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Successful Practices for Quality Management of Pavement Surface Condition Data Collection and Analysis

Final Report

Submitted to

U.S. Department of Transportation

Federal Highway Administration

Office of Innovation Implementation – Resource Center

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FOREWORD

The FHWA managed pooled fund study, TPF-5(299) Improving the Quality of Pavement Surface Distress and Transverse Profile Data Collection and Analysis, was established to assemble State Departments of Transportation (DOTs) and the Federal Highway Administration, alongside industry and academia to meet six main goals. (1) Identify pavement surface distress and transverse profile (PSDAT) data integrity and quality issues; (2) Suggest approaches to addressing identified issues and provide solutions; (3) Initiate and monitor pilot projects intended to address identified issues; (4) Disseminate results; (5) Assist in the deployment of research findings and recommendations; and (6) Support other efforts related to improving pavement surface distress and transverse profile data collection and analysis. This is the final report of an FHWA project, Guidance for Quality Management of Pavement Surface Condition Data Collection and Analysis, managed within TPF-5(299). The main goal of the project is to provide successful practices for DOTs to implement in quality management programs (DQMPs) that result in increased data accuracy, precision, and reliability while maintaining a cost-effective data collection process.

This report will be useful for personnel involved in network-level pavement surface condition data collection and analysis.

Shay K. Burrows, Director, Office of Innovation Implementation - Resource Center

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For years State Departments of Transportation (DOTs) have conducted pavement surface condition surveys to collect data to manage their pavement assets. These surveys involve a significant investment of time, money, and human resources. Understanding the pavement condition data's reliability in pavement management is vital. Repeatable and reliable pavement condition data is vital in developing condition indexes and performance models, understanding how and why pavements perform better than others, and finding cost-effective solutions to pavement rehabilitation and preservation needs. Quality pavement condition data also play an essential role in determining performance parameters. Several sources of information on Quality Management (QM) standards, procedures, and best practices are used to perform Quality Control (QC) and acceptance of pavement condition data. Implementing these processes improves data reliability to meet the needs of Pavement Management Programs (PMPs). The main goal of this report is to provide successful practices for DOTs consideration to implement in data quality management programs (DQMPs) that result in increased data accuracy, precision, and reliability while maintaining a cost-effective data collection process.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ACRONYMS

2D:	Two-dimensional
3D:	Three-dimensional
AASHTO:	American Association of State Highway and Transportation Officials
AFM:	Automated Fault Measurements
ASTM:	American Society for Testing and Materials
BMP:	Beginning Measurement Point
COV:	Coefficient of Variation
DCV:	Data collection vehicle
DMI:	Distance measuring instrument
DOT:	Department of Transportation
DQMP:	Data quality management plan
EMP:	End Measurement Point
FHWA:	Federal Highway Administration
GIS:	Geographic information system
GPS:	Global positioning systems
GRE:	Ground Reference Equipment
HPMS:	Highway Performance Monitoring System
HSIP:	High-Speed Inertial Profiler
IMU:	Inertial Measurement Unit
IRI:	International Roughness Index
JCP:	Jointed Concrete Pavement
KML:	Keyhole markup language
LCMS:	Laser Crack Measurement System
LiDAR:	Light detection and ranging

LRS: Location referencing system

LTPP: Long-Term Pavement Performance

MEPDG: Mechanistic-Empirical Pavement Design Guide

NCHRP: National Cooperative Highway Research Program

NHS: National Highway System

PCI: Pavement Condition Index

PCR: Pavement Condition Rating

PMS: Pavement Management System

PQI: Pavement Quality Index

PSI: Present Serviceability Index

PSC: Pavement Surface Characteristics or Pavement Surface Condition

PSR: Present Serviceability Rating

PWL: Percent within limits

QA: Quality Assurance

QC: Quality control

QM: Quality management

QMP: Quality management plan

ROW: Right-Of-Way

TPP: Transverse Pavement Profile

CHAPTER 1. INTRODUCTION

BACKGROUND

Many Departments of Transportation (DOTs) have transitioned from manual to high-speed automated pavement surface condition (PSC) data collection methods and from points-based to surface-based or three-dimensional (3D) measurement systems (Zimmerman 2017). The new 3D equipment has dramatically changed how data is collected and managed. Modern-day high-speed devices are equipped with multiple subsystems that simultaneously collect location information, road profiles, and high-quality video and imagery that can be used to extract pavement surface distress data. The laser/camera technologies and software collect dense-spaced elevation data. Several vendors have developed proprietary algorithms and software for calculating the fault, rut depths, crack types, crack lengths and severities, and other distresses from these high-speed 3D data.

DOTs use the collected PSC data for various maintenance and rehabilitation decision-making and budgeting processes. Since most DOTs report that their road networks are their largest asset, understanding data quality is paramount (Chang et al., 2020). However, data verification is not easily performed due to the variety of technologies and lack of certification standards. Under the Transportation Pooled Fund (TPF)-5(299)/(399), efforts are devoted to improving PSC data quality and management processes and developing standards to certify data collection equipment and evaluate the collected data. This report includes ready-to-implement data quality management practices from several TPF-5(299)/(399) projects and DOT programs.

Equipment Systems

A state-of-practice high-speed vehicle typically includes a high-speed inertial profiler (HSIP) system and a 3D system described in the following sections (Chang et al., 2020). Other systems and sensors mounted on vehicles can vary based on DOT needs.

