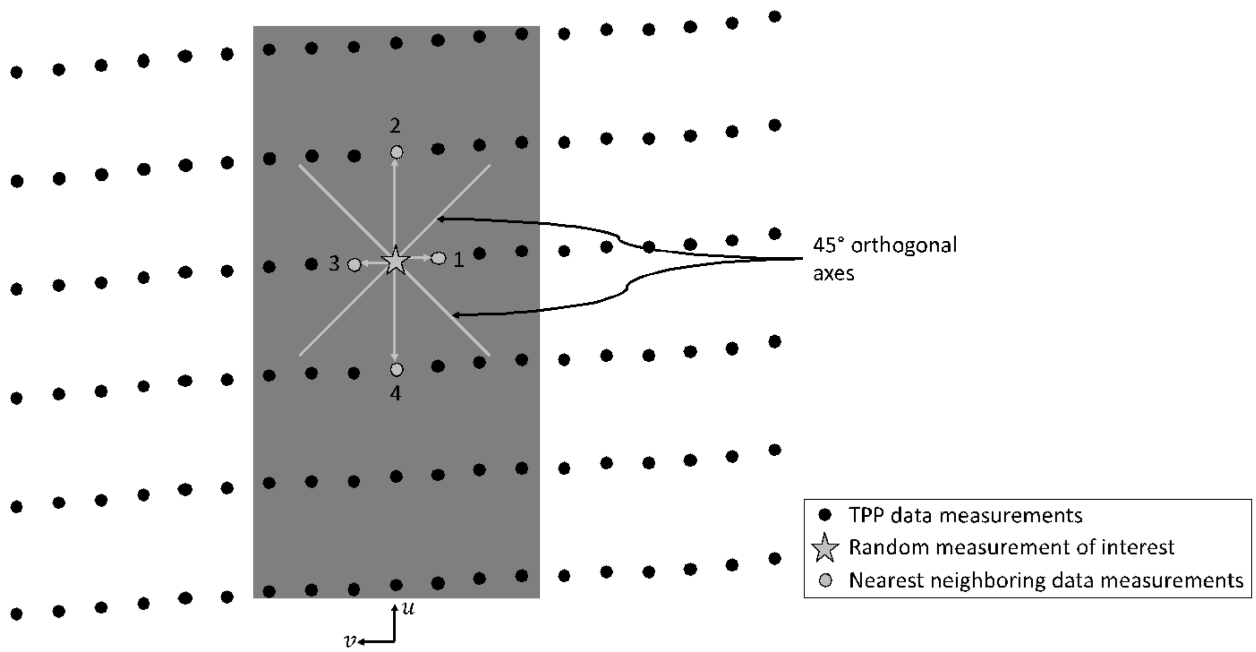

Figure 41. Illustration of four quadrants oriented with respect to the path coordinate system and identification of the nearest neighboring point in each respective quadrant.

8. REPORTING TEST STATISTICS

8.1 Vehicle Body Motion Error—Report the set of e_{bm} values.

8.2 Vertical Measurement Spacing—Report the set of v_{prof} values.

9. CERTIFICATION REQUIREMENT STATEMENT

9.1 Requirement statements for certification of body motion cancelation based on the use of the transverse profile measurements is provided in Table 2 for cross-slope, Table 3 for rut depth, and Table 4 for edge/curb drop off.

9.2 Certification shall be based on the final use and the frequency shall be as specified by the Certification Agency. The TPP must successfully perform the test procedures outlined in Section 6 and satisfy the requirement statements provided in Tables 27, 28, or 29 depending on the final use of the TPP data.

Table 27. Body motion cancelation requirement statement for cross-slope.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Vehicle Body Motion Error	-8	-5	NA	5	8
Vertical Measurement Spacing	NA	NA	NA	NA	1.0

Table 28. Body motion cancelation requirement statement for rut depth.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Vehicle Body Motion Error	-4	-2.5	NA	2.5	4
Vertical Measurement Spacing	NA	NA	NA	NA	0.1

Table 29. Body motion cancelation requirement statement for edge/curb drop-off.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Vehicle Body Motion Error	-4	-2.5	NA	2.5	4
Vertical Measurement Spacing	NA	NA	NA	NA	0.1

10. SYSTEM CALIBRATION & VERIFICATION

10.1 The process of calibrating and checking the performance of the transverse pavement profiler's mapping and location sensors is the responsibility of the TPP operator. TPP operator should evaluate and confirm the manufacturer's recommendations for calibrating and verifying performance of mapping and location sensors.

10.2 In addition to manufacturer recommended verification methods, the dynamic performance of the TPP must be verified on a weekly basis during typical operation. The dynamic performance of the TPP shall be evaluated by performing the body motion cancelation assessment. The procedures provided in Section 6, Data Collection and Reporting, shall be followed.

Note 3—For verification of the TPP system during collection of rut depth and/or cross slope measurements, only the central reference object is required. For verification of the TPP systems during edge/curb detection all three reference objects are required.

10.3 Data reduction provided in Section 7 shall be followed for analysis of the TPP data collected during verification.

10.4 Successful verification (passing) is based on the use of the transverse profile measurements is provided in table 27 for cross-slope, table 28 for rut depth, and table 29 for edge/curb drop off in the form of requirement statements containing bias and confidence intervals.

ANNEX A – REFERENCE OBJECT SPECIFICATIONS

A.1. Flat Plate

A.1.1. Specified tolerances

A.1.1.1. Top surface parallelism/flatness: ± 0.5 mm

ANNEX B – OUTPUT DATA FILE FORMAT

B.1. Point Cloud File Format

B.1.1. This is the format in which point cloud data from the TPP shall be reported to the certification agency. The data to be reported in this format includes metadata describing the conditions in which the profile was acquired and general information about the data.

B.1.2. Metadata:

B.1.2.1. Line 1: TPP vendor/operator/owner name [Tab] TPP system name/model/make

B.1.2.2. Line 2: Data and timestamp on which the data was acquired in UTC format

B.1.2.2.1. Format: YYYY-MM-DDTHH:MM:SS+OFFH:OFFM

B.1.2.2.2. Example: 2019-10-22T14:32+00:00

B.1.2.3. Line 3: Northing and Easting of the origin specified in UTM coordinates along with the Elevation of the origin specified in WGS84 coordinates.

B.1.2.3.1. Format: Easting [Tab] Northing [Tab] Elevation

B.1.2.3.2. Example: 725498.16 4196729.93 623.9375

B.1.2.4. Line 4: Standard practice performed

B.1.2.4.1. Format: Assessment Title – Point Cloud

B.1.2.4.2. Example: Assessment of Highway Performance – Point Cloud
B.1.2.5. Line 5: The total number of transverse profiles in the file
B.1.3. Profile points:
B.1.3.1. Line 6: Easting (X) coordinates of profile #1 separated by a [space] (meters)
B.1.3.2. Line 7: Northing (Y) coordinates of profile #1 separated by a [space] (meters)
B.1.3.3. Line 8: Elevation (Z) coordinates of profile #1 separated by a [space] (meters)
B.1.3.4. …
B.1.3.5. Line end: Elevation (Z) coordinates of last profile separated by a [space] (meters)

APPENDIX D. ASSESSMENT OF NAVIGATION DRIFT IN TRANSVERSE PAVEMENT PROFILING SYSTEMS

1. SCOPE

1.1. Transverse Pavement Profiling (TPP) systems that provide global positions of road surfaces are often susceptible to drift in the estimate of the global position over time. This practice describes the procedure to assess the amount of drift present in localization systems used in TPPs.

1.2. The minimum requirements stipulated herein are intended to focus on the need for accurate and repeatable transverse measurements for network and project level data collection.

1.3. If any part of this practice is in conflict with referenced documents, such as ASTM Standards, this practice takes precedence for its purposes.

1.4. This standard practice is intended to be conducted in conjunction with three other standard practices to fully assess and certify the TPP in typical operating conditions. For static assessment see R### Assessment of Static Performance in TPP Systems, for body motion assessment see R### Assessment of Body Motion Cancelation in TPP Systems, and for ground reference and transverse width assessment see R### Assessment of Highway Performance in TPP Systems.

1.5. This practice does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this practice to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

2. REFERENCED STANDARDS

2.1. AASHTO Standards:

- R010, Definition of Terms Related to Quality and Statistics as Used in Highway Construction
- Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems
- Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment

3. TERMINOLOGY

3.1. See AASHTO R###, Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment, for definition of terms used in this standard practice.

3.2. Table 1 provides the physical parameter definitions, symbols, and default values to be used when administering this standard.

Table 30. Physical parameter definitions and default values.

Physical Parameter	Symbol	Default Value(s)
Minimum length for the test section	L_T	54 m (178 ft)
Minimum width for the test section	W_T	24 m (79 ft)
Radius of figure-eight turn	R	10.0 ± 0.2 m (32.8 ± 0.7 ft)
Distance between center of turns	D	28.3 ± 0.5 m (92.8 ± 1.6 ft)
Minimum forward speed	v	13 kph (8 mph)
Minimum completion time	t	37 s
Minimum number of complete figure-eight loops to be collected	n_p	5
Maximum Horizontal width/length of the reference object	w_{obj}	540 ± 70 mm (21.25 ± 2.75 in)
Vertical height of the reference object	h_{obj}	75 ± 25 mm (3.0 ± 1.0 in)

4. SIGNIFICANCE AND USE

4.1. Measured transverse profiles of road surfaces are used to extract pavement deformation parameters such as rut depth, cross-slope, and edge/curb drop off. The accuracy of the estimated pavement deformation parameters depends on the measured transverse profile accurately representing a transverse section of the road surface.

4.2. Requirements on the above-mentioned specifications of the allowable drift in the location sensors ensures that the measured profile accurately represents the road surface.

4.3. This practice outlines standard procedures for certifying and verifying the operational accuracy and precision of transverse pavement profilers while undergoing lateral acceleration. The test requires the equipment to be driven in a figure-eight over a reference object with a known global position. By making multiple passes over the object, the test prescribes how to determine the position of the object in the global reference frame for each pass. The identified position of the reference object is compared to the known global position to determine the resulting error in the northing, easting, and elevation directions. Because the data are used for subsequent calculations for rut depth, cross slope, and edge/curb drop off, tables of the necessary accuracy and precision are provided in the form of bias and confidence intervals for each use.

5. EQUIPMENT

5.1. The TPP must be able to collect transverse profiles at a minimum sampling rate of 30 complete transverse profile scans per second.

5.2. Provide all collected transverse profiles of the test section in electronic text files following the format prescribed by Appendix X1.

6. DATA COLLECTION AND REPORTING

6.1. A test section of size L_T by W_T shall be selected to setup a figure-eight course for conducting the drift test. The test section shall contain minimal obstructions (e.g. poles, light posts, signs, etc.). If any obstructions are present in the test area care should be taken to ensure they are not in the figure-eight path and that the TPP can safely navigate around them when traveling at a speed of v around the path.

6.2. The figure-eight shall be marked-out in the test region using any desired method (e.g. cones, paint, reflective markers, etc.). The figure-eight is formed using two overlapping circles with a radius of R and centers of curvature separated by a distance D. Figure 42 provides a schematic of the test region and the figure-eight layout.

Note 1—The drift test is designed such that a target lateral acceleration of 0.13g occurs when a TPP drives along a curve of radius, , at a target speed of . In conjunction, the number of passes over the stationary object is defined to allow enough time for a significant amount of drift to occur in the global measurements of the object of interest. If the TPP is unable to perform the test at the default radius, then the radius of the figure-eight can be increased along with the target speed to maintain the target lateral acceleration of 0.13g. When the radius and speed are adjusted the number of passes over the stationary object may change to ensure the duration of the test is consistent. See, [CITE FINAL FHWA REPORT] for the connection between the figure-eight radius, target TPP speed, and number of passes.

6.3. A reference object, conforming to the materials/fabrication specifications provided in Appendix X2, with a maximum horizontal width/length of w_{obj} and vertical height h_{obj} shall be placed at the center of the figure-eight. When placing the reference object on the ground, any desired leveling method shall be used to ensure the reference object is level in the horizontal plane. The reference object shall be supported at only 3 locations along the bottom of the object to achieve a level top surface while ensuring the object will not move during the entire duration of the test.

6.4. A single reference point (e.g. corner or peak) on the reference object shall be established/known and the global position of the reference point shall be obtained and reported in a global reference frame. The global position shall be established using survey grade equipment and be known to within ±50 mm in the northing and easting directions.

6.5. The TPP operator shall drive along the figure-eight test section at a minimum forward speed of v. The TPP is only required to acquire transverse profiles of the reference object, no measurements of the remainder of the figure-eight are necessary, but are allowed.

6.6. The TPP shall complete at least n_p laps of the figure-eight course resulting in $2n_p$ measurements of the reference object.

Note 2—One full completion of the figure-eight is equivalent to two passes over the reference object.

6.7. The transverse measurements collected by the TPP shall be reported by the TPP operator as a point cloud. The specific file format of the point cloud is provided in Appendix X1. Each pass over the reference object shall be reported in separate point cloud files.

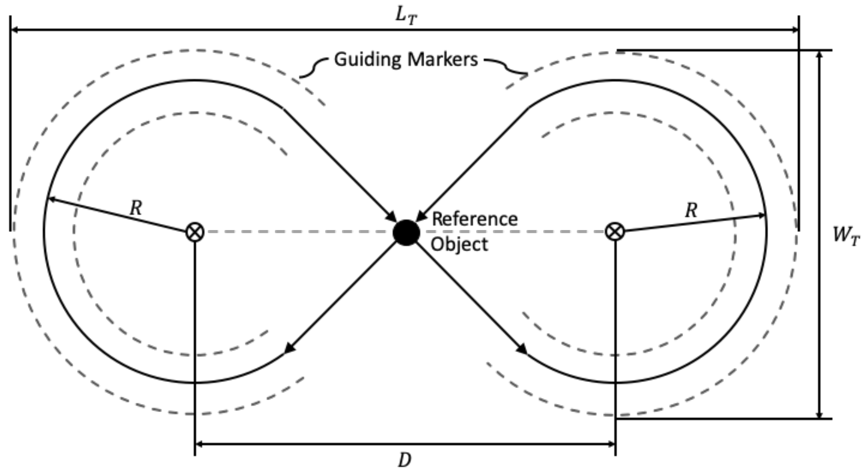

Figure 42. TPP drift assessment schematic.

7. DATA REDUCTION

7.1 The position of the reference object shall be identified using the global position of the reference point obtained in Section 6.4, after placing the reference object on the road surface. The position of the reference object shall be represented by three parameters: Easting (x_t), Northing (y_t), and Elevation (z_t).

7.2 For the reference object, a set of verifiable dimensions shall be known with respect to a single reference point (e.g. corner or peak) which correlates with the global position of the reference object collected during testing. The reference point shall be characterized by its three-dimensional measurement (x_o, y_o, and z_o) in the component reference frame. In figure 43a the center of the reference object is considered the reference point and is represented by the larger black circle.

7.3 The verifiable dimensions along with the reference point shall be used to establish a reference point cloud, S_{loc}, in a component reference frame. An example reference point cloud is illustrated by the smaller black dots and the larger black dot of the reference point in figure 43a.

7.4 Per reported point cloud, the measurements which correspond to the surfaces of the reference object shall be identified and added to the set S_{obj}.

7.5 The set S_{obj} shall be used to estimate the location of the reference point with respect to the TPP measurements in the set S_{obj}. To estimate the location of the reference point a registration (set of translations and rotations) required to find the best fit of S_{loc} to S_{obj} must be identified. The required registration shall be determined using an Iterative Closest Point (ICP) algorithm which minimizes the distance error between the measurements in S_{loc} and S_{obj}. When performing the ICP algorithm S_{obj} shall be considered the stationary/fixed measurement set and S_{loc} shall be considered the free/unfixed measurement set.

7.6 Upon determining the registration required to minimize the distance error, the estimated reference point of the reference object according to the TPP point cloud can be identified by applying the registration to the set S_{loc}. The resulting translated and rotated reference point, originally (x_o, y_o, and z_o), shall be stored as x_i, y_i, and z_i. In figure 43b the translated and rotated reference point is illustrated by the dark gray star with a black outline.

7.7 Error in the easting position, e_x, shall be calculated as the difference between the global easting position (x_t) and the estimated TPP easting position (x_i). The complete set of e_x values from all point clouds shall serve as a sample from the population of true easting position errors.

7.8 Error in the northing position, e_y, shall be calculated as the difference between the global northing position (y_t) and the estimated TPP northing position (y_i). The complete set of e_y values from all point clouds shall serve as a sample from the population of true northing position errors.

7.9 Figure 44 provides an illustration of the easting and northing position error for a single TPP point cloud. In figure 44 a zoomed in view of the center of the figure-eight is provided to show the global position of the reference object (highlighted by the darker gray box) and the estimated reference point of the reference object in the TPP point cloud (highlighted by the lighter gray box).

7.10 Repeatability in the elevation position, r_z, shall be calculated as the difference between the estimated TPP elevation position (z_i) and the mean estimated TPP elevation position of the reference object from all reported point clouds. The complete set of r_z values from all point clouds shall serve as a sample from the population of true elevation position repeatability.

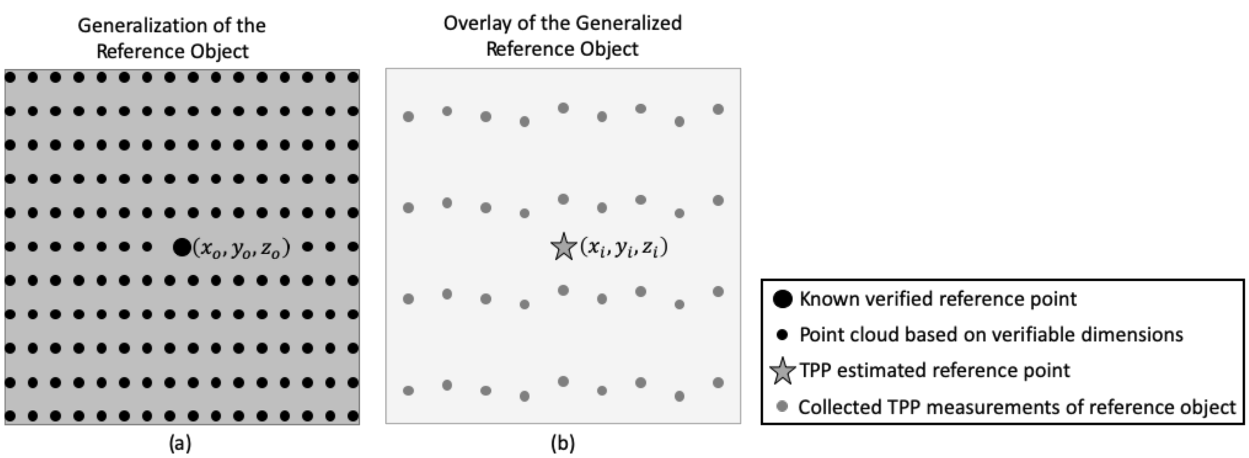

Figure 43. (a) Generalized reference object with reference point cloud based on verifiable dimensions which are referenced to the reference point (, , and). (b) Estimated location of the reference point based on the lowest distance error fit of the reference point cloud to the TPP point cloud measurements of the reference object.