High-speed Inertial Profiler Systems

During Phase I of this project, all existing DOT PSC DQMPs submitted in 2018 and 2019 were reviewed. Nearly all DOTs reported using HSIP systems that meet the requirements of AASHTO M328-14 Standard Specifications for Inertial Profiler in their DQMPs (Chang et al., 2020). The three measuring components of the HSIP system include: (1) a height sensor that measures the vertical distance between the sensor unit and the measured pavement surface; (2) an accelerometer that measures the vertical acceleration of the vehicle at the sensor unit in response to the pavement profile; (3) a distance sensor that provides a location reference for measurement location. The HSIP systems' software processes these three measurements into a true pavement profile by removing vehicle movements. An HSIP system measures the longitudinal profile, and the international roughness index (IRI) can be calculated based on the IRI algorithm per ASTM E1926. In addition to IRI, the longitudinal profile can be used to determine Automated Fault Measurements (AFM) according to AASHTO R 36.

Longitudinal profiles can also be collected using 3D systems. Since these systems collect point cloud elevation data of the road surface, longitudinal or transverse profiles can be extracted. 3D technologies have become more widely used to collect faulting data (Chang et al., 2012). In the 2019 DQMPs, no DOTs reported using 3D systems to collect IRI data.

High-speed 3D Systems

High-speed 3D data collection vehicles are comprised of multiple sensors. Altmann and Ferris (2020) classify the sensors into two categories, mapping sensors, and location sensors. Mapping sensors are described as sensors that acquire road surface measurements and report them in a local sensor reference frame (e.g., x, y, and z data). Mapping sensors can include but are not limited to, scanning lasers and cameras. Location sensors are described as sensors that acquire the position and orientation of the vehicle sensors. The data can be georeferenced or registered in a global reference frame (e.g., northing, easting, and elevation). When mapping sensor data is combined with location sensor data, the resulting set of measurements is considered a point cloud (Altman and Ferris 2020).

Based on information from the FHWA Standard Data Format for 2D/3D Pavement Image Data project, high-speed systems can generally collect TPPs at 4 m width, and some systems can record a TPP at an interval of 5 mm or even 1 mm. However, most agencies request a profile every 10 cm or 1 m. Global positioning system receivers are used to locate the data geospatially. 3D systems use a combination of lasers and cameras to capture high-resolution images and 3D range profiles of the driven lane at traffic speeds. A typical TPP image is 5 m long of the full lane width. 3D range data provides point cloud elevation data of the roadway surfaces.

Distress data can be determined from these systems using vendors' fully automated proprietary algorithms, manually by viewing images and video from a computer screen, or using a semi-automated combination of automated detection and manual post-processing. Automated detection generally uses a combination of pattern search and machine learning techniques. Based on the findings from Phase I of this project, many DOTs have different definitions for distress metrics. Therefore, the algorithms used for distress detection may vary by DOTs.

System Certification and Verification

All HSIP systems are produced based on a similar design by General Motors. The established and proven AASHTO R56 standard for HSIP equipment certification has existed since 2002. There are several regional certification sites nationwide, and some state DOTs manage their certification sites. According to DQMP-related peer exchange, DOTs reported very few issues with checking the data quality from HSIPs (Orthmeyer 2018).

Each predominant 3D equipment system has unique mapping and location sensors. Therefore, checking the data quality for each 3D system may vary. Since no national or international data quality procedures for 3D systems existed until recently, many DOTs struggled to implement successful certification and verification of these systems. In 2020, five AASHTO standards were developed under the TPF-5 (299)/(399) project titled "Calibration, Certification, and Verification of Transverse Pavement Profile Measurements." These standards include certifying and verifying 3D systems used to collect TPP data metrics (specifically, rut depth, cross slope, and edge or curb detection). These AASHTO standards have been piloted for various DOTs under two TPF-5(299)/(399) projects (including this project). The results and lessons learned under this project's pilot efforts were reported in the Phase II Task 3 report for FHWA. The lessons learned from the TPP pilot projects have been incorporated into this report and are further described in chapter 4.

DQMP Considerations

Typically, DOTs have pavement condition metrics specific to their decision-making processes. For example, many states have different definitions for cracking and record different cracking parameters, such as type, severity, and length. State pavement management programs depend on these specific data definitions for maintaining data consistency and making historical or year-to-year comparisons. In addition to state-specific metrics, DOTs also collect and report cracking, rutting, IRI, and faulting data per the Highway Performance Monitoring System (HPMS) field manual definitions as required per 23 CFR 490.319(c), as further described in the following section. This report intends to address both state-specific and HPMS data metrics. However, it is not practical to include every nationwide metric and definition. Therefore, DOTs can use their judgment as to which practices provided in this document best fit their data quality management needs.

Federal DQMP Requirements

High-quality data is a critical part of the performance-based management of highway pavements (FHWA 2018). The National Performance Management Measures: Assessing Pavement Condition for the National Highway Performance Program and Bridge Condition for the National Highway Performance Program (PM2) rule requires States to develop DQMPs appropriate for their agency per 23 CFR 490.319. FHWA defines DQMP as a document that defines the acceptable level of data quality and describes how the data collection process will ensure this quality level in its deliverables and processes (FHWA 2018).

HPMS data submitted under Federal Rule per 23 CFR 490 has requirements that DOTs must follow. These requirements are emphasized throughout the rest of this report using notice boxes (like the one used here). Under 23 CFR 490.319(c), the State DOT must develop a DQMP that addresses the following minimum critical areas:

A. Data collection equipment calibration and certification.

B. Certification process for persons performing manual data collection.

C. Data quality control measures are conducted before data collection begins and periodically during the data collection program.

D. Data sampling, review, and checking processes.

E. Error resolution procedures and data acceptance criteria.

These critical areas are further described in the relevant subsequent chapters.

Selecting Quality Measures, Frequencies, and Tolerances

This report aims to include successful practices that consider costs and labor resources. DQMPs may be comprised of various quality measures, frequencies, and tolerances. Certification procedures generally provide information about equipment sensors and system functions. Therefore, completing certification before data collection is critical to ensure the proper function of the systems and quality data. However, certification efforts may be more time-consuming and labor-intensive than daily or weekly quality control checks. Therefore, successful DQMPs include various quality activities that balance the amount of information gained with available time and labor efforts. Generally, the information gained decreases as the time and labor for an activity increase. DOTs can consider these competing concepts to establish reasonable testing measures and frequencies. More information regarding data quality activities is described in the following chapters.

Setting required tolerances for data checks may follow similar principles. For example, data checks performed at a certification site with a dense point cloud of ground reference data can reasonably use smaller error tolerances than differences from checking data against historical data from the previous year. Both procedures are methods for checking data quality, but the expectations for error tolerance may not be the same. One example of setting data verification tolerances for different quality measures is the United Kingdom's (UK's) use of tiered control sites throughout data collection (UK Roads Board 2012). This concept is further described in chapter 2.

PROJECT OBJECTIVE

This document is the final report for the Successful Practices for Quality Management of PSC Data Collection and Analysis Project. This project aimed to demonstrate successful practices and processes to State DOTs on implementing network-level PSC DQMPs.

During Phase I of this project, all DOT DQMPs from 2018 and 2019 were evaluated, and common successes and areas for improvement were identified. A summary of these findings and a comprehensive literature review were reported in the Phase I report titled Document of Successful Practices (Chang et al., 2020).

During Phase II of this project, three DOTs (Alabama [ALDOT], Washington [WSDOT], and Pennsylvania [PennDOT]) were selected to pilot Phase I successful practices. The most common area for improvement discovered during Phase I was related to the certification and verification of transverse pavement profile (TPP) systems. Therefore, emphasis was placed on piloting recently published certification and verification procedures for TPP systems, including collecting ground reference data. The pilot efforts were summarized in a Phase II Task 3 report and chapter 4 of this report.

Based on information gained during Phase I and the lessons learned during the Phase II Task 3 pilot projects, this report was developed, as further described in the following section.

DOCUMENT OBJECTIVE

The objective of this document is to summarize the information from the Phase I report and the lessons learned from the Phase II Task 3 report into a Final Report. This document aims to give DOTs options they can include in their DQMPs for monitoring and improving data quality related to network-level PSC data collection.

Because this report intends to be concise, the literature review and summary of the 2019 DQMP review findings are not repeated in this report. Instead, readers may reference the Phase I report for supplemental information. The lessons learned from the Phase II Task 3 pilot studies are discussed in chapter 4.

DOCUMENT UPDATES

Since the technology associated with PSC data collection is evolving rapidly, this document may be updated periodically to reflect changes in the state of practice data collection. Ongoing TPF-5(299)/(399) research projects may affect data definitions, certification procedures, and data acceptance criteria, among other elements.

HOW TO USE THIS DOCUMENT

DOTs can refer to the most current edition of this document as a template to update their DQMPs. The rest of this document (chapters 2 through 7) is structured mainly by the timeline of when the quality management activities occur. This document's structure is intended to translate into a useful DQMP outline or template. Based on the reviews of existing DQMPs, this timeline was generally followed by all DOTs and related DQMP documents, including the Practical Guide for Quality Management for Pavement Condition Data Collection (Pierce et al. 2013) and NCHRP Synthesis 401 Quality Management of Pavement Condition Data Collection. This timeline also addresses the five critical CFR areas (referenced in the previous notice box). The timeline contains three main phases, including:

- Before data collection.
- During data collection.
- After data collection.

Figure 1 shows a timeline of the three phases, with general tasks during each phase. Each chapter covers one of the tasks shown in Figure 1, as summarized in Table 1. Each chapter includes successful practices related to the task that DOTs can consider in their future DQMP updates.

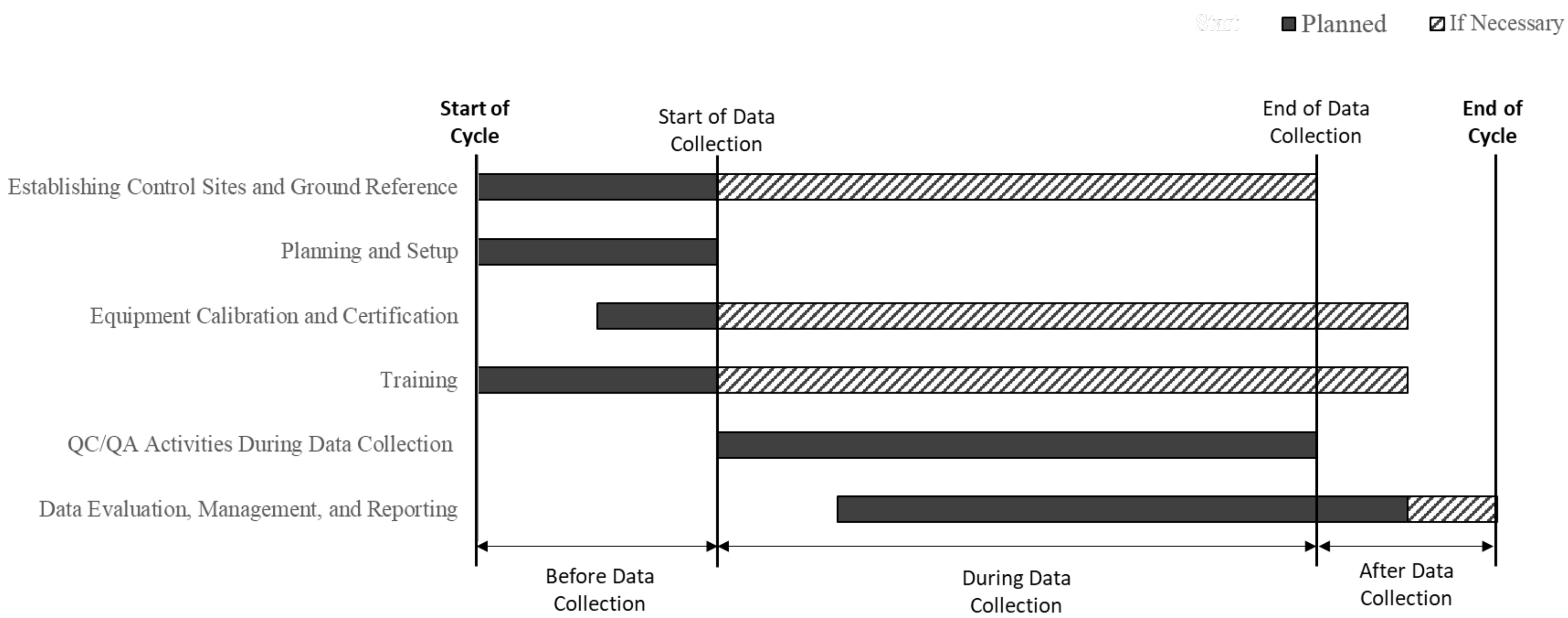
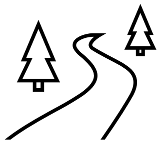
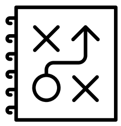
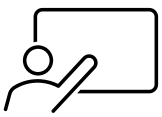
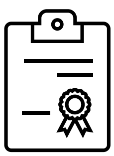
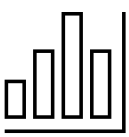
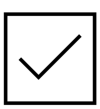