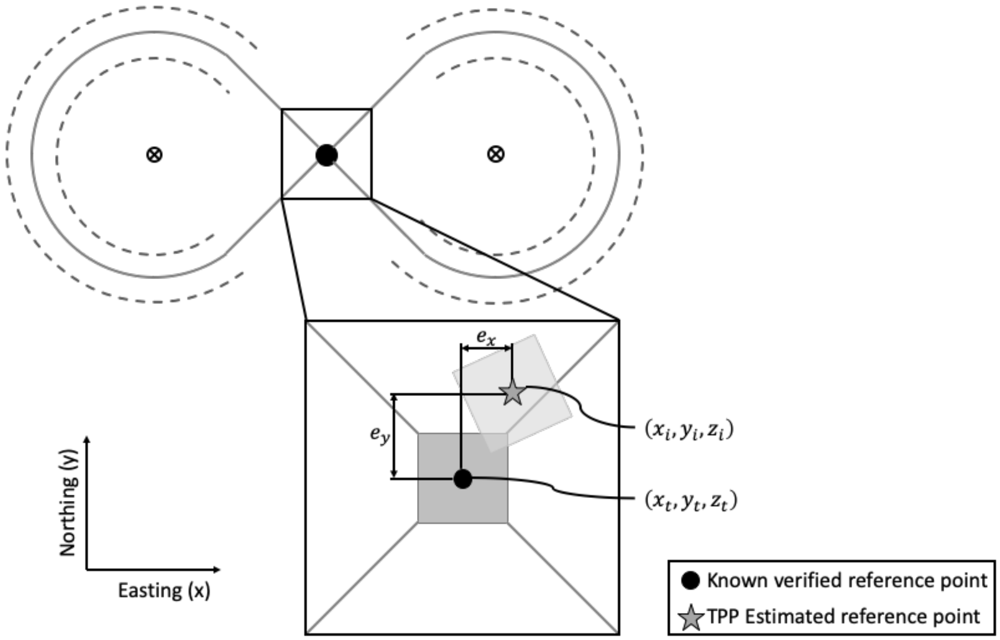

Figure 44. Illustration of the easting and northing position errors between the global position of the reference object and an estimated position of the object based on the TPP point cloud.

8. REPORTING TEST STATISTICS

8.1 Easting (x) Position Error—Report the set of e_x values.
8.2 Northing (y) Position Error—Report the set of e_y values.
8.3 Elevation (z) Position Repeatability—Report the set of r_z values.

9. CERTIFICATION REQUIREMENT STATEMENT

9.1 Requirement statements for certification of the navigation drift mitigation of the TPP based on the use of the transverse profile measurements is provided in table 31 for cross-slope, table 32 for rut depth, and table 33 for edge/curb drop off.

9.2 Certification shall be based on the use and the frequency shall be specified by the Owner-Agency. The TPP must successfully perform the test procedures outlined in Section 6 and satisfy the requirement statements provided in tables 31, 32, or 33 depending on the use of the TPP.

Table 31. Navigation drift requirement statement for cross-slope.

	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
Output Test Statistic	90% (5%)	50% (25%)		50% (25%)	90% (95%)

Easting (x) Position Error	-1000	-500	NA	500	1000
Northing (y) Position Error	-1000	-500	NA	500	1000
Elevation (z) Position Repeatability	-150	-100	NA	100	150

Table 32. Navigation drift cancelation requirement statement for rut depth.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Easting (x) Position Error	-1000	-500	NA	500	1000
Northing (y) Position Error	-1000	-500	NA	500	1000
Elevation (z) Position Repeatability	-150	-100	NA	100	150

Table 33. Navigation drift cancelation requirement statement for edge/curb drop-off.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Easting (x) Position Error	-1000	-500	NA	500	1000
Northing (y) Position Error	-1000	-500	NA	500	1000
Elevation (z) Position Repeatability	-150	-100	NA	100	150

10. SYSTEM CALIBRATION & VERIFICATION

10.1 The process of calibrating and checking the performance of the transverse pavement profiler's location sensors is the responsibility of the TPP operator. TPP operators should evaluate and confirm the manufacturer's recommendations for calibrating and verifying performance of location sensors.

10.2 In addition to manufacturer recommended verification methods, the navigation drift performance of the TPP should be periodically evaluated during typical operation. See Section 10 in [CITE Body Motion Cancelation] for details regarding verification process and output statistics to analyze.

ANNEX A – POINT CLOUD FILE FORMAT

A.1. Data Output Structure

A.1.1. This is the format in which point cloud data from the TPP shall be reported to the certification agency. The data to be reported in this format includes metadata describing the conditions in which the profile was acquired and general information about the data.

A.1.2. Metadata:

A.1.2.1. Line 1: TPP vendor name [space] TPP system name/model/make

A.1.2.2. Line 2: Dat3 and timestamp on which the data was acquired in UTC format

A.1.2.2.1. Format: YYYY-MM-DDTHH:MM:SS+OFFH:OFFM

A.1.2.2.2. Example: 2019-10-16T18:11:30+00:00

A.1.2.3. Line3: Nothing and Easting of the origin specified in UTM coordinates along with the Elevation of the origin specified in WGS84 coordinates.

A.1.2.3.1. Format: Easting [tab] Northing [tab] Elevation

A.1.2.3.2. Example: + 725498.16 4196729.93 623.9375

A.1.2.4. Line 4: Assessment Title

A.1.2.4.1. Example: Assessment of Navigation Drift

A.1.2.5. Line 5: The number of profiles in the file

A.1.3. Measured Point Cloud Data

A.1.3.1. Line 6: Easting (X) coordinates of Profile #1 separated by a [space] (meters)

A.1.3.2. Line 7: Northing (Y) coordinates of Profile #1 separated by a [space] (meters)

A.1.3.3. Line 8: Elevation (Z) coordinates of Profile #1 separated by a [space] (meters)

A.1.3.4. …

A.1.3.5. Line end: Elevation (Z) coordinates of last profile separated by a [space] (meters)

ANNEX B – REFERENCE OBJECT MATERIAL SPECIFICATIONS

B.1. Required Tolerances

B.1.1. Specified planar feature tolerances

B.1.1.1. Flatness: ± 0.1 mm

B.1.1.2. Parallelism: ± 0.1 mm

B.1.2. Surface finish

B.1.2.1. Note surface finish is only required on faces which the TPP will measure (i.e., top surfaces)
B.1.2.2. Must induce diffuse reflection
B.1.2.3. Allow no greater than 5% specular reflection

ANNEX C – Estimation of Global Position Error

C.1. Northing and Easting Position Error

C.1.1. When global location of a reference object is collected with a TPP to determine the navigation drift, there are three potential sources which contribute to the error in the collected measures: 1) error in the TPP's three-dimensional measurements of the reference object, 2) manufactured/calibration error in the surfaces of the reference object, 3) error in the surveyed global location of the object.

C.1.2. For the navigation drift test, the manufacturing/certification tolerance requirements on the reference object are defined such that the contribution to navigation drift can be considered trivial. Therefore, the primary external contributor to the navigation drift error is the error in the surveyed global position.

C.1.3. When this simplification and bounds are placed on the establishments of the TPP's global measurements, then the actual global position in each horizontal direction can be defined as the sum of the nominal horizontal dimension of the reference object and uncertainty in surveyed location of the reference object.

$$H = h + U$$

C.1.4. Similarly, we can consider that several measurements (several samples index by j) of the global location of the reference object is defined as the sum of the actuation horizontal location of the reference object and the j^{th} measurement error.

$$\delta_j = H + E_j$$

C.1.5. Therefore, the measurement error for the j^{th} measurement of the reference object can be calculated from the two above equations. This particular sample of the global measurement error is the sum of the deterministic term (the measured global location minus the nominal surveyed location) and a random variable (the uncertainty in the global location of the reference object).

$$E_j = (\delta_j - h) - U$$

C.1.6. The uncertainty in this particular sample of measurement error is then just the uncertainty with which the actual surveyed location of the reference object is known. While the uncertainty in the survey location of the reference object, U_i, may not be perfectly known, the surveyed location can be verified such that a bound on the uncertainty can be established. This is typically stated as a tolerance, such that the uncertainty is above some minimum tolerance, u_{min}, and below some maximum tolerance, u_{max}, for the final global location (including those in the particular sample).

$$u_{min} < U_i < u_{max}$$

C.1.7. The measurement error for the j^{th} measurement of the reference object is then bounded by these minimum and maximum bounds on the uncertainty.

$$(\delta_j - h) - u_{max} < E_j < (\delta_j - h) - u_{min}$$

C.1.8. To illustrate how the error in the TPP's measurement of global location of the reference object can be isolated from the error in the surveyed location of the reference object, a simple example is provided for global easting positions.

C.1.8.1. Example — A TPP is used to collect multiple global easting measurements of a reference object are collected using a TPP. Using these measurements a set of global easting measurements are identified. The surveyed easting location of the reference object is then subtracted from the easting measurements resulting in a distribution of error values. For error values are selected from this distribution to represent the requirement statement:

5% — -261 mm
25% — -115 mm
75% — 107 mm
95% — 232 mm

C.1.8.2. It is known that the reference object has a surveyed easting position verified to ±50 mm. Therefore, the true requirement statement for the TPP easting position error are:

5% — -261-50 = -311 mm
25% — -115-50 = -165 mm
75% — 107-(-50) = 157 mm
95% — 232-(-50) = 282 mm

APPENDIX E. ASSESSMENT OF HIGHWAY PERFORMANCE IN TRANSVERSE PAVEMENT PROFILING SYSTEMS

1. SCOPE

1.1. This practice describes procedures to assess the accuracy and precision of the Transverse Pavement Profiler (TPP) under typical dynamic operation. The particular specifications which will be assessed are: transverse measurement spacing, effective transverse width, longitudinal measurement spacing, and vertical measurement error.

1.2. In addition to the TPP specifications, the TPP will be evaluated on the following deformation parameters: rut depth, cross-slope, vertical magnitude of an edge/curb, and transverse location of an edge/curb. Evaluations will be performed by comparing the resulting TPP deformation parameters to ones calculated from ground reference data conforming to R###, Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment.

1.3. The minimum requirements stipulated herein are intended to focus on the need for accurate and repeatable transverse measurements for network and project level data collection.

1.4. If any part of this practice is in conflict with referenced documents, such as ASTM Standards, this practice takes precedence for its purposes.

1.5. This standard practice is intended to be conducted in conjunction with three other standard practices to fully assess and certify the TPP in typical operating conditions. For static assessment see R###, Assessment of Static Performance in TPP Systems, for body motion assessment see R###, Assessment of Body Motion Cancelation in TPP Systems, and for assessment of drift mitigation see R###, Assessment of Navigation Drift Mitigation in TPP Systems.

1.6. This practice does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this practice to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

2. REFERENCED STANDARDS

2.1. AASHTO Standards:

- R010, Definition of Terms Related to Quality and Statistics as Used in Highway Construction
- PP069, Determining Pavement Deformation Parameters and Cross Slope from Collected Transverse Profiles
- Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems
- Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment
- R87, Determining Pavement Deformation Parameters and Cross-Slope from Collected Transverse Profiles

3. TERMINOLOGY

3.1. See AASHTO R###, Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment, for definition of terms used in this standard practice.

3.2. Table 34 provides the physical parameter definitions, symbols, and default values to be used when administering this standard.

Table 34. Physical parameter definitions and default values.

Physical Parameter	Symbol	Default Value(s)
Exiting transverse width of transverse capability test section bounding beams	W_d	3.7 ± 0.05 m (12.1 ± 0.2 ft)
Total longitudinal length of the test site	L_{ts}	3.65 ± 0.05 m (12.0 ± 0.2 ft)
Total transverse width of the test site	W_{ts}	4.1 ± 0.05 m (13.5 ± 0.2 ft)
Transverse width of the ground reference test section	W_{gr}	4.0 ± 0.05 m (13.1 ft)
Longitudinal length of the ground reference test section	L_{gr}	500 mm (20 in)
Minimum height of bounding beams	h_b	25 mm (1.0 in)
Bounding beams minimum transverse width	w_b	40 mm (1.5 in)
Start of speed range	V_s	15 ± 2 kph (10 ± 2 mph)
End of speed range	V_f	105 ± 5 kph (65 ± 3 mph)
Increments of speed range	V_δ	15 kph (10 ± 2 mph)
Transverse width of virtual rectangle	w_M	15.0 mm (0.6 in)
Longitudinal length of virtual rectangle	L_M	250.0 mm (9.8 in)
Minimum number of passes though the test section at each speed	N_{tsp}	3
Number of measurements to randomly sample	N_r	50

4. SIGNIFICANCE AND USE

4.1. Measured transverse profiles of road surfaces are used to extract pavement deformation parameters such as rut depth, cross-slope, and edge/curb drop off. The accuracy of the estimated pavement deformation parameters depends on the measured transverse profile accurately representing a transverse section of the road surface.

4.2. Requirements on the TPP specifications ensure that the measured profile accurately represents the road surface. In addition, it is essential that the TPP sensors be able to accurately and precisely measure the height and transverse location of the road surface points.

4.3. This practice outlines standard procedures for certifying and verifying the operational accuracy and precision of transverse pavement profilers related to dynamic measurement components. This standard prescribes a procedure which is conducted at a full range of operating speeds to analyze the accuracy and precision of a TPP system during typical operating conditions. Because the data are used for subsequent calculations for rut depth, cross slope, and edge/curb drop off, tables of the necessary accuracy and precision for certification are provided in the form of bias and confidence intervals for each use.

5. EQUIPMENT

5.1. The TPP must be able to collect transverse profiles at a minimum sampling rate of 30 complete transverse profile scans per second and be capable of operating across the range of speeds provided in Table 1.

5.2. Provide all collected transverse profiles of the test section in electronic text files following the format prescribed in Annex A1 and Annex A2.

6. DATA COLLECTION AND REPORTING

6.1. Assessment shall be performed over a range of road and pavement conditions. Test sites shall be formed from a segment of the road surface with a longitudinal length of L_{ts} and a transverse width of W_{ts} and shall be characterized based on the final data requirement of interest. Each test site shall comprise of two adjacent test sections: transverse capability test section and ground reference test section, as shown in figure 45.

6.1.1. For assessment of rut depth, test sites shall exhibit a range of rut depths from low level rutting to high level rutting. For low level rutting, the minimum allowable rut depth is 2.0 mm. High level rutting is classified as rut depths greater than 20 mm. The rut depth shall be established by the ground reference equipment. For assessment of cross slope, the test site shall contain a cross slope greater than 0.5%. Bounding beams shall be placed on the transverse edges of the test site while conducting the assessment. These bounding beams allow for any selected road surface to be used for assessment of edge/curb detection.

6.1.2. The surface macrotexture for the test sites should reflect the variety of the pavement surfaces to be evaluated.

6.1.3. All test sites should have an ample length of road to allow for the TPP to achieve the target speed prior to entering the test site and come to a stop after exiting the test site. It is recommended that a minimum road length of 0.4 km (0.25 mi) is necessary to perform the full range of speeds.

6.2. Two reference lines (e.g. chalk lines) shall be marked on the road surface to ensure all bounding beams placed on the road surface are properly aligned. A central primary reference line shall be placed in the longitudinal direction of the test site. A secondary reference line shall be placed in the transverse direction.

6.3. Both the ground reference test section and the transverse capability test section shall be centered in the transverse direction about the primary reference line. The secondary reference line will serve as the start of the ground reference test section.

6.4. In the bounds of the test site a test section which contains a transverse width of W_{gr} and a longitudinal length of L_{gr} shall be identified for the ground reference test section.

6.5. Bounding beams of length L_{gr} and width w_b shall be placed along the transverse edges of the ground reference test sections. These blocks will remain along the transverse edges throughout the entire testing process and should not be moved.

6.6. The certification agency shall acquire ground reference data of the road surface corresponding to the ground reference test section that satisfies the requirement statement in R###, Assessment of Ground Reference Data for TPP System Assessment. The procedure for collecting ground reference data is provided in Annex B1.

6.7. Once acceptable ground reference data is collected the angled bounding beams of the transverse capability test section can be setup as shown in figure 45.

6.8. The angled beams shall be centered around the central primary reference line. The beams shall be positioned such that the ends of the beams adjoining the ground reference test section are a transverse distance W_d apart and the opposing ends are a transverse distance W_{ts} apart as illustrated in figure 45.

6.9. Upon placement of the bounding beams for the transverse capability test section, the complete test section shall have a longitudinal length of L_{ts}.

6.10. The TPP operator shall drive thru the complete test section with a target vehicle speed of V_s and acquire point cloud data of the complete test section. The TPP operators shall make at least N_{tsp} passes through the complete test region per target vehicle speed.

6.11. Acquisition of point cloud data shall be repeated at operational speeds ranging from V_s to V_F in increments of V_δ.

6.12. All reported point cloud data shall be reported in a global reference frame with a structure conforming to the point cloud format in Annex A1.

6.13. Regularly spaced gridded data for each collected pass through the test section shall be generated with a longitudinal grid spacing, l_g, and transverse grid spacing, t_g, defined by the TPP operator and provided in the header of the reported file. The file shall conform to the gridded data format in Annex A2.

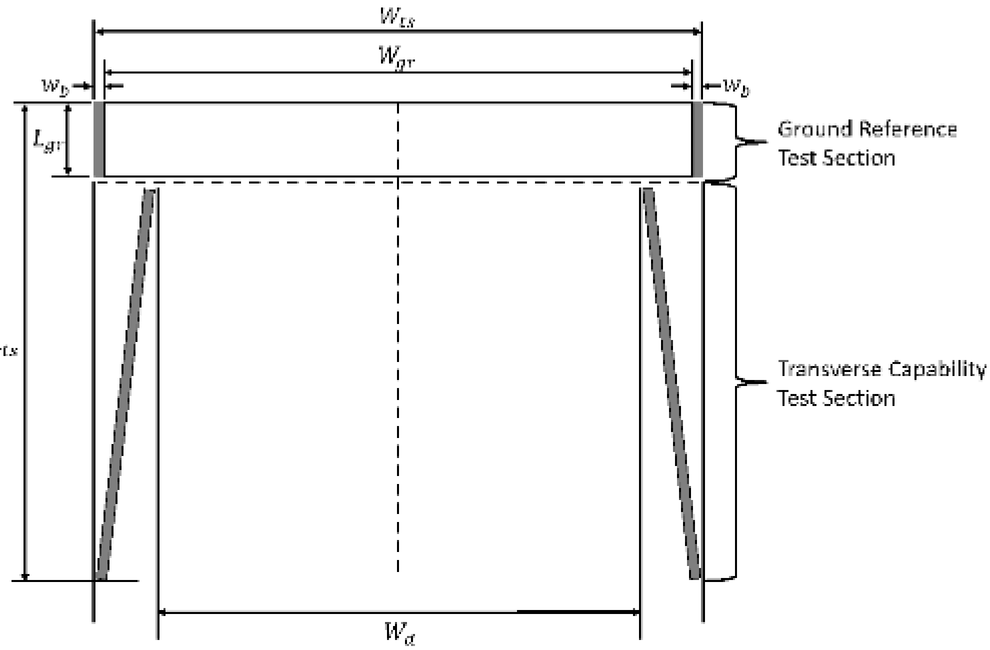

Figure 45. Schematic of the complete test site with the ground reference test section adjoining the transverse capability test section.

7. DATA REDUCTION

7.1 Transverse/Longitudinal Measurement Spacing:

7.1.1 Per reported initial point cloud N_r measurements shall be randomly chosen and added to the set S. These N_r measurements shall be used to estimate the transverse and longitudinal, measurement spacing of the TPP reported data.

7.1.2 For each measurement in the set S, the nearest neighboring point in each of four quadrants shall be identified (1 neighboring point per quadrant). The nearest neighboring measurement per quadrant shall be identified as the measurement point which is located in the quadrant of interest and has the shortest three-dimensional Euclidian distance. The quadrants shall be defined by a set of two dimensional orthogonal axes oriented at a 45º angle with respect to the transverse-longitudinal axes of the path coordinate system. See figure 46, for an example of the quadrants for a selected point and the identification of the nearest neighboring point per quadrant.

7.1.3 The identified nearest neighboring point in quadrants 1 and 3 shall, each, provide an estimate of the transverse spacing. The transverse point-to-point distance between the respective measurement in the set S and the identified nearest neighboring point in quadrant 1 and quadrant 3 shall be calculated and added to the set t_{prof}. The set t_{prof} shall serve as a sample from the population of true transverse measurement spacing.

7.1.4 The nearest neighboring point in quadrants 2 and 4 shall, each, provide an estimate of the longitudinal spacing. The longitudinal point-to-point distance between the respective measurement in the set S and the identified nearest neighboring point in quadrant 2 and quadrant 4 shall be calculated and added to the set l_{prof}. The set l_{prof} shall serve as a sample from the population of true longitudinal measurement spacing.

7.2 Effective Transverse Width:

7.2.1 Per reported point cloud each transverse profile which lies in the transverse capability test section shall be uniquely identified by index i and added to the set $S_{t,i}$.

7.2.2 Per identified transverse profile, four critical points shall be identified: 1) the outermost left measurement, 2) the measurement corresponding to the inside edge of the left angled bounding beam, 3) the measurement corresponding to the inside edge of the right angled bounding beam, and 4) the outermost right measurement. See figure 47 for an illustration of the four critical points in a single transverse profile.

7.2.3 Per identified transverse profile, the total transverse width, $t_{w,i}$, shall be taken as the transverse point-to-point distance between points 1 and 4.

7.2.4 Per identified transverse profile, the TPP transverse wander shall be taken as the average transverse measurement of points 2 and 3. The calculated average shall be denoted as $q_{veh,i}$.

7.2.5 Per identified transverse profile, the effective transverse width, w_{eff}, shall be taken as the shortest transverse distance between the TPP transverse wander (e.g. the centerline of the lane according to the point cloud) and the inside edge of the bounding beams. Therefore, the minimum transverse point-to-point distance between point 1 or point 4 and $q_{veh,i}$ shall be calculated as shown in the equation below to provide an estimate of the effective width of the TPP.

$$w_{eff} = 2 \cdot \max\left(\left|q_{veh,i} - p_{1,i}\right|, \left|q_{veh,i} - p_{4,i}\right|\right)$$

7.2.6 The complete set of w_{eff} values from all identified transverse profiles shall serve as a sample from the population of true effective transverse width.

7.3 Point Cloud Vertical Error:

7.3.1 All ground reference data is reported in a local path reference frame. To compare TPP point cloud data to the ground reference data a local registration between the TPP point cloud and the ground reference data is required. This registration requires translation of the TPP point cloud in the transverse and longitudinal directions.

7.3.2 Translation in the transverse direction can be achieved using the measurements of the transverse bounding beams for the ground reference test section. The transverse bounding beams in the ground reference test section remain in the same location between collection of ground reference data and testing of the TPP system. Therefore, by defining the inside edge of one or both of the transverse bounding beams the TPP point cloud data can be translated transversely to best align with the bounding beams in the ground reference data.

7.3.3 Translation in the longitudinal direction can be achieved using the angled beams in the transverse capability test section. Per reported transverse profile in the transverse capability test section, the inside edge of the transverse bounding beam can be identified. The TPP point cloud data can then be translated longitudinally to best align with the angled bounding beams of the transverse capability test section which are defined by the length of the beams used, the entrance width of the test section (W_{ts}), and the exit width of the test section (W_d).

7.3.4 Figure 48 provides an illustration of identifying the transverse bounding beam edges for the ground reference and transverse capabilities in the unaligned TPP point cloud data. These edges were identified based on the height, h_b, of the beams. In figure 49 the TPP point cloud data is translated in the transverse direction to best align the ground reference transverse bounding beams, in the transverse direction. In figure 50 the TPP point cloud data is translated in the longitudinal direction to best align the transverse capability test section angled beams.

7.3.5 After aligning the TPP point cloud data with the ground reference data, the reference point cloud data corresponding to the ground reference test section shall be added to the set S_{ref}. This point cloud data shall consist of a road surface with a transverse width W_{gr} and a longitudinal length L_{gr}. The ground reference data should also satisfy the criteria provided in Table 2 of R###, Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment.

7.3.6 A least squares error plane fit shall be applied to the measurements in set S_{ref} and the vertical point-to-plane distance between each measurement in set S_{ref} and the plane fit to the measurements shall be calculated and stored in the set z_{ref}. The set z_{ref} will be used as reference data to evaluate the vertical accuracy and precision in the TPP point cloud.

7.3.7 Per reported point cloud, all measurements which lie inside the ground reference test section after performing the local registration shall be added to the set $S_{pc,i}$.

7.3.8 A plane shall be fit to the set $S_{pc,i}$ and the vertical point-to-plane distance between each measurement in set $S_{pc,i}$ and the plane fit to the point cloud measurements shall be calculated. The plane fit to the measurements in the set $S_{pc,i}$ shall be adjusted to minimize the point cloud vertical measurement error. The resulting set of minimum vertical measurement errors shall be stored in the set $z_{pc,i}$.

7.3.9 Per each vertical point-to-plane distance stored in the set $z_{pc,i}$ a rectangular region of interest shall lie in the Universal Transverse Mercator (UTM) plane and be centered about the difference value of interest based on the reported transverse-longitudinal dimension of the measurement. The region shall have a transverse width of w_M and a longitudinal length of l_M. This region shall be used to identify the nearest neighboring vertical point-to-plane distances in the reference data. Figure 51 provides a schematic illustrating the region of interest centered about a single point-to-plane distance associated with the TPP point cloud.

7.3.10 All identified reference measurements which lie in the region of interest shall be used to generate the reference distribution (P_{ref}). The reference distribution, shall be defined by the average (μ_{ref}) and the standard deviation (σ_{ref}).

7.3.11 Per each point-to-plane distance in the set $z_{pc,i}$, the number of standard deviations the respective distance is away from the reference distribution shall be identify by calculating the Mahalanobis distance, D_M, of the vertical point-to-plane distance from the reference distribution, P_{ref}. The Mahalanobis distance shall be computed as shown below.

$$D_M = \frac{z_{pc,i} - \mu_{ref}}{\sigma_{ref}}$$

7.3.12 The Mahalanobis distance is an estimate of the TPP vertical measurement error for each measurement in the point cloud. The calculated Mahalanobis distance for each reported measurement in the TPP initial point cloud shall be added to the set $e_{z,pc}$.

Note 1—The Mahalanobis distance is a unit-less and scale-invariant distance.

7.3.13 The process of identifying a reference distribution and calculating the Mahalanobis distance shall be repeated for each vertical point-to-plane distance in the set $z_{pc,i}$. The complete set of $e_{z,pc}$ values shall serve as a sample from the population of true vertical measurement errors for the TPP point cloud.

7.4 Gridded Data Vertical Error:

7.4.1 All ground reference data is reported in a local path reference frame. To compare TPP gridded data to the ground reference data a local registration between the TPP gridded data and the ground reference data is required. This registration requires translation of the TPP gridded data in the transverse and longitudinal directions.

7.4.2 Translation in the transverse direction can be achieved using the transverse bounding beams of the ground reference test section. The transverse bounding beams in the ground reference test section remain in the same location between collection of ground reference data and testing of the TPP system. Therefore, by defining the inside edge of one or both of the transverse bounding beams the TPP gridded data can be translated transversely to best align with the bounding beams in the ground reference data.

7.4.3 Translation in the longitudinal direction can be achieved using the angled beams in the transverse capability test section. Per reported transverse profile in the transverse capability test section, the inside edge of the transverse bounding beam can be identified. The TPP gridded data can then be translated longitudinally to best align with the angled bounding beams of the transverse capability test section which are defined by the length of the beams used, the entrance width of the test section (W_{ts}), and the exit width of the test section (W_d).

7.4.4 Figure 48 provides an illustration of identifying the transverse bounding beam edges for the ground reference and transverse capabilities in the unaligned gridded data. These edges were identified based on the height, h_b, of the beams. In figure 49 the TPP gridded data is translated in the transverse direction to best align the ground reference transverse beams. In figure 50 the TPP gridded data is translated in the longitudinal direction to best align the transverse capability test section angled beams.

7.4.5 After aligning the TPP point cloud data with the ground reference data, the reference point cloud data corresponding to the ground reference test section shall be added to the set S_{ref}. This point cloud data shall consist of a road surface with a transverse width W_{gr} and a longitudinal length L_{gr}. The ground reference data should also satisfy the criteria provided in table 39 of Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment.

7.4.6 A least squares error plane fit shall be applied to the measurements in set S_{ref} and the vertical point-to-plane distance between each measurement in set S_{ref} and the plane fit to the measurements shall be calculated and stored in the set z_{ref}. The set z_{ref} will be used as reference data to evaluate the vertical accuracy and precision in the initial TPP gridded data.

7.4.7 Per reported gridded data set, all measurements which lie inside the ground reference test section after performing the local registration shall be added to the set $S_{gd,i}$.

7.4.8 A plane shall be fit to the set $S_{gd,i}$ and the vertical point-to-plane distance between each measurement in set $S_{gd,i}$ and the plane fit to the gridded data measurements shall be calculated. The plane fit to the measurements in the set $S_{gd,i}$ shall be adjusted to minimize the gridded data vertical measurement error. The resulting set of minimum vertical measurement errors shall be stored in the set $z_{gd,i}$.

7.4.9 Per each vertical point-to-plane distance stored in the set $z_{gd,i}$ a rectangular region of interest shall lie in the Universal Transverse Mercator (UTM) plane and be centered about the difference value of interest based on the reported transverse-longitudinal dimension of the measurement. The region shall have a transverse width of w_M and a longitudinal length of l_M. This region shall be used to identify the nearest neighboring vertical point-to-plane distances in the reference data. Figure 52 provides a schematic illustrating the region of interest centered about a single point-to-plane distance associated with the TPP gridded data.

7.4.10 All identified reference measurements which lie in the region of interest shall be used to generate the reference distribution (P_{ref}). The reference distribution, shall be defined by the average (μ_{ref}) and the standard deviation (σ_{ref}).

7.4.11 Per each point-to-plane distance in the set $z_{gd,i}$, the number of standard deviations the respective distance is away from the reference distribution shall be identified by calculating the Mahalanobis distance of the vertical point-to-plane distance from the reference distribution, P_{ref}. The Mahalanobis distance shall be computed as shown below.

$$D_M = \frac{z_{gd,i} - \mu_{ref}}{\sigma_{ref}}$$

7.4.12 The Mahalanobis distance is an estimate of the TPP vertical measurement error for each measurement in the gridded data. The calculated Mahalanobis distance for each reported measurement in the TPP gridded data shall be added to the set $e_{z,gd}$.

7.4.13 The process of identifying a reference distribution and calculating the Mahalanobis distance shall be repeated for each vertical point-to-plane distance in the set $z_{gd,i}$. The complete set of $e_{z,gd}$ values shall serve as a sample from the population of true vertical measurement errors for the TPP gridded data.

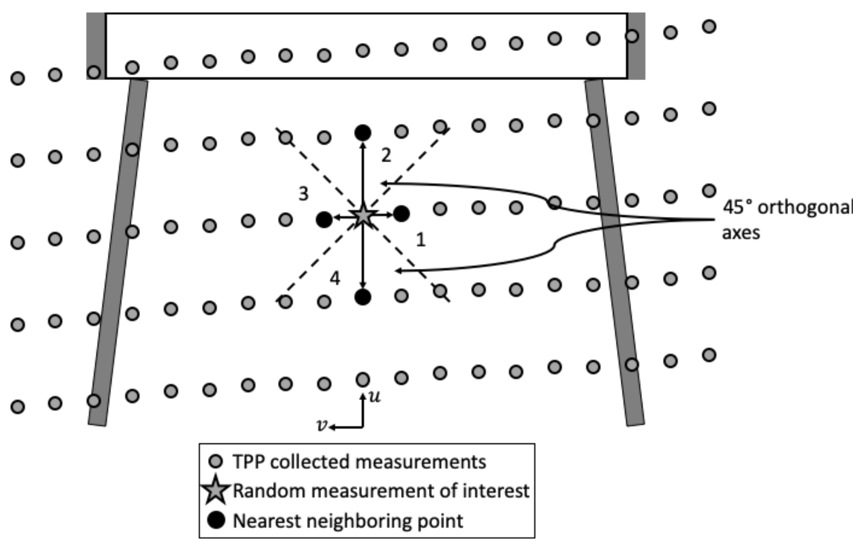

Figure 46. Illustration of four quadrants oriented with respect to the path coordinate system and identification of the nearest neighboring point in each respective quadrant.

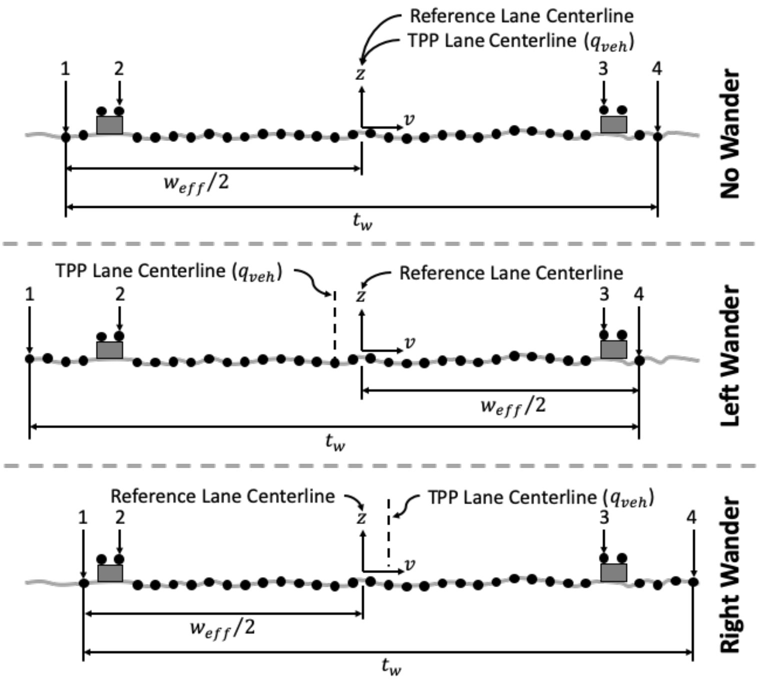

Figure 47. Representation of vehicle transverse wander in a single transverse profile.

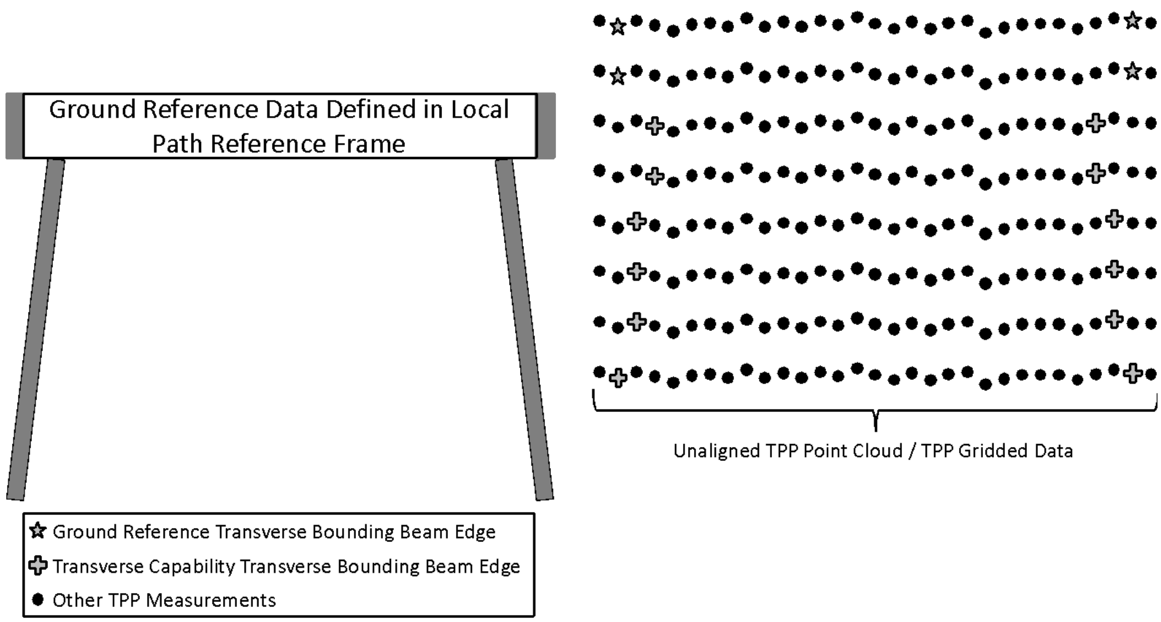

Figure 48. Identification of transverse bounding beam edges in the TPP dataset for the ground reference and transverse capabilities test section.

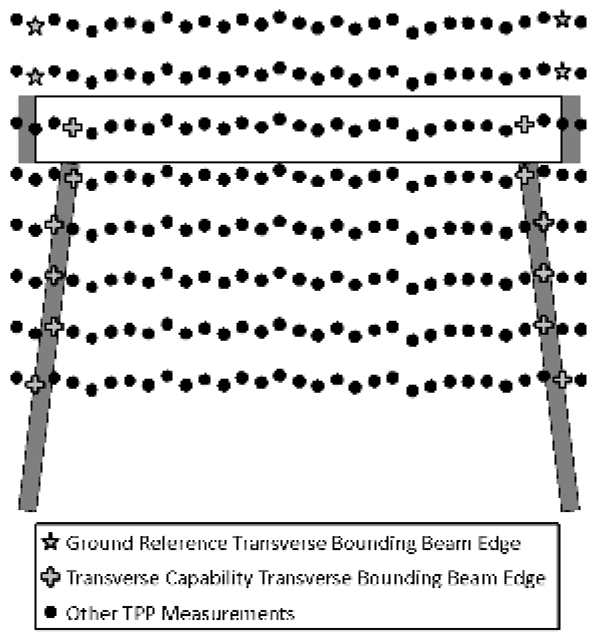

Figure 49. Transverse translation of the TPP dataset based on the best alignment of the ground reference transverse bounding beams.

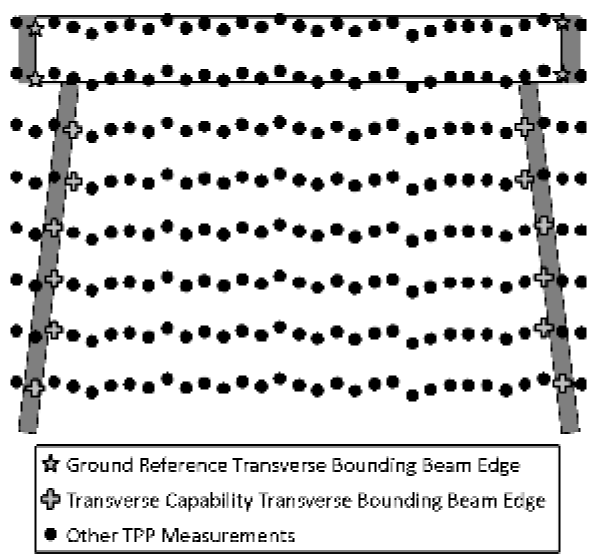

Figure 50. Longitudinal translation of the TPP dataset based on the best alignment of the angled bounding beams in the transverse capabilities test section.