Figure 1. Chart. Example timeline of each of the main data collection phases with general tasks that occur in each phase.

Table 1. Document Organization

Icon	Chapter	Description
	Chapter 2. Establishing Control Sites and Ground Reference.	Information for establishing control sites and ground reference data. DQMPs may include multiple control sites for different quality assurance activities.
	Chapter 3. Planning and Setup.	Successful practices for planning network-level data collection.
	Chapter 4. Equipment Calibration and Certification.	Successful practices for equipment calibration and certification, including case studies of piloting recently published AASHTO standards for certification and verification of TPP equipment.
	Chapter 5. Training.	Information and successful practices for training for data collection, data evaluation, and manual rater certification programs.
	Chapter 6. QC/QA Activities During Data Collection.	Successful practices for quality assurance activities during data collection, such as daily data reasonableness checks, checks at control sites, and others.
	Chapter 7. Data Evaluation, Management, and Reporting.	Successful practices for evaluating data after data collection include reasonableness checks, checks against historical data, and others. Includes data management practices, reporting, and periodic updating of DQMPs.
	Chapter 8. Summary.	Summarizes the report.

CHAPTER 2. ESTABLISHING CONTROL SITES AND GROUND REFERENCE

INTRODUCTION

A common data verification method uses control sites with known ground reference data. High-speed HSIP and 3D vehicles can drive through the control sites, and the collected data is compared to the known ground reference. Control sites, ground reference data, comparison tolerances, and other related considerations are included in the following sections.

CONTROL SITE CRITERIA

According to the FHWA Guidelines for Development and Approval of State Data Quality Management Programs (FHWA 2018), control sites should include the typical range of values for the pavement condition metrics that the equipment will be certified against. The data types can generally be classified as longitudinal profile metric (e.g., IRI), TPP metric (e.g., rut depth, cross slope, and edge or curb detection), or other surface distress metric (e.g., cracking, raveling). Finding one control site with a range of longitudinal profiles, TPP, and distress metrics can be challenging. Therefore, many states report using separate control sites for different metrics.

Most DOT DQMPs reported using control sites for IRI data verification. AASHTO R56-14 describes certification procedures for HSIP. There are several regional HSIP certification sites located across the US. However, fewer DOTs reported having control sites suitable for faulting, TPP metric, or distress verification. Until recently, there were no published standards to assist with setting control sites for these metrics. Recently completed research projects under the TPF-5(299)/(399) provide methods and procedures for control sites and ground reference data for TPP and cracking metrics. AASHTO R36-13 describes measuring the faulting of concrete pavement joints and cracks using manual methods and HSIP data. AASHTO R36-13 includes limited verification recommendations. There is an ongoing TPF-5(299)/(399) project related to control sites and ground reference for faulting. However, there are no implementable procedures from the research at this time. The control site recommendations for PSC metrics based on published standards or recently completed research are summarized in Table 2.

AASHTO R56-14 Standard Practice for Certification of Inertial Profiling Systems and AASHTO R36-13 Evaluating Faulting of Concrete Pavements are required under 23 CFR 490.

Table 2. Summary of control site criteria from published standards or recently completed research.