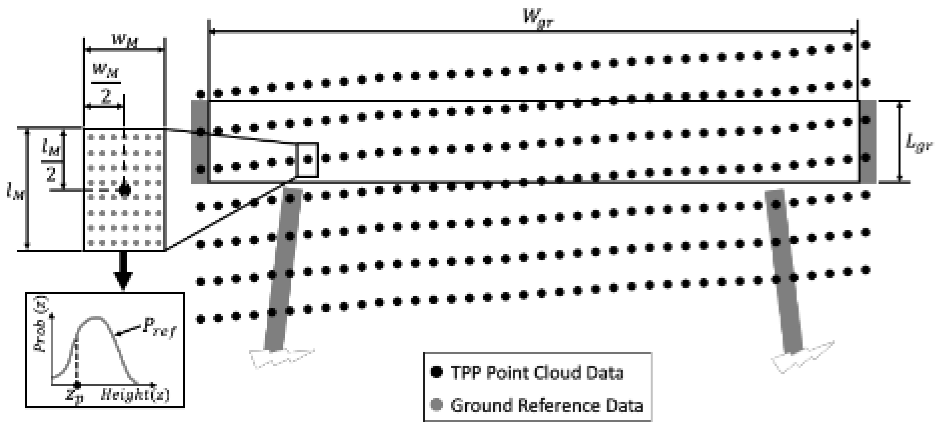

Figure 51. Ground reference rectangular region of interest to determine point cloud vertical error.

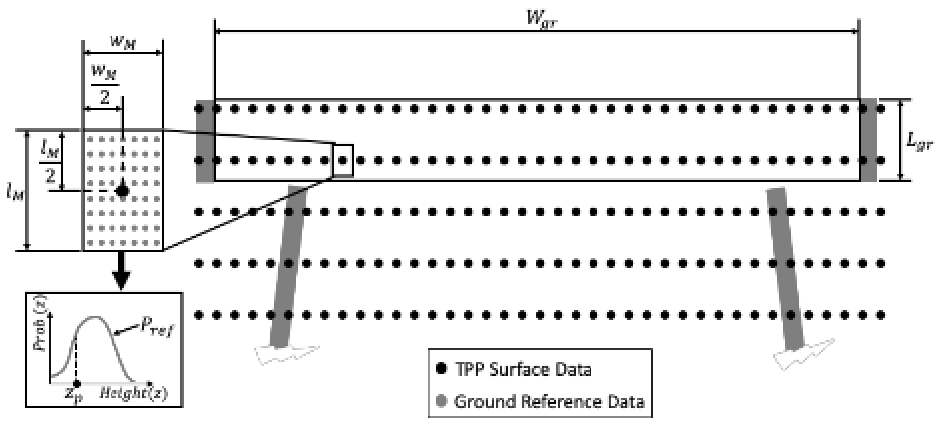

Figure 52. Ground reference rectangular region of interest to determine gridded data vertical error.

8. CALCULATION OF DEFORMATION PARAMETERS

8.1 Cross Slope:

8.1.1 Per reported TPP transverse profile in the ground reference test section, the cross slope shall be calculated based on the process provided in AASHTO R87 or as specified by the certification agency. For calculation of the cross slope, only measurements which constitute the road surface between the transverse bounding beams shall be considered.

8.1.2 Prior to calculation of the cross slope, the ground reference data should be oriented in the transverse-vertical plane such that the ground reference data measurements of the top surface of the straight edge are level. Figure 53 provides a two-dimensional illustration of the proper orientation of the ground reference data prior to calculating the reference cross slope.

8.1.3 To determine the reference cross slope from the ground reference point cloud, the average longitudinal position of the respective TPP transverse profile with respect to the start of the ground reference test section shall be determined. A virtual rectangle with a transverse width of W_{gr} and a longitudinal length of l_M shall be centered about the average longitudinal position of the transverse profile. All measurements in the ground reference data which lie inside the bounds of the virtual rectangle shall be added to the set $S_{cs,ref}$. See figure 54 for an illustration of the virtual rectangle for a single transverse profile in the ground reference test section.

8.1.4 Using the transverse and vertical data from the set $S_{cs,ref}$, the reference cross slope shall be calculated using AASHTO R87 or as specified by the certification agency. For calculation of the reference cross slope, only ground reference data points which constitute the road surface between the transverse bounding beams shall be considered. When evaluating the TPP cross slope, the same process for calculating the cross slope in the TPP data shall be used for calculating the reference cross slope from the ground reference data

8.1.5 The difference in cross slope between the respective TPP transverse profile and the reference cross slope identified from set $S_{cs,ref}$ shall provide an estimate of the error in cross slope for the TPP. The calculated difference shall be added to the set e_{cs}. The set e_{cs} shall serve as a sample from the population of true cross slope error.

8.1.6 This process shall be repeated for all TPP transverse profiles which lie within the ground reference test section.

8.2 Rut Depth:

8.2.1 Per reported TPP transverse profile in the ground reference test section, the rut depth height(s) shall be calculated based on the process provided in AASHTO R87 or as specified by the certification agency.

8.2.2 Per transverse profile, reference rut depth height(s) shall be established using the neighboring ground reference data. The neighboring ground reference data shall be established based on the average longitudinal position of the TPP transverse profile. A virtual rectangle with a transverse width of W_{gr} and a longitudinal length of l_M shall be centered about the average longitudinal position of the transverse profile. All measurements in the ground reference data which lie inside the bounds of the virtual rectangle shall be added to the set $S_{rd,ref}$. See figure 54 for an illustration of the virtual rectangle for a single transverse profile in the ground reference test section.

8.2.3 Using the transverse and vertical data from the set $S_{rd,ref}$, the reference rut depth height(s) shall be calculated using AASHTO R87 or as specified by the certification agency. When evaluating the TPP rut depth, the same process for calculating the rut depth in the TPP data shall be used for calculating the reference rut depth from the ground reference data.

8.2.4 The difference in rut depth height(s) between the respective TPP transverse profile and the reference rut depth height(s) identified from set $S_{rd,ref}$ shall provide an estimate of the error in rut depth for the TPP. The calculated difference shall be added to the set e_{rd}. The set e_{rd} shall serve as a sample from the population of true rut depth error.

8.2.5 This process shall be repeated for all TPP transverse profiles which lie within the ground reference test section.

8.3 Edge/Curb:

8.3.1 Per reported TPP transverse profile in the ground reference test section, the edges/curbs shall be identified and characterized by their vertical height and transverse location. The vertical height and the transverse location for each transverse bounding beam in the ground reference test section shall be identified as illustrated in figure 55.

8.3.2 Based on the setup of the ground reference test section the transverse bounding beams shall be considered the edge/curb which should be identified in the transverse profile.

Therefore, the transverse location of the edge/curb shall be half of the transverse width of the ground reference test section ($W_{gr}/2$). In addition, the vertical height of the edge/curb shall be taken as the height of the transverse bounding beam (h_b), see figure 56.

8.3.3 The difference in curb transverse location between the respective TPP transverse profile and the reference transverse location ($W_{gr}/2$) shall provide an estimate of the error in the edge/curb transverse location for the TPP. The calculated difference shall be added to the set e_{tl}, where the set e_{tl} shall serve as a sample from the population of true edge/curb transverse location error.

8.3.4 The difference in the curb vertical magnitude between the respective TPP transverse profile and the reference vertical height (h_b) shall provide an estimate of the error in the edge/curb vertical magnitude for the TPP. The calculated difference shall be added to the set e_{vm}, where the set e_{vm} shall serve as a sample from the population of true edge/curb vertical magnitude error.

8.3.5 This process shall be repeated for all TPP transverse profiles which lie within the ground reference test section.

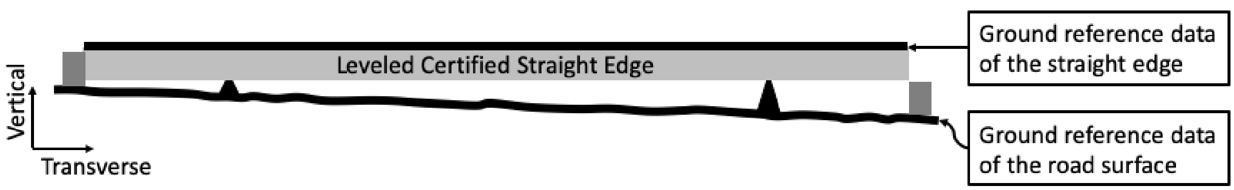

Figure 53. Proper orientation of the ground reference data, when viewed in the transverse-elevation plane, for calculation of cross slope.

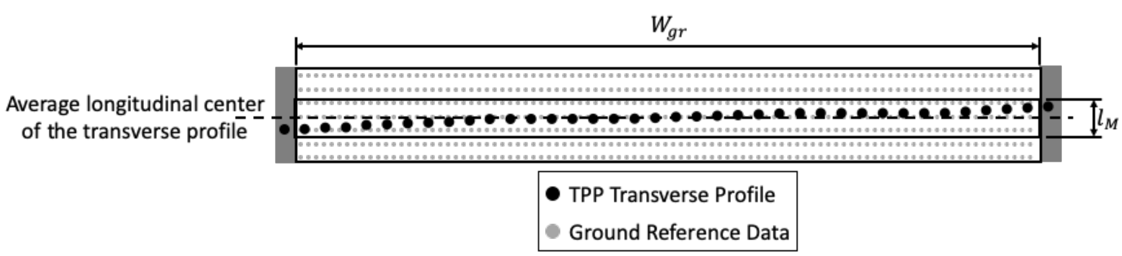

Figure 54. Identification of the ground reference data points for calculation of reference cross-slope and rut-depth.

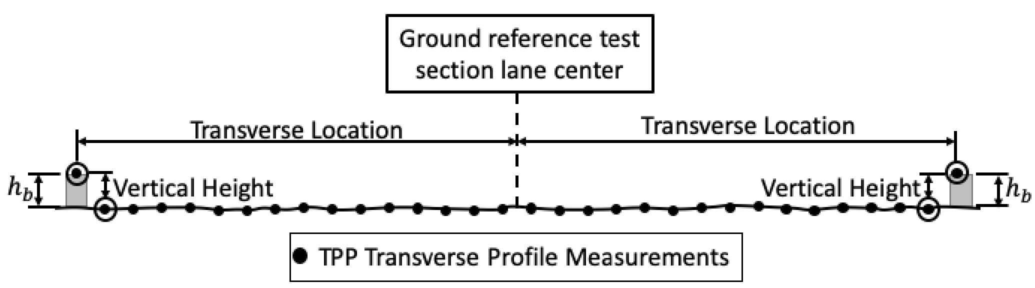

Figure 55. Identification of the vertical height and transverse location for the transverse bounding beams in the ground reference test section from the TPP transverse profile measurements.

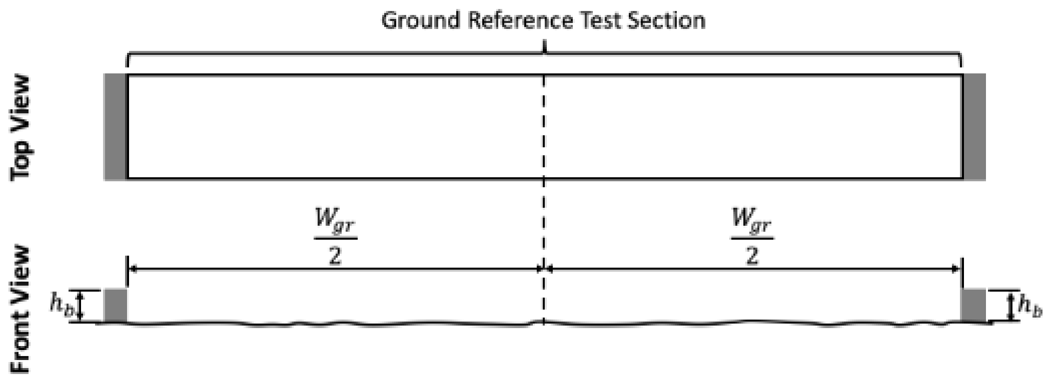

Figure 56. The curb transverse location is known based on the ground reference test section transverse width (W_{gr}) and the height of the curbs are known based on the height of transverse bounding beams (h_b).

9. REPORTING TEST STATISTICS

9.1 Transverse Measurement Spacing—Report the set of t_{prof} values.
9.2 Longitudinal Measurement Spacing—Report the set of l_{prof} values.
9.3 Effective Transverse Width—Report the set of w_{eff} values.
9.4 Point Cloud Vertical Error—Report the set of $e_{z,pc}$ values.
9.5 Gridded Data Vertical Error—Report the set of $e_{z,gd}$ values.
9.6 Cross Slope Error—Report the set of e_{cs} values.
9.7 Rut Depth Error—Report the set of e_{rd} values.
9.8 Edge/Curb Transverse Location Error—Report the set of e_{tl} values.
9.9 Edge/Curb Vertical Magnitude Error—Report the set of e_{vm} values.

10. CERTIFICATION REQUIREMENT STATEMENT

10.1 Requirement statements for certification of the dynamic performance of the TPP system is provided in table 35 for cross-slope, table 36 for rut depth, and table 37 for edge/curb drop off.
10.2 Certification shall be based on the final use and the frequency shall be as specified by the Certification agency. The TPP must successfully perform the test procedures outlined in Section 6 and satisfy the requirement statements provided in tables 35, 36, or 37 depending on the final use of the TPP data.

Table 35. Highway performance requirement statement for cross-slope.

	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
Output Test Statistic	90% (5%)	50% (25%)		50% (25%)	90% (95%)

Transverse Measurement Spacing	NA	NA	NA	NA	25
Effective Transverse Width	3800	NA	NA	NA	NA
Longitudinal Measurement Spacing – Network	NA	NA	NA	NA	3000
Longitudinal Measurement Spacing – Project	NA	NA	NA	NA	500
Point Cloud Vertical Error (as standard deviation from a reference distribution)	-2.5	-1.0	NA	1.0	2.5
Gridded Data Vertical Error (as standard deviation from a reference distribution)	-1.7	-0.7	NA	0.7	1.7
Cross Slope Error (as percent)	-0.4	-0.15	NA	0.15	0.4

Table 36. Highway performance cancelation requirement statement for rut depth.

	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
Output Test Statistic	90% (5%)	50% (25%)		50% (25%)	90% (95%)

Transverse Measurement Spacing	NA	NA	NA	NA	10
Effective Transverse Width	4000	NA	NA	NA	NA
Longitudinal Measurement Spacing – Network	NA	NA	NA	NA	3000
Longitudinal Measurement Spacing – Project	NA	NA	NA	NA	500
Point Cloud Vertical Error (as standard deviation from a reference distribution)	-2.5	-1.0	NA	1.0	2.5
Gridded Data Vertical Error (as standard deviation from a reference distribution)	-1.7	-0.7	NA	0.7	1.7
Rut Depth Error	-2.5	-1.0	NA	1.0	2.5

Table 37. Highway performance cancelation requirement statement for edge/curb drop-off.

	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
Output Test Statistic	90% (5%)	50% (25%)		50% (25%)	90% (95%)

Transverse Measurement Spacing	NA	NA	NA	NA	10
Effective Transverse Width	4250	NA	NA	NA	NA
Longitudinal Measurement Spacing – Network	NA	NA	NA	NA	3000
Longitudinal Measurement Spacing – Project	NA	NA	NA	NA	500
Point Cloud Vertical Error (as standard deviation from a reference distribution)	-2.5	-1.0	NA	1.0	2.5
Gridded Data Vertical Error (as standard deviation from a reference distribution)	-1.7	-0.7	NA	0.7	1.7
Edge/Curb Transverse Location Error	-50	-25	NA	25	50
Edge/Curb Vertical Magnitude Error	-2.5	-1.0	NA	1.0	2.5

11. SYSTEM CALIBRATION & VERIFICATION

11.1 The process of calibrating and checking the performance of the transverse pavement profiler's mapping and location sensors is the responsibility of the TPP operator. TPP operators should evaluate and confirm the manufacturer's recommendations for calibrating and verifying performance of both the mapping and location sensors.

11.2 In addition to manufacturer recommended verification methods, the highway performance of the TPP should be evaluated on a weekly basis during typical operation. See Section 10 in R###, Assessment of Body Motion Cancelation of TPP Systems, for details regarding the verification process to be performed.

ANNEX A – OUTPUT DATA FILE FORMAT

A.1. Point Cloud File Format

A.1.1. This is the format in which point cloud data from the TPP shall be reported to the certification agency. The data to be reported in this format includes metadata describing the conditions in which the profile was acquired and general information about the data.

A.1.2. Metadata:

A.1.2.1. Line 1: TPP vendor/operator/owner name [Tab] TPP system name/model/make

A.1.2.2. Line 2: Data and timestamp on which the data was acquired in UTC format

A.1.2.2.1. Format: YYYY-MM-DDTHH:MM:SS+OFFH:OFFM

A.1.2.2.2. Example: 2019-10-22T14:32+00:00

A.1.2.3. Line 3: Northing and Easting of the origin specified in UTM coordinates along with the Elevation of the origin specified in WGS84 coordinates.

A.1.2.3.1. Format: Easting [Tab] Northing [Tab] Elevation

A.1.2.3.2. Example: 725498.16 4196729.93 623.9375

A.1.2.4. Line 4: Standard practice performed

A.1.2.4.1. Format: Assessment Title – Point Cloud

A.1.2.4.2. Example: Assessment of Highway Performance – Point Cloud

A.1.2.5. Line 5: The total number of transverse profiles in the file

A.1.3. Profile points:

A.1.3.1. Line 6: Easting (X) coordinates of profile #1 separated by a [space] (meters)

A.1.3.2. Line 7: Northing (Y) coordinates of profile #1 separated by a [space] (meters)

A.1.3.3. Line 8: Elevation (Z) coordinates of profile #1 separated by a [space] (meters)

A.1.3.4. …

A.1.3.5. Line end: Elevation (Z) coordinates of last profile separated by a [space] (meters)

A.2. Gridded Data File Format

A.2.1. This is the format in which gridded data from the TPP shall be reported to the certification agency. It is expected that the points shall be reported with a uniform transverse and longitudinal spacing. The data to be reported in this format includes metadata describing the conditions in which the profile was acquired and general information about the data including processing performed.

A.2.2. Metadata:

A.2.2.1. Line 1: TPP vender/operator/owner name [Tab] TPP system name/model/make

A.2.2.2. Line 2: Data and timestamp on which the data was acquired in UTC format

A.2.2.2.1. Format: YYYY-MM-DDTHH:MM:SS+OFFH:OFFM

A.2.2.2.2. Example: 2019-10-22T14:32+00:00

A.2.2.3. Line 3: Northing and Easting of the origin specified in UTM coordinates along with the elevation of the origin specified in WGS84 coordinates.

A.2.2.3.1. Format: Easting [Tab] Northing [Tab] Elevation

A.2.2.3.2. Example: 725498.16 4196729.93 623.9375

A.2.2.4. Line 4: Standard practice performed

A.2.2.4.1. Format: Assessment Title – Gridded Data

A.2.2.4.2. Example: Assessment of Highway Performance – Gridded Data

A.2.2.5. Line 5: The total number of profiles in the file
A.2.2.6. Line 6: Transverse spacing between profiles points, (meters)
A.2.2.7. Line 7: Longitudinal spacing between profile points, (meters)
A.2.3. Vertical heights of profile points:
A.2.3.1. Line 8: Regularly spaced vertical measurement heights of transverse profile #1 separated by a [space] (meters)
A.2.3.2. Line 9: Regularly spaced vertical measurement heights of transverse profile #2 separated by a [space] (meters)
A.2.3.3. …
A.2.3.4. Line end: Regularly spaced vertical measurement heights of the last transverse profile separated by a [space] (meters)

ANNEX B – ACQUISITION OF GROUND REFERENCE DATE

B.1. Procedure for Collecting Ground Reference Data

B.1.1. All reference data inside the ground reference test section must meet or exceed the requirement statement provided in R###, Assessment of Ground Reference Data for TPP System Assessment.

B.1.2. Upon selection of a test site a ground reference test section with a transverse width W_{gr} and longitudinal length L_{gr} shall be selected conforming to the requirements in 6.1.1. For a test site, the data collection and reporting procedures (Section 5) in R###, Assessment of Ground Reference Data for TPP System Assessment, shall be followed to properly collect ground reference data.

B.1.3. To ensure the ground reference data is acceptable analysis of the collected data, as defined in R### Assessment of Ground Reference Data for TPP System Assessment shall be performed and the results of the analysis must meet or exceed the requirement statement provided in Section 11.

B.1.4. Upon successful fulfillment of the ground reference data requirement statement, the data collected can be considered ground reference data for the ground reference test section and can be used in the assessment of the TPP point cloud and gridded data assessment.

APPENDIX F. ASSESSMENT OF GROUND REFERENCE DATA FOR TRANSVERSE PAVEMENT PROFILING ASSESSMENT

1. SCOPE

1.1. This practice describes the procedures used to assess ground reference data used in R### Assessment of Highway Performance in TPP Systems.

1.2. This practice describes the accuracy and precision analysis needed to ensure a Ground Reference Equipment (GRE) system is collecting acceptable quality ground reference data. The accuracy and precision are evaluated using four surfaces: a certified straight edge, a straight edge with gauge blocks, a road surface, and a macrotexture surface. The measures evaluated are: transverse, longitudinal, and vertical measurement error; transverse, longitudinal, and vertical measurement spacing; transverse straightness; and horizontal plane flatness.

1.3. If any part of this practice is in conflict with referenced documents, such as ASTM Standards, this practice takes precedence for its purposes.

1.4. This test is designed to be conducted as the first steps in assessing a newly proposed ground reference data acquisition device and when acquiring ground reference data for R### Assessment of Highway Performance in TPP Systems.

1.5. This practice does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this practice to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use.

2. REFERENCED STANDARDS

2.1. AASHTO Standards:

- Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment
- Assessment of Highway Performance in Transverse Pavement Profiling Systems

3. TERMINOLOGY

3.1. See AASHTO R###, Definition of Terms Related to Transverse Pavement Profiling Systems and Ground Reference Equipment, for definition of terms used in this standard practice.

3.2. Table 38 provides the physical parameter definitions, symbols, and default values to be used when administering this standard

Table 38. Physical parameter definitions and default values.

Physical parameter	Symbol	Default Value(s)
Minimum straight edge length and transverse width of the road surface	L_{fs}	4.0 m (13.1 ft)
Minimum straight edge width	W_{fs}	25 mm (1 in)
Width of transverse bounding beams	w_b	40.0 ± 2.0 mm (1.5 ± 0.1 in)
Vertical height of gauge blocks	$h_{g,1}$ $h_{g,2}$	75 ± 2 mm, 50 ± 1 mm, 25 ± 1 mm 25 ± 1 mm, 12 ± 1 mm, 6 ± 1 mm
Minimum gauge block transverse width	w_g	20.0 mm (0.75 in)
Transverse distance from the base of the gauge block	d_s	25.0 mm (1 in)
Longitudinal length of the road surface	L_s	0.5 ± 0.05 m (19.5 ± 2 in)
Desired transverse locations of gauge blocks from the transverse centerline	d_t	2.0 ± 0.05 m (78.75 ± 2 in)
Longitudinal length of the macrotexture surface	l	150.0 ± 5.0 mm (6 ± 0.2 in)
Transverse width of the macrotexture surface	w	150.0 ± 5.0 mm (6 ± 0.2 in)
Minimum longitudinal length of flat plate	L_p	1.0 m (3.28 ft)
Minimum transverse width of flat plate	W_p	0.5 m (20 in)
Longitudinal offset of the macrotexture surface from a reference corner of a flat plate	l_o	175.0 ± 5.0 mm (6.8 ± 0.2 in)
Transverse offset of the macrotexture surface from a reference corner of a flat plate	w_o	25.0 ± 5.0 mm (1.0 ± 0.2 in)
Measurement error longitudinal grid spacing	l_g	10.0 mm (0.4 in)
Measurement error transverse grid spacing	t_g	10.0 mm (0.4 in)
Number of random measurements to select	N_r	100

4. SIGNIFICANCE AND USE

4.1. Accurate ground reference data are needed for assessment of Transverse Pavement Profiling (TPP) systems. Ground reference data are needed to quantify the vertical measurement error present in TPP systems when collecting measurements for cross-slope, rutting, and edge/curb detection. For specifics regarding the highway performance

TPP assessment process and usage of ground reference data, see R### Assessment of Highway Performance in TPP Systems.

4.2. In R### Assessment of Highway Performance in TPP Systems a road surface with a transverse width of L_{fs} and a longitudinal length of L_s shall be selected to test for accuracy and precision of a TPP system when measuring rutting, cross-slope, and edges/curbs. For this segment of road surface, the process of collecting ground reference data using GRE is provided, in detail, in this standard practice.

4.3. This standard prescribes tests to evaluate the transverse spacing between measurements; total width of measurements; vertical resolution of the measurements; straightness of the transverse measurements; vertical, transverse, and longitudinal accuracy and precision; and error associated with measuring macrotexture. Since collected ground reference data shall be used to evaluate the accuracy and precision of TPP systems, a table of the necessary accuracy and precision requirements for the ground reference data are provided in the form of bias and confidence intervals.

4.4. The testing procedure and data analysis presented in this standard verify that measurement equipment is collecting acceptable quality ground reference data. This standard practice should be performed any time ground reference data is collected for the assessment outlined in R###, Assessment of Highway Performance in TPP Systems.

5. DATA COLLECTION AND REPORTING

5.1. A road surface segment which contains a transverse width of L_{fs} and a longitudinal length of L_s shall be selected. The selected road surface shall be bounded along the longitudinal edges by a leveled certified straight edge and leveled straight edge with gauge blocks. The transverse edges of the selected road surface shall be bounded by blocks of width w_b. Figure 57, provides a schematic of the test section with the dimensions appropriately illustrated.

5.2. To limit the amount of vertical distance between consecutive steps, two sets of stair-stepped gauge blocks shall be used having vertical heights of $h_{g,1}$ and $h_{g,2}$ with each step having a minimum transverse width of w_g.

5.3. Details regarding the dimensioning, tolerances, surface finish, and material properties of the straight edge and gauge blocks are given in Annex A1 and A2.

5.4. Nearby to the selected road surface a flat plate with a transverse minimum width of W_p and a minimum longitudinal length of L_p shall be placed on the ground. On top of the plate a macrotexture surface with a transverse width of w and a longitudinal length of l shall be centered on the plate such that an offset of w_o and l_o are present from a reference corner in the transverse and longitudinal directions, respectively. Details regarding the tolerances and surface finish of the macrotexture surface are given in Annex A3.

5.5. One continuous scan of the selected road surface along with the leveled straight edge and leveled straight edge with gauge blocks shall be collected. In the same scan or in a separate secondary scan the flat plate with the macrotexture surface shall be collected. If a secondary scan is used to collect measurements of the flat plate, no adjustments can be made to the equipment used.

5.6. All data collected shall be reported in an initial point cloud format, see Annex C1 for details regarding this format.

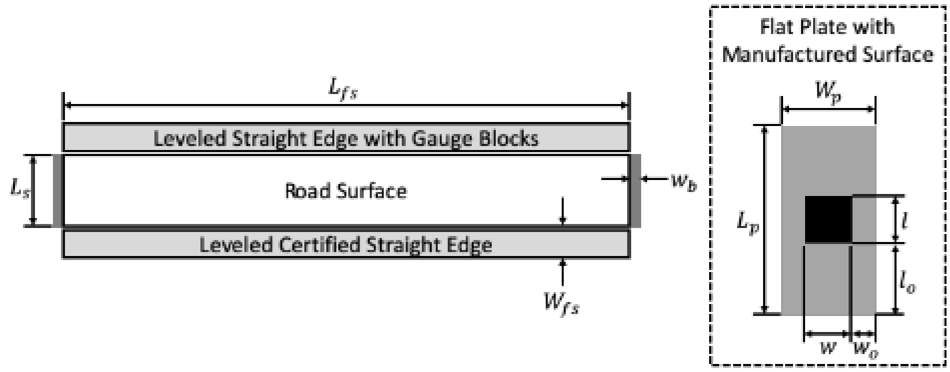

Figure 57. General layout of the test section with the bounding straight edges and manufactured surface off to the side of the road surface of interest.

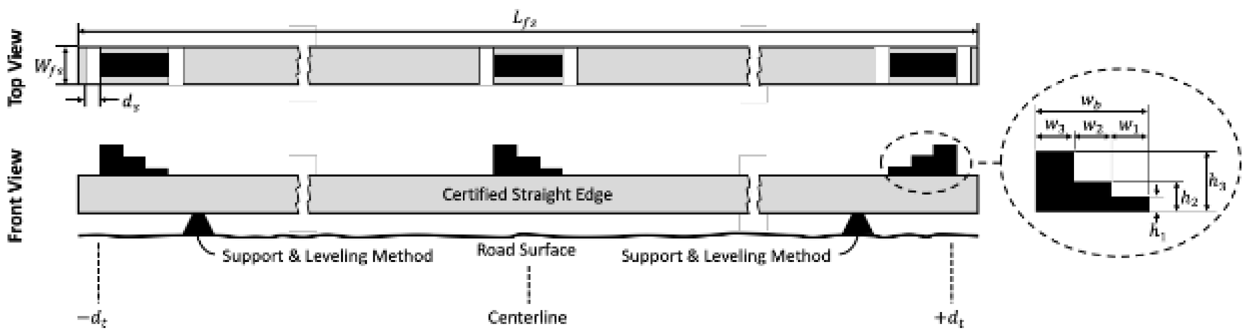

Figure 58. Detailed schematic of the layout of the gauge blocks on the leveled straight edge.

6. ROAD SURFACE ANALYSIS

6.1 Transverse and Longitudinal Measurement Spacing:

6.1.1 From the measurements in the ground reference region, N_r measurements shall be randomly selected and added to the set S_s. All S_s measurements in the set S_s shall be used to estimate the transverse and longitudinal measurement spacing.

6.1.2 For each measurement in the set S_s, the nearest neighboring point in each of four quadrants shall be identified (1 neighboring point per quadrant). The nearest neighboring measurement per quadrant shall be identified as the measurement point which is located in the quadrant of interest and has the shortest three-dimensional Euclidian distance. The quadrants shall be defined by a set of two dimensional orthogonal axes oriented at a 45º angle with respect to the transverse-longitudinal axes of the path coordinate system. Figure 59 illustrates the orientation and numbering scheme for the four quadrants.

6.1.3 The nearest neighboring point in quadrants 1 and 3 shall, each, provide an estimate of the transverse spacing. The transverse point-to-point distance between the respective measurement in the set S_s and the identified nearest neighboring point in quadrant 1 and quadrant 3 shall be calculated and added to the set r_t. The set r_t shall serve as a sample from the population of true transverse measurement spacing.

6.1.4 The nearest neighboring point in quadrants 2 and 4 shall, each, provide an estimate of the longitudinal spacing. The longitudinal point-to-point distance between the respective measurement in the set S_s and the identified nearest neighboring point in quadrant 2 and quadrant 4 shall be calculated and added to the set r_l. The set r_l shall serve as a sample from the population of true longitudinal measurement spacing.

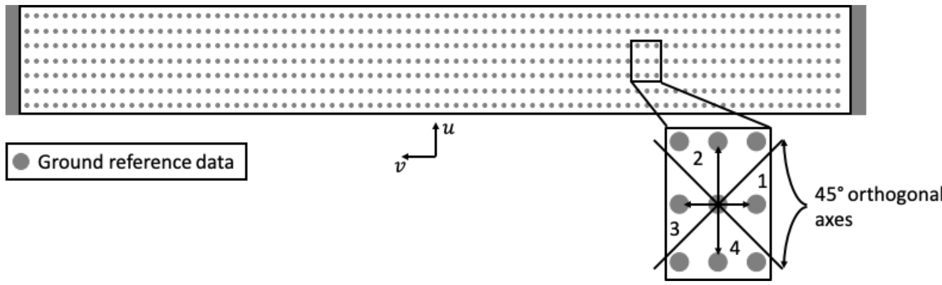

Figure 59. Illustration of four quadrants oriented with respect to the path coordinate system and identification of the nearest neighboring point in each respective quadrant.

7. GAUGE BLOCKS ANALYSIS

7.1 Per measured gauge block, the set of associated measurements shall be separated into sets of measurements based on edges between surfaces. Each set of measurements shall be organized into one of three categories: transverse, longitudinal, or vertical to define the respective direction the set of measurements shall provide measure errors.

7.2 For each category (transverse, longitudinal, and vertical) a single set of measurements in the category shall be used to establish a reference plane using a least squares error fit to the measurements. In total, per gauge block, three reference planes shall be defined to be used for point-to-plane distances.

7.3 Vertical Measurement Error:

7.3.1 Using the vertical measurement reference plane, the point-to-plane distance from each measurement set in the vertical category (omitting the set of points used to establish the reference plane) shall be calculated. The known certified vertical height corresponding to the point-to-plane distance shall be subtracted from the calculated point-to-plane distance to provide the vertical measurement error. See figure 60, for an example of identification of surfaces which provide vertical measurement error and a respective point-to-plane distance for each identified surface set.

7.3.2 For each point-to-plane distance the vertical measurement error shall be added to the set e_v. The complete set of e_v values shall serve as a sample from the population of true vertical measurement accuracy and precision.

7.4 Transverse Measurement Error:

7.4.1 Using the transverse measurement reference plane, the point-to-plane distance from each measurement set in the transverse category (omitting the set of points used to establish the reference plane) shall be calculated. The known certified transverse width corresponding to the point-to-plane distance shall be subtracted from the calculated point-to-plane distance to provide the transverse measurement error. See figure 61, for an example of identification of surfaces which provide transverse measurement error and a respective point-to-plane distance for each identified surface set.

7.4.2 For each point-to-plane distance the transverse measurement error shall be added to the set e_w. The complete set of e_w values shall serve as a sample from the population of true transverse measurement accuracy and precision.

7.5 Longitudinal Measurement Error:

7.5.1 Using the longitudinal measurement reference plane, the point-to-plane distance from each measurement set in the longitudinal category (omitting the set of points used to establish the reference plane) shall be calculated. The known certified longitudinal length corresponding to the point-to-plane distance shall be subtracted from the calculated point-to-plane distance to provide the longitudinal measurement error. See figure 62, for an example of identification of surfaces which provide longitudinal measurement error and a respective point-to-plane distance for each identified surface set.

7.5.2 For each point-to-plane distance the longitudinal measurement error shall be added to the set e_l. The complete set of e_l values shall serve as a sample from the population of true longitudinal measurement accuracy and precision.

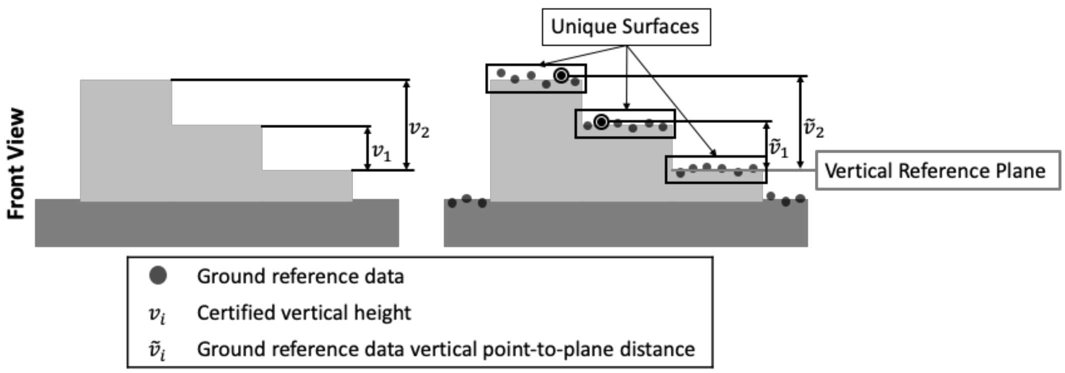

Figure 60. Identification of unique surfaces of a gauge block corresponding to vertical error measurement in the ground reference data point cloud, and example vertical point-to-plane distances for each unique surface set.

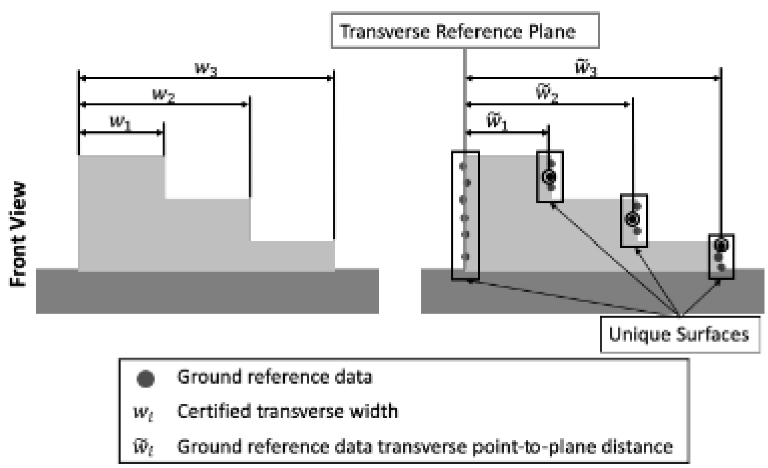

Figure 61. Identification of unique surfaces of a gauge block corresponding to transverse error measurement in the ground reference data point cloud, and example transverse point-to-plane distances for each unique surface set.

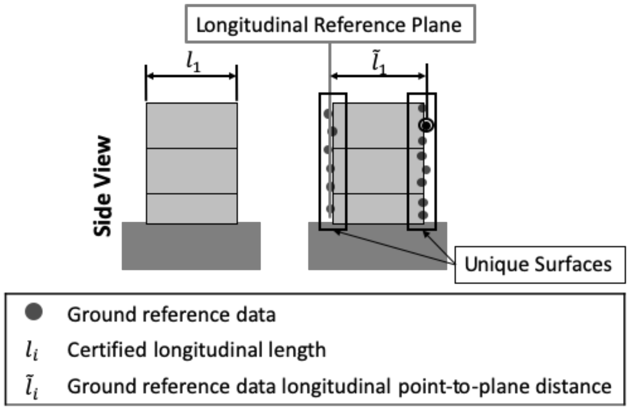

Figure 62. Identification of unique surfaces of a gauge block corresponding to longitudinal error measurement in the ground reference data point cloud, and example longitudinal point-to-plane distances for each unique surface set.

8. STRAIGHT EDGE ANALYSIS

8.1 Transverse Straightness:

8.1.1 A plane shall be fit to all measurements in the transverse straightness region using a least squares error fit.

8.1.2 The point-to-plane distance shall be calculated between each measurement and the fitted plane. The point-to-plane distance directly provides the measurement deviation from a flat surface. All point-to-plane distances shall be added to the set e_f. The complete set of e_f values shall serve as a sample from the population of true transverse straightness.

8.2 Transverse Width:

8.2.1 The transverse width (w_t) shall be calculated as the transverse surface distance of the complete set of measurements corresponding to the transverse straightness region.

9. MACROTEXTURE SURFACE ANALYSIS

9.1 Using an Iterative Closest Point (ICP) algorithm a set of translations and rotations shall be identified to map the known point cloud composed of the macrotexture verifiable dimensions in a component reference frame onto the same coordinate system as the macrotexture region in the collected ground reference data. The identified set of translations and rotations shall allow the known verifiable dimensions and the collected ground reference data to be considered in the same coordinate system.

9.2 Macrotexture Surface Error:

9.2.1 For the macrotexture surface the set of certified dimensions shall be used to generate a reference point cloud for evaluation of the measurement error in the ground reference data.

9.2.2 The macrotexture surface shall be divided into virtual rectangles each having a transverse width t_g and a longitudinal length l_g, as illustrated in figure 64.

9.2.3 Per virtual rectangle, a reference distribution, P_{ref}, of vertical (z-coordinate) heights shall be defined using the reference point cloud. The reference distribution, per virtual rectangle, can be approximated using the mean, μ_{ref}, and the standard deviation, σ_{ref}, of the vertical heights of the data points which lie inside the bounds of the virtual rectangle.