Metric	Control Site Criteria	Reference
IRI	• Smooth section – IRI range of 30-75 inches/mile. • Medium-smooth section – IRI range of 95-135 inches/mile. • Medium-rough section – IRI range of up to 200 inches/mile. • Surface macrotexture should reflect common surfaces being collected. • At least 528 feet in length for IRI with lead in and lead out. • No significant grade or grade change. • Horizontal curvature or superelevation should be avoided.	AASHTO R56-14, Standard Practice for Calibration of Inertial Profiling Systems.
TPP (e.g., rut depth, cross slope, or edge and curb detection)	• Range of road and pavement conditions. • Low-level rutting – minimum of 2.0 mm (0.08 inches). • High-level rutting – minimum of 20 mm (0.79 inches). • Cross slope greater than 0.5%. • Surface macrotexture should reflect the variety of the pavement surfaces to be evaluated. • Minimum road length of 0.25 miles.	AASHTO PP109-21, Standard Practice for Assessment of Highway Performance of Transverse Pavement Profiling Systems.
Cracking (or other similar distress)	• Should represent the types and severity levels of distress normally experienced by an agency for each pavement type to be evaluated. • Should consist of asphalt concrete pavements, jointed concrete pavements (JCP), and continuously reinforced concrete pavements (CRCP). • A minimum of three sections of each pavement type should be included, although as many as six will increase statistical reliability. • Asphalt and CRCP should be a minimum of 0.3 miles in length, and JCP should be a minimum of 0.5 miles or 100 slab lengths, whichever is greater. • Additional sections may be considered for different roughness values, as roughness may affect image quality, surface textures, tined or grooved conditions, and the presence of other distresses on the pavement.	Morian et al., 2020, Developing Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection/Analysis Systems and/or Services.
Faulting (measured with HSIP)	• Control sites should have known faulting, the range of heights is not specified. • Distance should be at least 1.0 miles long. • The height transducer should be statically calibrated using machine reference blocks at heights of 0.50, 1.00, and 2.00 inches.	AASHTO R36-13, Evaluating Faulting of Concrete Pavements

GROUND REFERENCE DATA COLLECTION

The method for collecting ground reference data depends on the data being collected and the purpose of the control site. Ground reference equipment and procedures recommended for certification sites based on published AASHTO standards and TPF-5(299)/(399) research reports are summarized in Table 3. The following section, Tiered Control Sites, describes other concepts for measuring reference data for verification events.

Table 3. Summary of ground reference collection methods from published standards or recently completed research.

Metric	Ground Reference Collection Methods	Reference
IRI	• It is recommended that a reference profiling device meet the repeatability and accuracy criteria for measuring IRI specified in the Benchmark Test Evaluation Report (Karamihas, 2011). • A device that can collect data at 1-inch intervals or less. • At least three repeat runs should be performed along each trace with the reference device. • After performing the runs, evaluate the repeatability using cross-correlation. The three runs' average repeatability and accuracy values should be at least 0.98 for the reference data to be acceptable for IRI. Any of the three reference runs can be used as the reference profile. • Devices that measure and integrate differential elevations, such as the Dipstick® and walking profilers, may be used to meet the interval requirement. However, rod-and-level measurement locations should be used to check the profiles no more than 100 feet apart.	AASHTO R56-14, Standard Practice of Inertial Profiling Systems.
TPP (e.g., rut depth, cross slope, or edge and curb detection)	• This practice describes the accuracy and precision analysis needed to ensure a ground reference equipment (GRE) system collects acceptable quality ground reference data. • The accuracy and precision are evaluated using four surfaces: a certified straightedge, a bounding beam with gauge blocks, a road surface, and a macrotexture surface. The standard provides recommendations for setting up the test section, as shown in Figure 2. • The metrics evaluated are transverse, longitudinal, and vertical measurement error; transverse, longitudinal, and vertical measurement spacing; transverse straightness; and horizontal plane flatness. Each evaluation has recommended error tolerances. • There are no specific equipment requirements, and any equipment that can meet the requirements for the measurements is considered acceptable. An example of the equipment used during the Phase II Task 3 pilot projects is shown in Figure 3.	AASHTO PP110-21, Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment.
Cracking (or other similar distress)	• Manual in-person or “boots-on-the-ground” ratings are recommended. • Raters should be trained in the specific distress definition before rating. • A single rating or consensus rating should be used as the ground reference. Ratings should not be averaged. • All cracking equal to or greater than 1 mm wide should be reported. • Control sites should be sectioned into subsections. Each subsection should be marked with a start, end, and intermediate point. • A template or markings should be used to identify the wheel paths, as shown in Figure 4. • Cracking or similar distresses should reflect the definitions used by the DOT or HPMS.	Morian et al., 2020, Developing Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection/Analysis Systems and/or Services.

Metric	Ground Reference Collection Methods	Reference
Faulting (measured with HSIP)	• Limited guidance is given in AASHTO R36 for collecting ground reference data. Ongoing research projects under TPF-5(299)/(399) aim to provide procedures for collecting ground reference data for faulting.	AASHTO R36-13, Evaluating Faulting of Concrete Pavements

Source: Chang et al., 2020

Figure 2. Photograph. Ground reference test section for TPP control site.

Source: Chang et al., 2020

Figure 3. Photograph. GRE used for the TPP ground reference test section during the Phase II Task 3 pilot projects.

Source: Morian et al., 2020

Figure 4. Photograph. Example of wheel path markings before the crack survey.

TIERED CONTROL SITES

It may not be feasible or reasonable for a DOT to use certification-level control sites for all quality assurance checks. Less reliable control sites may be appropriate for some quality assurance activities and be less labor and resource intensive to establish. DQMPs may include a balance of different tiers of control sites for different data quality checks. One example of a tiered control site approach used by the UK Roads Board is illustrated in Figure 5.

The UK Roads Board uses a tiered approach to control sites, ground reference collection, testing frequency, and error tolerances. The “top tier” is a certification event. Certification is typically performed annually before data collection begins, if equipment sensors or instruments are replaced, or if troubleshooting is needed to diagnose data errors. Certification control sites result in the most information gained (as further described in chapter 4).