9.2.4 Per virtual rectangle, the ground reference data points shall be identified and added to the set GRE_{raw}. For each measurement height (z_p) in the set GRE_{raw} the Mahalanobis distance of the vertical height value of z_p from the reference distribution shall be computed as defined in the equation below

$$D_m = \frac{z_p - \mu_{ref}}{\sigma_{ref}}$$

9.2.5 The Mahalanobis distance for the height of a measured point, z_p, from the reference distribution, P_{ref}, is a measure of the error in points height value. Therefore, the Mahalanobis distance is added to the set e_z. Figure 64 provides an illustration for a single z_p point inside the t_g by l_g virtual rectangle.

9.2.6 This process shall be repeated for each virtual rectangle and the Mahalanobis distance of each ground reference data measurement shall be added to the set e_z. The set of all e_z values serve as a sample from the population true accuracy and precision values for the GRE.

9.3 Planar Flatness Error:

9.3.1 A plane, P_{flat}, shall be fit to all measurement points which lie on the flat plate, using a least squares error fit.

9.3.2 The residual errors from the least squares error fit shall be used as a measure of the ground reference data error corresponding to the measurement of a flat plate and be added to the set e_p. The set e_p shall serve as a sample from the population of true planar flatness error values for the ground reference data.

9.4 Vertical Measurement Spacing:

9.4.1 A plane, P_{flat}, shall be fit to all measurement points which lie on the flat plate. The vertical point-to-plane distance between each measurement on the flat plate and the plane, P_{flat}, (i.e. the planar flatness error associated with a measurement shall be representative of the vertical height).

9.4.2 From the measurement points which lie on the flat plate, N_r measurements shall be randomly selected and added to the set S_r. These N_r measurements shall be used to estimate the vertical measurement spacing of the ground reference data.

9.4.3 For each measurement in the set S_r, the nearest neighboring point in each of four quadrants shall be identified (1 neighboring point per quadrant). The nearest neighboring measurement per quadrant shall be identified as the measurement point which is located in the quadrant of interest and has the shortest three-dimensional Euclidian distance. The quadrants shall be defined by a set of two dimensional orthogonal axes oriented at a 45º angle with respect to the transverse-longitudinal axes of the path coordinate system. See figure 63, for an example of the quadrants for a selected point and the identification of the nearest neighboring point per quadrant.

9.4.4 The vertical point-to-point distance between the respective measurement in the set S_r and each of the four nearest neighboring points shall provide four estimates of the vertical spacing. The four calculated point-to-point distances shall be added to the set s_v. The set s_v shall serve as a sample from the population of true vertical measurement resolution.

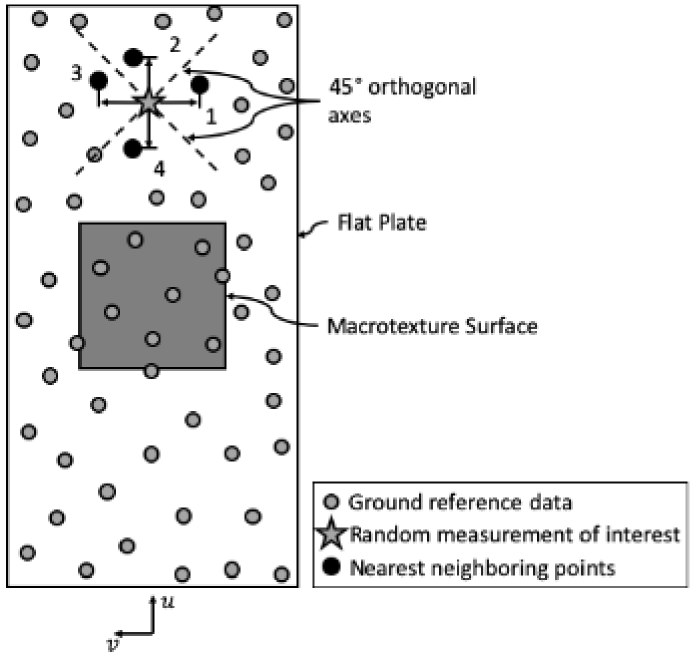

Figure 63. Illustration of four quadrants oriented with respect to the path coordinate system and identification of the nearest neighboring point in each respective quadrant for an example measurement of the flat plate.

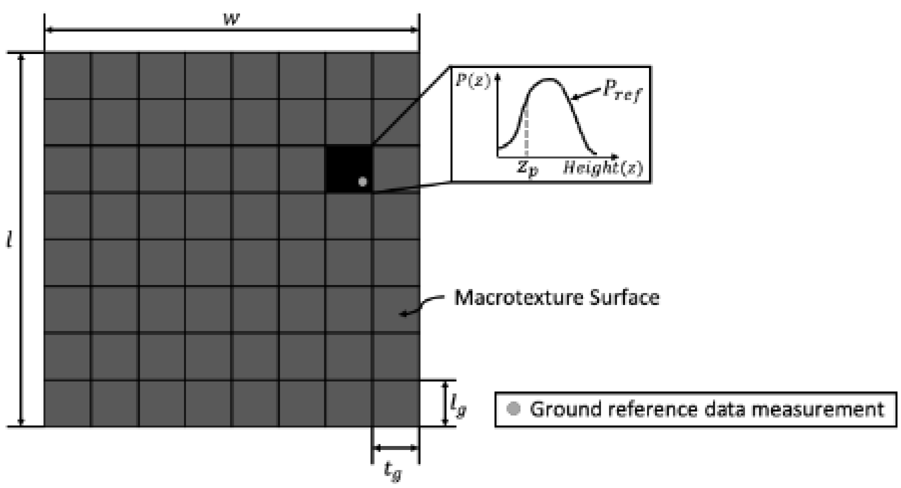

Figure 64. Gridding to determine the vertical accuracy and precision of ground reference data on a manufactured surface.

10. REPORTING TEST STATISTICS

10.1 Transverse Measurement Spacing—Report the set of r_t values.
10.2 Longitudinal Measurement Spacing—Report the set of r_l values.
10.3 Transverse Measurement Error—Report the set of e_w values.
10.4 Longitudinal Measurement Error—Report the set of e_l values.
10.5 Vertical Measurement Error—Report the set of e_v values.
10.6 Transverse Flatness Error—Report the set of e_f values.

10.7 Transverse Width—Report the value w_t.
10.8 Macrotexture Surface Error—Report the set of e_z values.
10.9 Planar Flatness Error—Report the set of e_p values.
10.10 Vertical Measurement Spacing—Report the set of s_v values.

11. ACCEPTANCE REQUIREMENT STATEMENT

11.1 Requirement statement for acceptance of ground reference data for TPP assessment is provided in table 39.

Table 39. Ground reference data requirement statement.

Output Test Statistic	Accuracy and Precision Defined as Bias and Confidence Intervals (mm)				
	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
	90% (5%)	50% (25%)		50% (25%)	90% (95%)
Transverse Measurement Spacing	NA	NA	NA	NA	2.0
Longitudinal Measurement Spacing	NA	NA	NA	NA	2.0
Transverse Measurement Error	-0.3	-0.15	NA	0.15	0.3
Longitudinal Measurement Error	-0.3	-0.15	NA	0.15	0.3
Vertical Measurement Error	-0.3	-0.15	NA	0.15	0.3
Transverse Flatness Error	-1.0	-0.5	NA	0.5	1.0
Transverse Width	NA	NA	NA	NA	4000
Macrotexture Surface Error (as standard deviation from a reference distribution)	-1.7	-0.7	NA	0.7	1.7
Planar Flatness Error	-1.0	-0.5	NA	0.5	1.0
Vertical Measurement Spacing	NA	NA	NA	NA	0.03

12. SYSTEM CALIBRATION & VERIFICATION

12.1 The process of calibrating and checking the performance of equipment used for ground reference measurements is the responsibility of the operator. Operators should evaluate and confirm the manufacturer's recommendations for calibrating and verifying the performance of the equipment prior to collecting ground reference data.

ANNEX A – REFERENCE OBJECT PROPERTIES

A.1. Straight Edge

A.1.1. Specified tolerances

A.1.1.1. Straightness/Flatness: ± 0.5 mm

A.1.1.2. To surface parallelism: ± 0.3 mm

A.1.2. Surface finish

A.1.2.1. Surface finish is only required on the top edge of the straight edge which will be measured by the GRE.

A.1.2.2. Surface finish shall induce diffuse reflection using any method of coating or media blasting desired while maintaining the specified tolerances in Section A1.1.

A.1.2.3. No greater than 5.0% specular reflection is allowed.

A.2. Gauge Block

A.2.1. Specified tolerances

A.2.1.1. Height, width, and length: ± 0.05 mm

A.2.1.2. Flatness/Parallelism: ± 0.01 mm

A.2.2. Surface finish

A.2.2.1. Surface finish is only required on the surfaces that the GRE will scan.

A.2.2.2. Surface finish shall induce diffuse reflection using any method of coating or media blasting desired while maintaining the specified tolerances in Section A2.1.

A.2.2.3. No greater than 5.0% specular reflection is allowed.

A.3. Macrotexture Surface

A.3.1. Specified tolerances

A.3.1.1. Overall dimensions: ± 0.05 mm

A.3.1.2. Minimum Mean Profile Depth: 1.0 mm

A.3.2. Surface finish

A.3.2.1. Surface finish is only required on the surfaces that the GRE will scan.

A.3.2.2. Surface finish shall induce diffuse reflection using any method of coating or media blasting desired while maintaining the specified tolerances in Section A2.1.

A.3.2.3. No greater than 5.0% specular reflection is allowed.

ANNEX B – ESTIMATION OF MEASUREMENT ERROR

B.1. Vertical Measurement Error

B.1.1. To determine the vertical measurement error of a gauge block, there are four potential sources which contribute to the error in the collected measurements: 1) Error in the measured height of the gauge block, 2) Error in the measured height of the straight edge, 3) Manufactured/calibration error in the height of the gauge block, 4) Manufactured/calibration error in the flatness of the straight edge

B.1.2. For the vertical measurement accuracy, the error of interest is the combination of the error in the measured height of the gauge block and the measure error in the measured height of the straight edge, together these can be referred to as the error in vertical measurement. In addition, data points along the straight edge are only considered within a distance d_s from the base of the gauge block to ensure that the straight edge can be considered a flat datum and no associated flatness error is needed in the vertical measurement. Thus, as long as d_s is maintained to be sufficiently small the fourth contribution can be considered trivial.

B.1.3. When these simplifications and bounds are placed on the establishments of the ground reference vertical height measurement, then the actual vertical height of the specified ith surface can be defined as the sum of the nominal vertical height of the surface and the uncertainty in the vertical height of the ith surface of the gauge block.

$$H_i = h + U_i$$

B.1.4. Similarly, we can consider that several measurements (several samples index by j) of the actual height of the ith surface of the gauge block is defined as the sum of the actual height of the ith surface and the jth measurement error.

$$\delta_{i,j} = H_i + E_{i,j}$$

B.1.5. Therefore, the measurement error for the jth measurement of the ith surface can be calculated from the two above equations. This particular sample of the vertical measurement error is the sum of the deterministic term (the measured height minus the nominal vertical height of the surface) and a random variable (the uncertainty in the height of the ith surface of the gauge block).

$$E_{i,j} = (\delta_{i,j} - h) - U_i$$

B.1.6. The uncertainty in this particular sample of measurement error is then just the uncertainty with which the actual height of the gauge block surface is known. While the uncertainty in the vertical height of the ith surface of the gauge block, U_i, may not be perfectly known, the gauge block can be certified such that a bound on the uncertainty can be established. This is typically stated as a tolerance on the manufacturing process, such that the uncertainty is above some minimum tolerance, u_{min}, and below some maximum tolerance, u_{max}, for all gauge block surfaces (including those in the particular sample).

$$u_{min} < U_i < u_{max}$$

B.1.7. The measurement error for the jth measurement of the ith surface is then bounded by these minimum and maximum bounds on the uncertainty.

$$(\delta_{i,j} - h) - u_{max} < E_{i,j} < (\delta_{i,j} - h) - u_{min}$$

B.1.8. To illustrate how the error in the ground reference measurement of vertical height of the gauge block surface can be isolated from the manufactured/certified error in the height of the gauge blocks, a simple example is provided.

B.1.8.1. Example — Ground reference measurements of a gauge block surface and the surface of a straight edge are taken. Using these measurements a set of vertical height measurements are identified. The nominal height of the gauge block then subtracted from the vertical heights resulting in a distribution of error values. Four error values are selected from this distribution to represented the requirement statement:
5% — -0.261 mm
25% — -0.115 mm
75% — 0.107 mm
95% — 0.232 mm

B.1.8.2. It is known that the gauge block surface has a vertical height certified to ±0.05 mm. Therefore, the true requirement statement for the ground reference vertical measurement error are:
5% — -0.261-0.05 = -0.311 mm
25% — -0.115-0.05 = -0.165 mm
75% — 0.107-(-0.05) = 0.157 mm
95% — 0.232-(-0.05) = 0.282 mm

B.2. Horizontal Measurement Error

B.2.1. When measurements of the horizontal width/length of the gauge block are collected, there are two potential sources which contribute to the error in the collected measurements: 1) Error in the measured width/length of the gauge block, 2) Manufactured/calibration error in the width/length of the transverse surface.

B.2.2. When collecting data, several ground reference samples can be taken to identify the horizontal dimensions of a specified surface of a gauge block. However, for each sample taken both errors are connected so a method for identifying the ground reference horizontal measurements capabilities is needed.

B.2.3. The actual horizontal width of the specified i^{th} surface can be defined as the sum of the nominal horizontal width of the surface and the uncertainty in the horizontal width of the i^{th} surface of the gauge block.

$$W_i = w + U_i$$

B.2.4. Similarly, we can consider that several measurements (several samples index by j) of the actual width of the i^{th} surface of the gauge block is defined as the sum of the actual width of the i^{th} surface and the j^{th} measurement error.

$$\delta_{i,j} = W_i + E_{i,j}$$

B.2.5. Therefore, the measurement error for the j^{th} measurement of the i^{th} surface can be calculated from the two above equations. This particular sample of the transverse measurement error is the sum of the deterministic term (the measured width minus the nominal transverse width of the surface) and a random variable (the uncertainty in the width of the i^{th} surface of the gauge block).

$$E_{i,j} = (\delta_{i,j} - w) - U_i$$

B.2.6. The uncertainty in this particular sample of measurement error is then just the uncertainty with which the actual width of the gauge block surface is known. While the uncertainty in the transverse width of the i^{th} surface of the gauge block, U_i, may not be perfectly known, the gauge block can be certified such that a bound on the uncertainty can be established. This is typically stated as a tolerance on the manufacturing process, such that the uncertainty is above some minimum tolerance, u_{min}, and below some maximum tolerance, u_{max}, for all gauge block surfaces (including those in the particular sample).

$$u_{min} < U_i < u_{max}$$

B.2.7. The measurement error for the j^{th} measurement of the i^{th} surface is then bounded by these minimum and maximum bounds on the uncertainty.

$$(\delta_{i,j} - w) - u_{max} < E_{i,j} < (\delta_{i,j} - w) - u_{min}$$

B.2.8. To illustrate how the error in the ground reference measurement of horizontal width of the gauge block surface can be isolated from the manufactured/certified error in the width of the gauge blocks, a simple example is provided.

B.2.8.1. Example — Ground reference measurements are acquired of a gauge block surface and the surface of a straight edge. Using these measurements a set of horizontal width measurements are identified. The nominal width of the gauge block then subtracted from the horizontal width resulting in a distribution of error values. Four error values are selected from this distribution to represented the requirement statement:
5% — -0.261 mm
25% — -0.115 mm
75% — 0.107 mm
95% — 0.232 mm

B.2.8.2. It is known that the gauge block surface has a transverse width certified to ±0.05 mm. Therefore, the true requirement statement for the ground reference horizontal measurement error are:
5% — -0.261-0.05 = -0.311 mm
25% — -0.115-0.05 = -0.165 mm
75% — 0.107-(-0.05) = 0.157 mm
95% — 0.232-(-0.05) = 0.282 mm

ANNEX C – OUTPUT DATA: GROUND REFERENCE POINT CLOUD

C.1. Data Output Structure

C.1.1. This is the file format for the ground reference point cloud data. The data to be reported in this format includes metadata describing the conditions in which the ground reference measurements were acquired and the measured data points.

C.1.2. Metadata:

C.1.2.1. Line 1: Ground Reference Equipment (GRE) vendor name [space] GRE system name/model/make

C.1.2.2. Line 2: Data and timestamp on which profile was acquired in UTC format

C.1.2.2.1. Format: YYYY-MM-DDTHH:MM:SS+OFFH:OFFM

C.1.2.2.2. Example: 2019-10-16T18:11:30+00:00

C.1.2.3. Line 3: Origin of the data in a local path reference frame (transverse, longitudinal, and elevation) all provided in meters)

C.1.2.3.1. Format: Transverse [Tab] Longitudinal [Tab] Elevation

C.1.2.3.2. Example: 0.000000 0.000000 0.000000

C.1.2.4. Line 4: The number of measurement points in the file

C.1.3. Measured data points:

C.1.3.1. Line 5: Transverse (x) coordinate [space] Longitudinal (y) coordinate [space] Elevation (z) coordinate of measurement point #1 (meters)

C.1.3.2. Line 6: Transverse (x) coordinate [space] Longitudinal (y) coordinate [space] Elevation (z) coordinate of measurement point #2 (meters)

C.1.3.3. …

C.1.3.4. Line end: Transverse (x) coordinate [space] Longitudinal (y) coordinate [space] Elevation (z) coordinate of last measurement point (meters)

APPENDIX G. STATIC PERFORMANCE GAUGE BLOCK HEIGHT

The primary objective of the static performance assessment is collecting transverse and vertical measurements of traceable objects (i.e., gauge blocks) to establish measures of transverse and vertical accuracy and precision. Therefore, it was decided that gauge blocks with certified heights and transverse widths shall be used during assessment. In the remainder of this appendix, supporting information and reasoning for the locations and heights of the gauge blocks during assessment is provided.

TRANSVERSE LOCATION OF THE GAUGE BLOCKS

Based on recommendations from the project panel, the gauge blocks shall be placed at three locations: center of the TPP (lane center), 2.0m to the left of the center of the TPP and 2.0m to the right of the center of the TPP. These three locations were chosen because it allows for the central data collection range of the TPP to be tested along with the transverse extrema of the TPP, with minimal amounts of data collection. If a TPP is not capable of collecting transverse measurements at one or more of these three locations adjustments can be made to the transverse position of the gauge block to ensure at least two gauge block transverse positions are measured for each mapping sensor. If deviations are made from the three transverse locations, they should be noted.

VERTICAL HEIGHTS OF GAUGE BLOCKS

In addition to assessing at multiple transverse locations per mapping sensor, a range of gauge blocks heights is necessary to measure the accuracy and precision throughout the vertical range of the TPP system. It was decided that a stair-stepped gauge block shall be used to allow for multiple gauge block heights to be tested at one time and to allow for horizontal accuracy and precision to be measured at multiple vertical distances from the mapping sensor. To minimize the chance of shadowing or blocking of horizontal surfaces from the mapping sensor it was decided that two groups of gauge block heights shall be tested (6 mm, 12 mm, and 25 mm) and (25 mm, 50 mm, and 75 mm). Table 40, below, provides reasoning for the five gauge block heights used.

Table 40. Supporting reasons for assessment gauge block height.

Gauge Block Height	Reasoning
6 mm	Equivalent to a low profile rut which the TPP should be capable of accurately measuring and reporting.
12 mm	Splits the difference between a low profile rut and a low-level curb.
25 mm	Representative of a low-level curb or edge of the lane.
50 mm	Splits the difference between the low-level curb and the upper vertical extrema height.