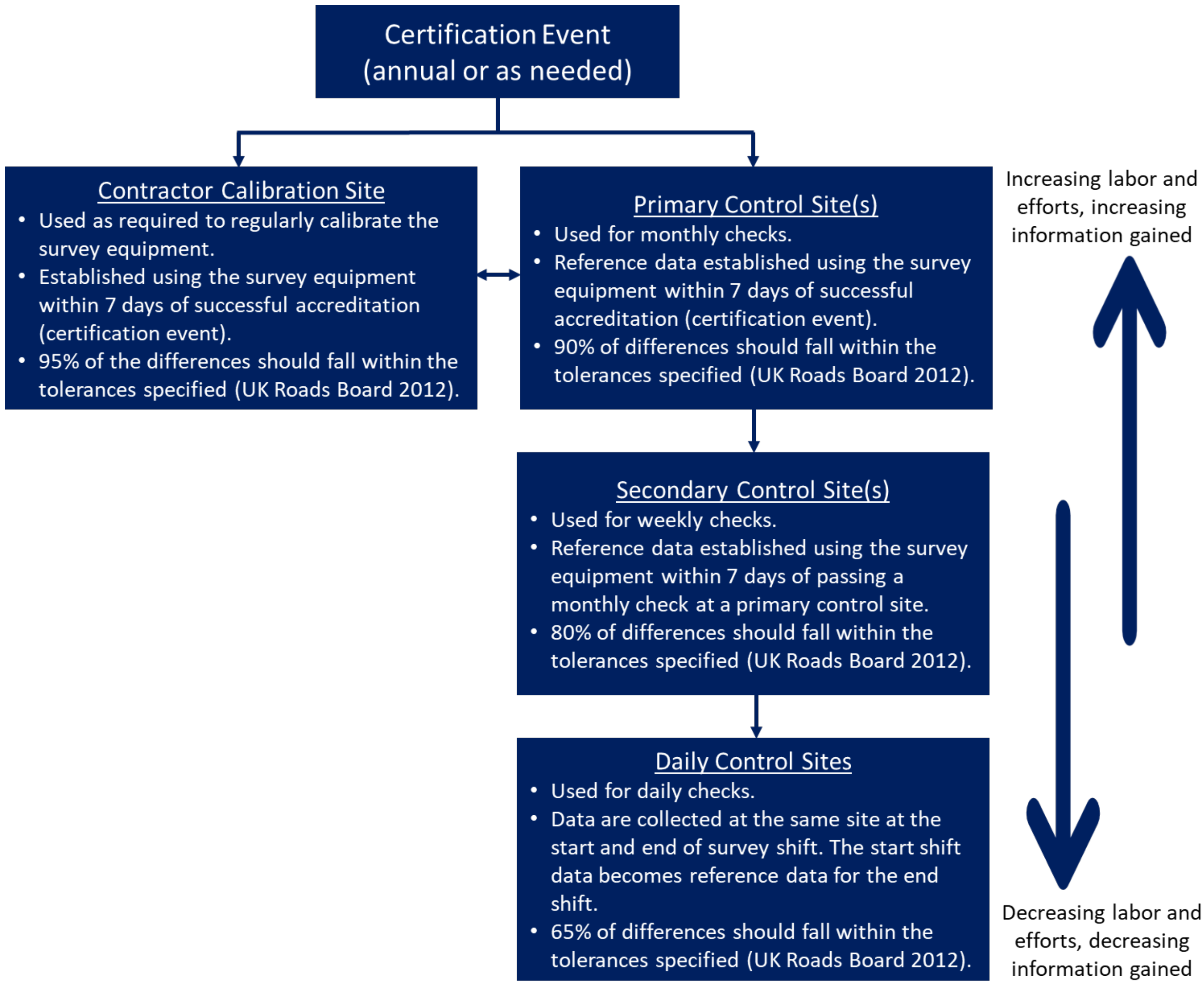


Figure 5. Chart. Example of UK Roads Board tiered control site approach to data QA (adapted from UK Roads Board 2012).

The UK Roads Board's tiered approach includes the following types of control sites:

- Certification (accreditation)
- Contractor's Calibration Site
- Primary Control Sites
- Secondary Control Sites
- Daily Control Sites

Each tier is described in the following sections, adapted from the UK Roads Board Specifications (UK Roads Board 2012). The descriptions below are written from the perspective of using a vendor or contractor to collect the data, but the same concepts can be adapted for DOT-owned equipment. More information on the UK Roads Board Quality Assurance Methods, including required tolerances when comparing data to the ground reference, can be found in the SCANNER surveys for Local Roads User Guide and Specification Volume 4 Version 1.1 2012 edition.

Certification Site

Information on certification sites is included in chapter 4.

Contractor's Calibration Site

The Contractor's Calibration Site is established within seven days of passing an accreditation (certification) event. The Contractor Calibration Site uses the contractor's high-speed equipment (or survey equipment) to collect ground reference data. This site is likely near the Contractor's main operational base for operational convenience. The purpose of this site is to calibrate the equipment regularly and monitor long-term data trends. Since this site is used for calibration purposes, it has the strictest error tolerance, and 95 percent of verification data must meet the required tolerances compared to the reference data.

Primary Control Sites

One or more Primary Control Sites are established using the contractor's high-speed equipment to collect ground reference data. The reference data must be collected within seven days of the successful certification event. The UK Roads Board requires monthly verification checks at a Primary Control Site. Since the data are established immediately (within seven days) following a certification event, there is higher confidence in the ground reference data. Therefore, 90 percent of verification data must meet the required tolerances compared to the reference data.

Secondary Control Sites

One or more Secondary Control Sites are established using the contractor's high-speed equipment to collect ground reference data. The reference data must be collected within seven days of a successful monthly verification at a Primary Control Site. The UK Roads Board requires weekly verification checks at a Secondary Control Site. The UK Roads Board specifies that 80 percent of verification data must meet the required tolerances compared to the reference data. The verification criteria are reduced for Secondary Control Sites since the ground reference data is collected after "passing" a Primary Control Site verification, which may introduce some errors.

Daily Control Sites

The UK Roads Board requires Daily Control Sites verifications. For Daily Control Sites, the same stretch of roadway is collected at the beginning and end of a shift, where a shift is up to 24 hours long (e.g., the data can be collected each morning). Therefore, having the Daily Control Site near the nightly lodging facility makes sense. The data collected from the beginning of a shift becomes the reference profile for the data collected at the end of the shift, and the two data sets are compared to each other. Data collected during a shift is "enclosed" between the verification checks. If the verification checks meet the set thresholds, the data collected during the shift is likely valid. This concept can be described using a "bookending" analogy, as illustrated in Figure 6. Bookending refers to verification events on either end (beginning and end) of a stretch of collected data (shift, week, month, etc.). Bookending can be a useful quality assurance tool. According to the UK Roads Board requirements, 65 percent of the differences between the start and end of shift surveys should fall within the tolerances specified.

The UK Roads Board allows some flexibility with Daily Control Sites. For example, if weather conditions make it impractical or impossible to complete a daily check, it should be recorded and completed when possible. A new Daily Control Site is set up if the survey vehicle moves to a new location.

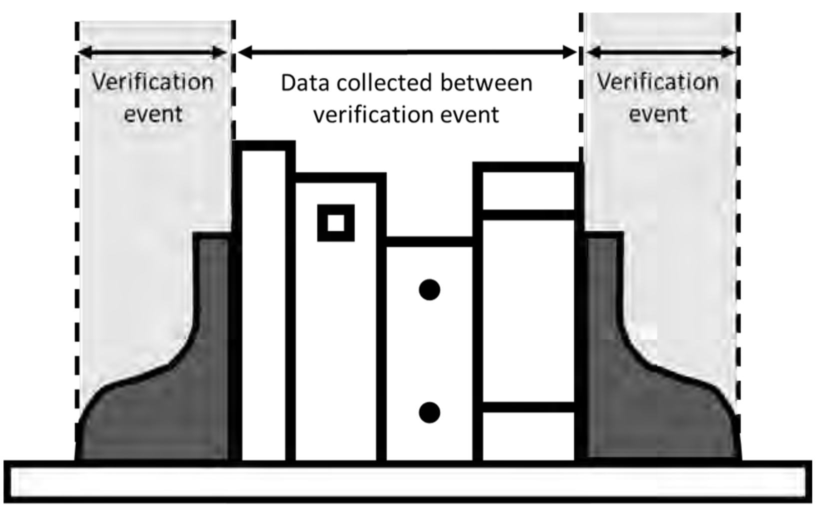


Figure 6. Graphic. A "bookending" analogy describes data collected between two verification events.

Blind Control Sites

Blind control sites can be used as QC or quality acceptance tools. Blind control site locations are not disclosed to the data collection team before data collection but only after testing is completed. Blind control sites primarily check data accuracy since it occurs after data collection, and repeat runs cannot be made.

A benefit to using blind control sites during data collection is reducing the potential for increased efforts from the data collection team during (known) control site testing than efforts used during typical network collection.

If a DOT elects to use blind control sites, the frequency depends on other QC and acceptance measures. For example, a DOT using a blind control site as an acceptance tool can want to perform blind control site checks at a regular frequency to ensure the data being collected meets their requirements.

BLIND CONTROL SITE CASE STUDY

The following is an example of Pennsylvania DOT's (Pennsylvania DOT 2018) use of blind verification sites as a QC tool.

PennDOT selects 125 segments before the start of testing to use as blind control sites. The segments are distributed statewide to represent the full range of conditions and are not disclosed to the vendor (or data collection team). PennDOT evaluates the images from this site using a minimum of three raters performing a minimum of two evaluations each. The accuracy of the vendor's Blind control site data shall be within ±10% of the average PennDOT ratings.

The vendor's blind control site data is also compared to data from the previous two years. Unexplained differences (i.e., when no maintenance or construction work was done on the Segment) of more than ± 10% for distress ratings are flagged for review. These segments are sent to the vendor for verification and resubmission.

OTHER CONTROL SITES

DOTs may use other methods to establish control sites to fit the needs of their programs. Several DOTs report using manual distress ratings to establish ground reference data at control sites. These control sites and ground reference data may be useful for different quality management activities.

CHAPTER 3. PLANNING AND SETUP

INTRODUCTION

Each DOT's decision-making processes, PSC data definitions, and needs are unique. Therefore, each DOT can evaluate its own data needs during the planning and setup activities of data collection.

Each DOT must provide certain PSC information based on HPMS standardized definitions per 23 CFR 490.319(c). Most DOTs reported only HPMS-defined metrics within their DQMPs that were reviewed during Task 1 of this project. Though not required under Federal Rule, it may be useful for DOTs to also include other data metrics collected and used in their unique decision-making processes.

This chapter provides information for DOTs to consider during the planning and setup of data quality activities, including sections describing data quality, identifying data metrics and protocols, establishing control sites and ground reference, scheduling, and other general planning.

DESCRIBING DATA QUALITY

Many industries have described data quality. Table 4 provides standard data quality aspects related to PSC data collection (adapted from Rodriguez 2017). Considering these data quality aspects may be useful for establishing successful DQMPs.

Table 4. Summary of data quality dimensions related to PSC data collection (adapted from Rodriguez 2017).

Data Quality Aspects	Description
Accessibility	DOTs can easily locate and access the data. DOTs can work with their data collection vendors or manufacturers to ensure that the data is stored in an easily accessible database. DOT employees may need to be trained to use vendors' proprietary software.
Consistency	The data is integrated and coordinated. If different vendors or equipment are used, the information does not change. Consistency may be challenging for DOTs moving from manual to automated data collection and may be considered during planning and setup.
Relevance	The data is relevant, clear, concise, and processed to meet DOT's unique decision-making processes. Each DOT can work with equipment vendors or manufacturers to ensure the data they receive is specific to their decision-making processes.
Completeness	The data used to make decisions is available, and the data can be completely processed to be ready for implementation in DOT decision-making processes.
Accuracy and Precision	The data received is accurate and precise. Based on FHWA peer reviews, establishing accuracy and precision tolerances can be one of the most difficult parts of a data quality program. There are recently published AASHTO standards with suggested accuracy and precision statements that DOTs can implement in their DQMPs.
Believability	DOTs can trust the data received. Proper QC and acceptance activities, along with documentation, make the data believable. DOTs can easily access QC and QA activities associated with data to achieve data believability.
Timely for Use	The data is received on time. PSC data collection is accessible to DOTs before making network-level decision-making processes.