75 mm	Near the upper extreme of vertical heights a TPP should be capable of measuring.

APPENDIX H. BODY MOTION CANCELATION EXCITATION BOARD DESIGN

OVERVIEW

To ensure ride and roll body motion is present in the TPP system when collecting measurement in the body motion excitation test section excitation boards shall be placed in the wheel path of the TPP. A generalized layout of the excitation board is provided in figure 65, where the two longer length boards are designed to excite the primary ride of the vehicle and the five shorter cleats are used to excite wheel hop.

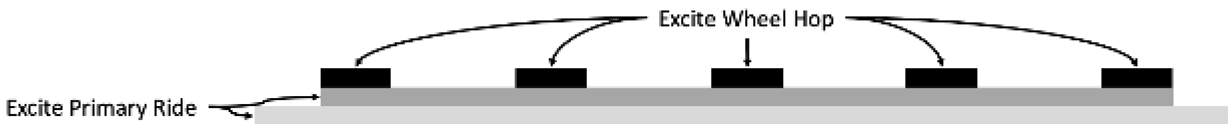

Figure 65. General design of an excitation board to excite primary ride and wheel hop natural frequencies of a vehicle.

When designing the excitation boards used in the body motion cancelation test a bounds on the tire diameter was needed to ensure the excitation board did not allow for tire enveloping to occur, reducing the effect of the excitation board. Based on average tire diameters of TPP systems, a tire diameter of 800 mm was used during the design phase.

CLEAT HEIGHT & EXCITATION BOARD LENGTH

The limiting factor on the length of the excitation board is the height of the cleats attached to the top of the excitation board. The wheels of the TPP must come into contact with the base of the excitation board so the higher the cleats are the wider the spacing must be between the cleats. To improve feasibility and cost of manufacturing the excitation board, it was assumed that the excitation board is constructed out of plywood and therefore the cleat thickness is limited to typical plywood grades available. When sizing typical plywood grades, it should be noted that the nominal reported thickness of plywood is not equivalent to the physical thickness of the plywood; it is common to assume the physical thickness is 1/32 inches thinner than the nominal thickness.

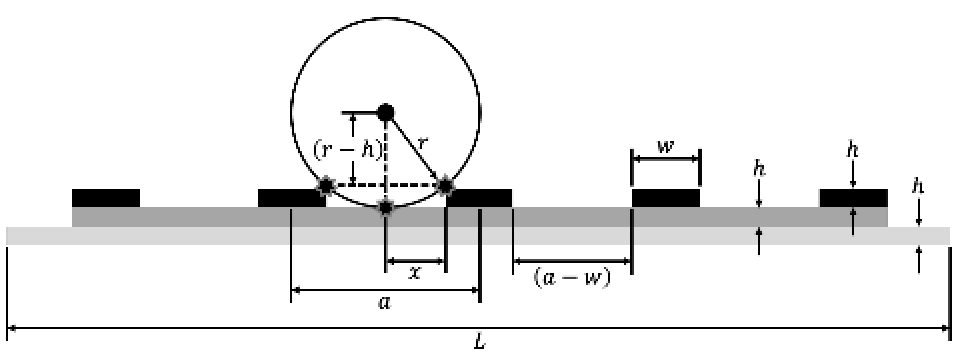

Figure 66. Dimensioned excitation board schematic with typical tire diameter represented by the black ring.

When designing the excitation board it is necessary to ensure that the tire does not envelope and touches all top surfaces of the excitation board. Based on the cleat height, h, a measure of the necessary half distance between cleats, x, can be established using the radius of the TPP tire, r as shown in equation 1.

$$x = \sqrt{r^2 - (r-h)^2} \tag{1}$$

Since x corresponds to half the distance between the cleats, the total distance between consecutive cleats is equivalent to $2x$. Both x and the total distance between cleats is provided in table 41 for a variety of plywood thickness values.

Table 41. Distance between cleats based on plywood thickness.

Nominal Thickness	**Actual Thickness**	**Half Distance Between Cleats**	**Distance Between Cleats**
¼ in	6.35 mm (¼ in)	71.0 mm	142.0 mm
⅜ in	8.73 mm (11/32 in)	83.1 mm	166.2 mm
½ in	11.9 mm (15/32 in)	96.8 mm	193.6 mm
⅝ in	15.1 mm (19/32 in)	108.9 mm	217.8 mm
¾ in	18.3 mm (23/32 in)	119.6 mm	239.2 mm
1 ⅛ in	28.6 mm (1 ⅛ in)	148.5 mm	297.0 mm

For design of the excitation board there are two critical dimensions: the distance between consecutive cleats, a, and the width of the cleats, w. The cleat width can be defined as a function of the ratio of the cleat spacing to the cleat width, w/a, over varying vehicle damping ratios. Assuming a typical vehicle damping ratio of 0.3 the ratio can be defined as $w/a = 0.35$.(19) Using the identified ratio of cleat width and cleat spacing along with the definition of x, all three variables can be related together by defining the distance between cleats as shown in equation 2.

$$2x = a - w = a - 0.35a = 0.65a \tag{2}$$

The excitation boards are used to excite the two main ride frequencies:

1. Primary ride (f_1): ~1.5 Hz
2. Wheel hop (f_2): ~15 Hz

The frequencies provided above are typical frequency values,

To make an excitation board which excites both frequencies, then the length of the board and the spacing of the cleats must be defined to properly excite the frequency components of interest. The spacing of the cleats (a) is a function of the two ride frequencies (f_1, f_2) and the complete length of the excitation board as defined in equation 3.

$$a = 2L\left(\frac{f_1}{f_2}\right) \quad (3)$$

When the common 1:10 ratio of ride frequencies for a passenger vehicle is substituted into equation 3 a simplified method of identifying the cleat spacing is presented in equation 4.

$$a = \left(\frac{1}{5}\right)L \quad (4)$$

Using the relationship in equation 2, the cleat spacing and cleat width of the excitation board can be established. The total length the excitation board must be can be established with equation 4. All of these calculated values for the varying plywood thicknesses are provided in table 42.

Table 42. Excitation board dimensions based on plywood thickness.

Nominal Thickness	**Distance Between Cleats** $(a-w)$	**Cleat Spacing** (a)	**Cleat Width** (w)	**Total Length** (L)
¼ in	142.0 mm	218.5 mm	76.5 mm	1092.5 mm (3.6 ft)
⅜ in	166.2 mm	255.7 mm	89.5 mm	1278.5 mm (4.2 ft)
½ in	193.6 mm	297.8 mm	104.2 mm	1489.0 mm (4.9 ft)
⅝ in	217.8 mm	335.1 mm	117.3 mm	1675.5 mm (5.5 ft)
¾ in	239.2 mm	368.0 mm	128.8 mm	1840.0 mm (6.0 ft)
1 ⅛ in	297.0 mm	456.9 mm	159.9 mm	2284.5 mm (7.5 ft)

For the body motion cancelation test a flat plate is placed on the road surface and measured by the TPP, the measurements of this plate ensures that the body motion of the TPP from the excitation boards is properly canceled out. To ensure that the body motion is properly canceled out the length of the flat plate must be approximately equal to the length of the excitation board. This equivalency is necessary because the excitation board length is equivalent to half of a vehicle ride oscillation and the flat plate must capture at least half of the ride oscillation. Therefore, to keep a reasonable length, using the dimensions in table 24, the excitation boards should be made out of ⅜ inch plywood. When ⅜ inch plywood is used an approximately 4 ft long excitation board and flat plate are needed.

IDENTIFICATION OF VEHICLE SPEED

The length of the excitation boards are equivalent to half of primary ride oscillation of a vehicle, to ensure this characteristic is achieved while conducting the standard practice a target vehicle speed must be prescribed. The target vehicle speed, V, can be calculated based on frequency and the excitation board parameters: distance between cleats and total excitation board length, see equation 5.

$$
\begin{aligned}
V &= af_2 \\
V &= 2Lf_1
\end{aligned}
\tag{5}
$$

For a passenger vehicle the primary ride frequency is between 1-2 Hz. To account for this potential range of primary frequencies during assessment, a range of speeds over the excitation board during the assessment is necessary. Table 43 provides the required speed of the TPP based on the primary ride frequency; based on these results the body motion cancel test shall be run at three speeds: 9 kph, 13 kph, and 18.5 kph.

Table 43. Target TPP speeds over the excitation boards.

Primary Ride Frequency (Hz)	**Speed (m/s)**	**Speed (kph)**	**Speed (mph)**
1.0	2.6	9.2	5.7
1.5	3.8	13.8	8.6
2.0	5.1	18.4	11.5

APPENDIX I. NAVIGATION DRIFT TEST SITE LAYOUT DESIGN

DEFINING THE FIGURE-EIGHT RADIUS & SPEED

According to the AASHTO *Policy on Geometric Design of Highway and Streets* the minimum radius (R_{min}) a road should be designed to contain can be defined based on the vehicle speed (V), the maximum superelevation (e_{max}), and the maximum side friction factor (f_{max}). This relationship is provided in equation 6.[20]

$$R_{min} = \frac{V^2}{127\,(0.01e_{max} + f_{max})} \tag{6}$$

In the policy, design values for the side friction factor are 0.13-0.14 for a vehicle velocity of 80.5 kph (50 mph). In addition, the policy recommends a low maximum rate of superelevation, usually around 4-6%. However, if we assume no bank angle is present (like in a typical parking lot) the superelevation will be zero. Thus, using equation 6 a relationship between the radius of a turn and the vehicle speed can be established. However, for measurement systems, transverse acceleration is a more meaningful measure to analyze rather than forward velocity. To identify the transverse acceleration resulting from a turn the TPP can be assumed to be a point mass, resulting in the relationship provided in equation 7.

$$a = \frac{V^2}{R} \tag{7}$$

Table 44 shows the minimum radius of a turn for vehicle speeds of 80.5 kph (50 mph) at three superelevation values. For all turns the minimum design value for friction factor (0.13) was used. The minimum radius was calculated using the equation 6 and the respective superelevation value and the resulting lateral acceleration was calculated using equation 7.

Table 44. Lateral acceleration based on the radius and superelevation of a turn.

Superelevation	Friction Factor	Minimum Radius	Lateral Acceleration
0	0.13	392.2 m	0.13 g
4	0.13	299.9 m	0.17 g
6	0.13	268.3 m	0.19 g

It is believed that when assessing navigation drift, the assessment will be conducted in an open parking lot. Therefore, there will likely be no bank angle present when conducting the assessment and it will not be reasonable to achieve a speed of 80.5 kph (50 mph) safely. Therefore, a turn with a smaller radius and lower speed will be developed to ensure a lateral acceleration of 0.13 g is experienced in the TPP. Using equation 7, table 45 was compiled using a lateral acceleration of 0.13 g and three prescribed velocities.

Table 45. Necessary target speed and turn radius to achieve the desired lateral acceleration.

Target Speed	Minimum Radius
2.24 m/s (5.0 mph)	3.92 m
3.58 m/s (8.0 mph)	10.0 m
4.47 m/s (10 mph)	15.7 m

While a target speed of 5.0 mph resulted in a small test site area because of a small radius, there is concern that the radius of the turn would be too tight for a typical TPP system to make. Therefore, a speed of 8 mph and a radius of 10 m was selected for the figure-eight because it allows for a reasonably small test site to be constructed but still have turns which can be navigated by TPPs.

To ensure no sharp turns or steep transition angles are present when driving over the reference object used in the assessment, it was decided that for 10 m radius turns a 30 m spacing between the two centers of the turns shall be used. With this spacing and a minimum TPP speed of 8 mph the TPP shall be able to complete one full lap of the figure eight in approximately 40 sec.

DETERMINING THE CERTIFICATION OBJECT SIZE

Using a provided minimum sampling of 30 Hz a set of minimum dimensions on the reference object can be established. The minimum sampling rate was provided by the transverse measurement community. At the minimum TPP speed of 8 mph and a sampling rate of 30 Hz, it can be concluded that there will be a spacing of 117 mm between consecutive transverse profiles. To provide an adequate number of data points for proper identification of global position of the reference object in the northing, easting, and elevation directions at least four transverse profiles are needed. Therefore, a minimum nominal length of the reference object shall be 468 mm (18.5 in).

APPENDIX J. HIGHWAY PERFORMANCE TEST DESIGN

LOCAL REGISTRATION

In the TPP Highway Performance assessment there are two test sections: transverse capability test section and ground reference test section. For the ground reference test section a high density higher accuracy set of reference measurements will be known to assess the measurement quality of the TPP. For this reason, the transverse and longitudinal location of the TPP measurements in the ground reference test section must be known, within reason, with respect to the ground reference test section. To eliminate the need for surveying the test section and identifying a global position of the ground reference test section, the bounding beams in the transverse capability test section can be angled to perform a local longitudinal registration. This registration is a single translation of all data in the longitudinal direction.

The localization can be performed by identifying the TPP measurements which lie on the beam surface. Then a best fit between the identified measurements and the constrained dimensions of the bounding beams in the transverse capability test section can be used to establish the longitudinal translation for the localization with the ground reference data. The angle of the bounding beams used to define the transverse capability test section will have an effect on the accuracy of the localization. When a shallow angle is present (i.e. the bounding beams are nearly longitudinal) the localization resolution will decrease because the TPP data can be significantly shifted before the measurements which are on the beam surface would no longer be on the beam surface. Conversely, when a larger angle is present the allowable longitudinal translation of the TPP data is reduced.

Figures 67 and 68 provide a representation of the transverse capability test section where four transverse profiles were collected. In both figures the stars indicate measurements which lie on the surface of the bounding beam. In figure 67 the bounding beams are placed at a shallow angle, whereas in figure 68 a steeper angle of the beams is used. Allowable longitudinal translations are defined by the longitudinal shift which can be applied to the data set and result in the identified bounding beam measurements lying on a surface of the bounding beam. Due to the shallow angle used in figure 67 a larger amount of longitudinal translation of the TPP data is allowed in comparison to the steeper angle used in figure 68.

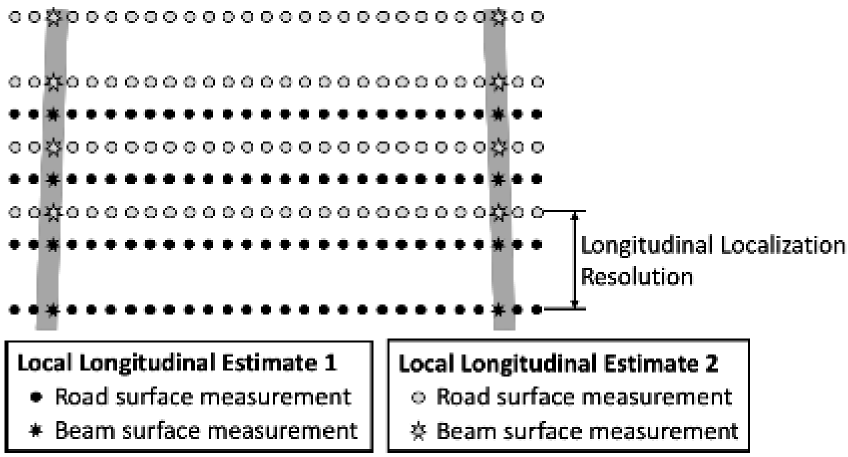

Figure 67. Shallow angle longitudinal localization resolution.

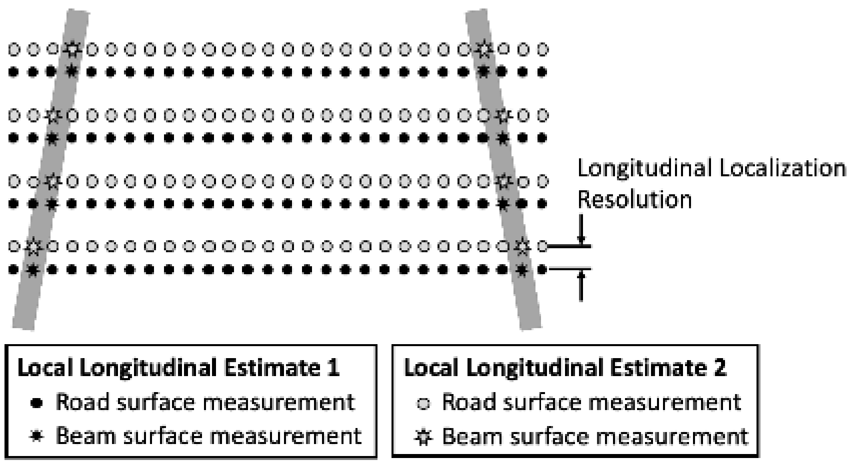

Figure 68. Steep angle longitudinal localization resolution.

APPENDIX K. CREAFORM METRASCAN CAPABILITY STATEMENT

Two capability statements for the Creaform MetraSCAN system are provided in tables 46 and 47. Each capability statement corresponds to the date the system was tested. All bolded values in the table passed the necessary confidence intervals in the requirement statement.

Table 46. Creaform March 22, 2019 capability statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Total transverse width	4385	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	**2**
Longitudinal measurement spacing	N/A	N/A	N/A	N/A	**2**
Vertical measurement spacing	N/A	N/A	N/A	N/A	0.37
Transverse measurement error	**-0.05**	**0.04**	N/A	**0.13**	**0.21**
Longitudinal measurement error	**-0.04**	**0.06**	N/A	**0.16**	**0.23**
Vertical measurement error	**-0.03**	**0.00**	N/A	**0.08**	**0.13**
Transverse straightness error	**-0.34**	**-0.24**	N/A	**0.21**	**0.55**
Macrotexture surface error	**-0.5**	**-0.2**	N/A	**0.2**	**0.5**
Planar flatness error	**-0.31**	**-0.13**	N/A	**0.14**	**0.28**

Table 47. Creaform May 23, 2019 capability statement (in millimeters).

	Lower Bounds (percentiles)		**Bias**	**Upper Bounds (percentiles)**	
	90% (5%)	50% (25%)		50% (75%)	90% (95%)
Total transverse width	4877	N/A	N/A	N/A	N/A
Transverse measurement spacing	N/A	N/A	N/A	N/A	**0.14**
Longitudinal measurement spacing	N/A	N/A	N/A	N/A	**0.15**
Vertical measurement spacing	N/A	N/A	N/A	N/A	**0.003**

Transverse measurement error	**-0.04**	**0.01**	N/A	**0.07**	**0.13**
Longitudinal measurement error	**-0.08**	**0.05**	N/A	**0.09**	**0.21**
Vertical measurement error	**-0.16**	**-0.08**	N/A	**0.001**	**0.08**
Transverse straightness error	-2.46	-1.0	N/A	0.99	1.38
Macrotexture surface error	**-0.22**	**-0.10**	N/A	**0.10**	**0.22**
Planar flatness error	**-0.27**	**-0.11**	N/A	**0.12**	**0.24**

APPENDIX L. BILL OF MATERIALS FOR STANDARD PRACTICES

Below is a bill of materials for the equipment used during the two transverse profile equipment rodeos and testing of the ground reference equipment.

GENERAL PURPOSE MATERIALS

The following materials were used throughout the assessments performed.

- Chalk line
- Tape measure
- Marking cones

STATIC PERFORMANCE ASSESSMENT

The following list of materials was used to conduct the static performance assessment during the second equipment rodeo:

- Certified 16 ft long straight edge
    - Quantity: 1
    - URL: http://petsch.cnc.net/web/Runway/RunwayStraighEdge.htm
- 1-2-3 gauge block set
    - Quantity: 3
- Metric 4A-Step Calibration Block, 7075 Aluminum
    - Quantity: 2
- Anti-glare 3D scan spray
    - URL: https://3dscanspray.com/

BODY MOTION CANCELATION

The following list of materials was used to conduct the static performance assessment during the second equipment rodeo:

- ⅜ inch plywood
    - Quantity: 1 4x8 ft sheet
- Aluminum plate, 2ft x 4ft, 0.3125 in thickness
    - Quantity: 3
- Machinist level with 0.001 in graduation sensitivity per 10 in
    - Quantity: 1
    - URL: https://www.mscdirect.com/product/details/06530166

NAVIGATION DRIFT MITIGATION

The following list of materials was used to conduct the navigation drift mitigation assessment during the second equipment rodeo:

- Custom manufactured certification object, navigation drift object
    - 20 in x 20 in x 2 in, 6061 aluminum
    - See Appendix I for dimensioned drawing of the part

- Dual-Antenna Differential GPS Base station

HIGHWAY PERFORMANCE

The following list of materials was used to conduct the highway performance assessment during the second equipment rodeo:

- 12 ft long by 1.5 in wide aluminum beam
  - Quantity: 2
- 20 in long by 1.5 in wide aluminum beam
  - Quantity: 2

GROUND REFERENCE DATA ASSESSMENT

The following list of materials was used to conduct the ground reference data assessment during the two evaluations of Creaform system.

- Certified 16 ft long straight edge
  - Quantity: 1
  - URL: http://petsch.cnc.net/web/Runway/RunwayStraighEdge.htm
- 1-2-3 gauge block set
  - Quantity: 3
- Metric 4A-Step Calibration Block, 7075 Aluminum
  - Quantity: 2
- Aluminum plate, 2ft x 4ft, 0.3125 in thickness
  - Quantity: 3
- Machinist level with 0.001 in graduation sensitivity per 10 in
  - Quantity: 1
  - URL: https://www.mscdirect.com/product/details/06530166
- Custom manufactured certification object, macrotexture surface
  - 120 mm x 120 mm, 3D printed plastic
  - See Appendix I for dimensioned drawing of the part

APPENDIX M. RODEO 1 VENDOR CAPABILITY STATEMENT

The capabilities for three vendors who participated in the first equipment rodeo are provided in tables 48, 49, and 50 based on the corresponding assessment performed. During Rodeo 1, a certified straight edge was not used for the static assessment, therefore a straightness error was not evaluated. For the navigation drift assessment, the reference object used was found to be too small to be accurately detected in the collected transverse profiles. In addition, the surveyed global location of the reference object was not collected. Therefore, no assessment of navigation drift is provided. Lastly, for the highway performance assessment no ground reference data was collected, so the vertical measurement error of the point cloud and gridded data along with rut depth, cross slope, and edge/curb detection errors were not evaluated.

Table 48. Rodeo 1 static performance capability statement (in millimeters).

	Vendor	**Lower Bounds (percentiles)**		**Bias**	**Upper Bounds (percentiles)**	
		90% (5%)	50% (25%)		50% (75%)	90% (95%)
Total transverse width	**Req** A1 B1 C1	**4000.0** 3885.2 4216.1 3592.3	N/A	N/A	N/A	N/A
Transverse measurement spacing	**Req** A1 B1 C1	N/A	N/A	N/A	N/A	**10.0** 2.20 9.35 10.0
Vertical measurement spacing	**Req** A1 B1 C1	N/A	N/A	N/A	N/A	**0.10** 0.05 0.1 0.003
Vertical measurement error	**Req** A1 B1 C1	**-1.5** -2.8 - -5.1	**-1.0** -1.3 - -1.8	N/A	**1.0** 0.6 - 0.8	**1.5** 2.4 - 3.6

Table 49. Rodeo 1 body motion cancelation performance capability statement (in millimeters).

	Vendor	**Lower Bounds (percentiles)**		**Bias**	**Upper Bounds (percentiles)**	
		90% (5%)	50% (25%)		50% (75%)	90% (95%)

Vehicle body motion error	**Req** A1 B1 C1	**-4.0** -16.6 -12.3 -1.8	**-2.5** -8.6 -2.5 -0.7	N/A	**2.5** 6.6 4.0 0.6	**4.0** 23.5 6.9 1.4

Table 50. Rodeo 1 highway performance capability statement (in millimeters).

	Vendor	**Lower Bounds (percentiles)**		**Bias**	**Upper Bounds (percentiles)**	
		90% (5%)	50% (25%)		50% (75%)	90% (95%)
Total transverse width	**Req** A1 B1 C1	**4000.0** 3252.0 3302.0 3174.0	N/A	N/A	N/A	N/A
Vehicle Transverse Wander	**Req** A1 B1 C1	**4000.0** 254.6 184.6 90.0	N/A	N/A	N/A	N/A
Transverse measurement spacing	**Req** A1 B1 C1	N/A	N/A	N/A	N/A	**10.0** 2.0 8.5 10.0
Longitudinal measurement spacing - Network	**Req** A1 B1 C1	N/A	N/A	N/A	N/A	**3000** 25.2 99.4 222.4
Longitudinal measurement spacing - Project	**Req** A1 B1 C1	N/A	N/A	N/A	N/A	**500** 25.2 99.4 222.4

APPENDIX N. FABRICATED PARTS FOR RODEO 2

CERTIFICATION OBJECT: NAVIGATION DRIFT

Figure 69 provides the overall dimensions associated with the reference object used for assessment of navigation drift during the second equipment rodeo. Since the reference object contains several angled surfaces which are not uniform, figure 70 contains the angle dimensions associated with each of the angled surfaces.

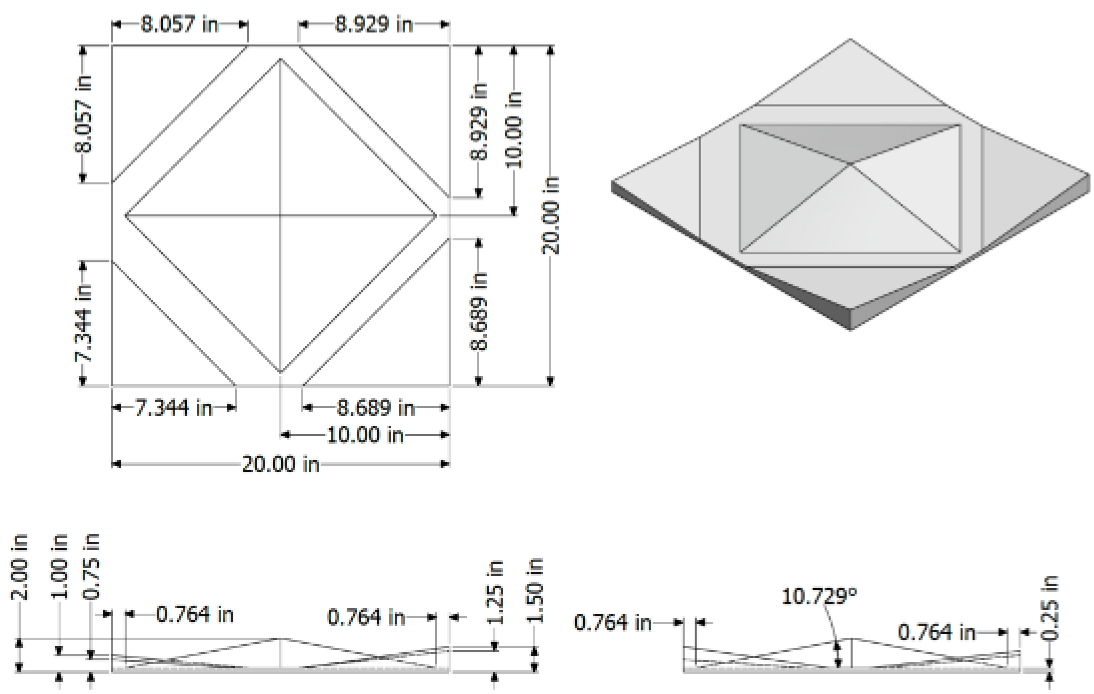

Figure 69. Dimensioned drawing of the reference object used in the navigation drift assessment during the second equipment rodeo.

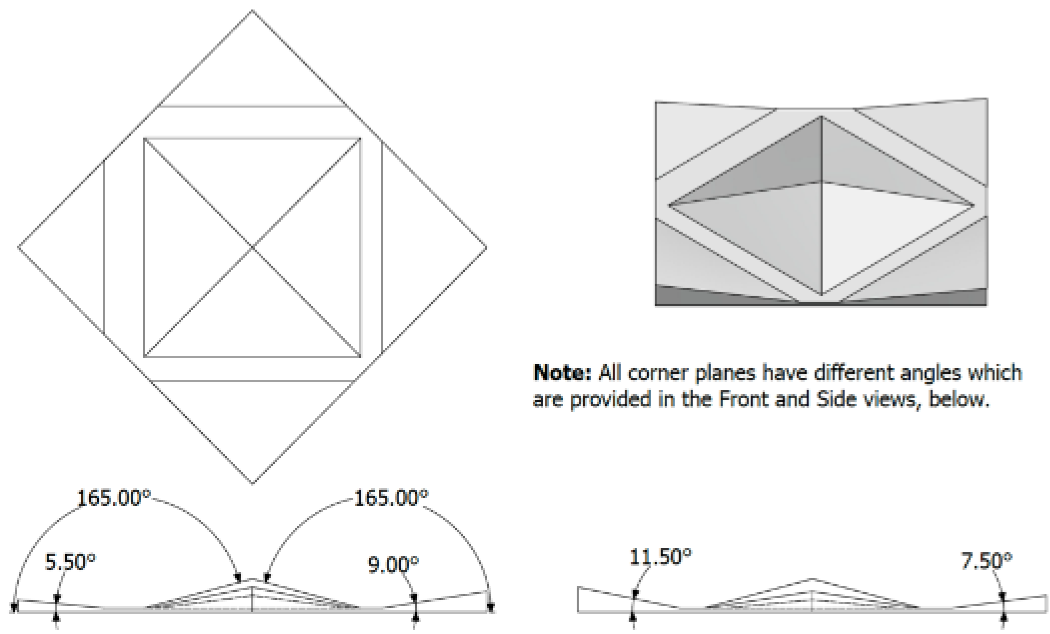

Figure 70. Dimensions of the angled surfaces associated with the reference object used for the navigation drift assessment during the second equipment rodeo.

CERTIFICATION OBJECT: MACROTEXTURE SURFACE

Figure 71 provides the overall dimensions associated with the macrotexture surface used for assessment of the ground reference data. The detailed view (Detail A), in figure 71 provides a side view of the uniform three-dimensional sine wave constituting the macrotexture.

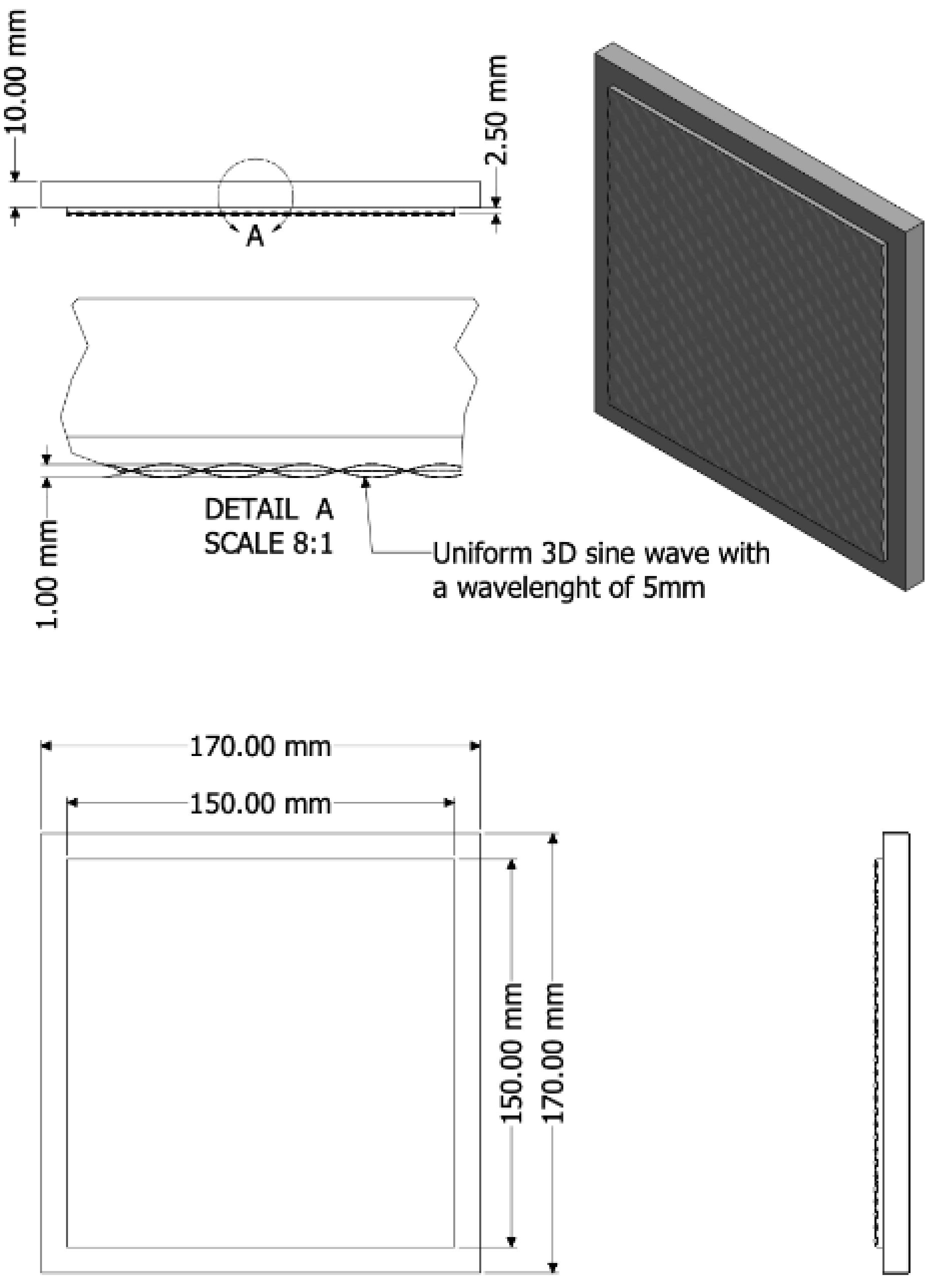

Figure 71. Dimensioned drawing of the macrotexture surface used during the assessment of ground reference data.

APPENDIX O. RODEO 2 VENDOR CAPABILITY STATEMENT

The capabilities for three vendors who participated in the second equipment rodeo are provided in tables 51, 52, 53, and 54 based on the corresponding assessment performed.

Table 51. Rodeo 2 static performance capability statement (in millimeters).

	Vendor	Lower Bounds (percentiles)		Bias	Upper Bounds (percentiles)	
		90% (5%)	50% (25%)		50% (75%)	90% (95%)
Total transverse width	**Req** A2 B2 C2	**4000.0** 3960.5 4167.2 3987.8	N/A	N/A	N/A	N/A
Transverse measurement spacing	**Req** A2 B2 C2	N/A	N/A	N/A	N/A	**10.0** 1.93 5.06 5.08
Vertical measurement spacing	**Req** A2 B2 C2	N/A	N/A	N/A	N/A	**0.10** 1.27 0.61 0.10
Transverse measurement error	**Req** A2 B2 C2	**-7.5** 0.3 1.8 3.8	**-5.0** 2.2 2.6 3.8	N/A	**5.0** 4.2 6.7 8.9	**7.5** 5.5 6.8 8.9
Vertical measurement error	**Req** A2 B2 C2	**-1.5** 2.3 -1.0 -2.2	**-1.0** 3.6 0.2 -1.5	N/A	**1.0** 4.8 1.1 -0.1	**1.5** 6.5 2.1 0.6
Straightness error	**Req** A2 B2 C2	**-2.50** -1.46 -2.31 -1.60	**-1.50** -0.64 -0.46 -0.02	N/A	**1.50** 0.56 0.71 0.02	**2.50** 1.52 1.51 1.50

Table 52. Rodeo 2 body motion cancelation performance capability statement (in millimeters).

	Vendor	Lower Bounds (percentiles)	Bias	Upper Bounds (percentiles)

		90% (5%)	50% (25%)		50% (75%)	90% (95%)
Vehicle body motion error	**Req** A2 B2 C2	**-4.0** -10.8 -2.3 -1.7	**-2.5** -4.3 -0.9 -0.5	N/A	**2.5** 4.7 2.1 0.6	**4.0** 9.7 3.4 1.2
Vertical measurement spacing	**Req** A2 B2 C2	N/A	N/A	N/A	N/A	**0.10** 2.10 2.94 0.78

Table 53. Rodeo 2 navigation drift performance capability statement (in millimeters).

	Vendor	**Lower Bounds (percentiles)**		**Bias**	**Upper Bounds (percentiles)**	
		90% (5%)	50% (25%)		50% (75%)	90% (95%)
Easting (x) Position Error	**Req** A2 B2 C2	**-1000** -35940 -1522 -2084	**-500** -35860 -1300 -2070	N/A	**500** -34700 -854 -2015	**1000** -34540 -522 -2007
Northing (y) Position Error	**Req** A2 B2 C2	**-1000** 33070 30 707	**-500** 33180 220 739	N/A	**500** 33560 520 790	**1000** 33570 700 807
Elevation (z) Repeatability	**Req** A2 B2 C2	**-125** -43.6 -124 -9.5	**-50** -30.8 -104 -3.3	N/A	**50** 32.4 183 5.4	**125** 38.1 381 8.0

Table 54. Rodeo 2 highway performance capability statement (in millimeters).

	Vendor	**Lower Bounds (percentiles)**		**Bias**	**Upper Bounds (percentiles)**	
		90% (5%)	50% (25%)		50% (75%)	90% (95%)
Effective transverse width	**Req** A2 B2	**4000.0** 3764.1 3903.7	N/A	N/A	N/A	N/A

	C2	3730.6				
Transverse measurement spacing	**Req** A2 B2 C2	N/A	N/A	N/A	N/A	**10.0** 1.93 4.45 5.08
Longitudinal measurement spacing - Network	**Req** A2 B2 C2	N/A	N/A	N/A	N/A	**3000** 25 153 127
Longitudinal measurement spacing - Project	**Req** A2 B2 C2	N/A	N/A	N/A	N/A	**500** 25 153 127
Point cloud vertical error (standard deviation from reference distribution)	**Req** A2 B2 C2	**-2.5** -3.4 -5.0 -3.5	**-1.0** -0.6 -2.1 -1.2	N/A	**1.0** -0.6 1.5 1.0	**2.5** 2.3 4.5 2.7
Gridded data vertical error (standard deviation from reference distribution)	**Req** A2 B2 C2	**-1.7** -3.4 - -	**-0.7** -0.6 - -	N/A	**1.0** -0.6 - -	**1.7** 2.3 - -
Rut depth error	**Req** A2 B2 C2	**-2.5** -1.1 -2.0 -2.1	**-1.5** -0.3 -0.9 -0.7	N/A	**1.5** 1.3 0.6 0.5	**2.5** 2.1 1.3 1.9
Cross slope error (percent)	**Req** A2 B2 C2	**-0.4** -3.18 -5.51 -0.05	**-0.15** -3.15 -5.40 0.06	N/A	**0.15** -1.08 -5.12 0.08	**0.4** -1.02 -4.97 0.08
Edge/Curb transverse location error	**Req** A2 B2 C2	**-50** 124.3 -21.7 -	**-25** 128.1 -11.0 -	N/A	**25** 133.9 20.1 -	**50** 139.7 42.5 -
Edge/Curb vertical magnitude error	**Req** A2 B2 C2	**-2.5** -5.0 -4.4 -	**-1.5** -3.4 -3.6 -	N/A	**1.5** -0.3 -1.3 -	**2.5** 2.5 0.4 -