IDENTIFYING DATA METRICS, STANDARDS, AND PROTOCOLS

Based on existing DQMP reviews, DOTs typically consider critical data metrics in their data collection program. A critical data metric can be described as one used to classify pavement conditions or treatment types. Under 23 CFR 490, DOTs must collect and report the standardized HPMS Field Manual data metrics. The HPMS field manual’s definitions may differ from the data definitions used for DOT decision-making processes, such as calculating pavement condition indices, using decision trees, or establishing and calibrating design models. Most DOTs only included HPMS-required metrics in their DQMPs submitted to FHWA. Developing similar plans for all collected data may be useful.

HPMS Pavement Surface Condition Required Data

The DQMPs that were evaluated for this project were submitted under the requirements of 23 CFR 490.319(c) and included HPMS-defined metrics, including IRI, rutting (for asphalt and composite pavements only), faulting (for jointed concrete pavement only), and cracking percent. These metrics have associated required protocols that DOTs must reference and enforce to meet the requirements of the CFR, and DQMPs must reference these required protocols. Many DOTs referenced these protocols in a table format in their approved DQMPs. An example of a reference table meeting all of the HPMS data metric required protocols is shown in Table 5. This table has been adapted from the Maryland DOT Pavement Data Quality Management Program (Maryland DOT 2018).

DOTs must include and follow the standards and protocols listed in Table 5 for HPMS-related data according to 23 CFR 490.319.

Table 5. Example of a reference table showing all required standards and protocols for each of the required HPMS-defined data metrics adapted from Maryland DOT’s 2018 DQMP.

Data Element (Metric)	Standards and Protocol
IRI - for all pavement types	• IRI collection device following AASHTO Standards M328-14. • Collection of IRI data following AASHTO Standard R57-14. • Quantification of IRI data following AASHTO Standard R43-13. Also, an “Acceleration Adjustment” is applied to the computed IRI values to correct for the effect of acceleration or deceleration of the survey van. • Certification of IRI data following AASHTO Standard R56-14.
Cracking Percent - for all pavement types	• Collection of pavement surface images following AASHTO Standard PP 68-14 (R86). • Quantification of cracking from pavement surface images following AASHTO Standard PP 67-16 (R85). • Computation of Cracking Percent for each pavement type following definitions in the HPMS Field Manual. All longitudinal cracking on asphalt surfaces within each wheel path is interpreted as fatigue cracking, including both sealed and unsealed cracks.

Data Element (Metric)	Standards and Protocol
Rutting - for asphalt pavements	• Collection of transverse pavement profiles following AASHTO Standard PP 70-14 (R88). • Quantification of Rut Depth values following AASHTO Standard PP 69-14 (R87), with the modifications specified in the HPMS Field Manual. or • Collection of rut depth values conforming to AASHTO Standard R48-10, with the modifications specified in the HPMS Field Manual.
Faulting - for jointed concrete pavements	• Faulting computed based on AASHTO Standard R36-13 with the parameters specified in the HPMS Field Manual.

The CFR specifies the years of AASHTO standards used during HPMS data collection and reporting. Many of these standards have been updated or are currently being updated, and it is suggested that updated versions are followed as long as they meet the requirements of the version listed in the CFR.

Several ongoing projects plan to update or have recently updated these standards, including:

- AASHTO Standard Practice R87: NCHRP Project 20-07/Task 411 includes proposed updates for The Practice for Determining Pavement Deformation Parameters and Cross Slope from Collected Transverse Profiles. The proposed updates include a complete revision of the method of establishing cross slope and a complete revision of the calculation of rut depth, including the elimination of the identification of the five key zones, normal rut depth calculation, center, and rut depth calculation.
- AASHTO Standard Practice R36: TPF-5(299)/(399) Jointed Concrete Pavement Faulting Collection and Analysis proposes updates for the Standard Practice for Evaluation Faulting of Concrete Pavements. Intended updates include improving the definition of faulting, removing manual faulting measurements, and adding certification procedures.
- AASHTO R85-NCHRP 01-57A: Standard Definitions for Comparable Pavement Cracking Data project was completed in July 2020 and included standard definitions for cracking. The proposed definitions are categorized into three "tiers" where Level 3 is the least detailed and Level 1 is the most detailed. The report states that Level 3 definitions satisfy HMPS requirements. The newly proposed definitions are reported as highly repeatable but were not tested against ground reference data under the study.

These standards are evolving and may affect future data collection programs.

DOT Specific Data

As stated earlier, DOTs have unique data needs and use different indices to classify pavement conditions. This document intends to provide successful practices for quality management processes that can improve all data being collected regardless of the type of definition. For example, the certification processes for TPP systems (described in chapter 4) may improve all rut depth data collected, regardless of the unique rut definition used. Many case studies in this document use standardized HPMS-defined metrics as examples. Still, DOTs may implement similar practices appropriate for all critical data metrics in their network data collection.

SCHEDULING

Scheduling is essential to data quality, as environmental conditions can affect PSC data. Including scheduling statements in a DQMP may be useful to improve data quality based on environmental conditions and ensure data is timely for use. The following successful practices on scheduling items that were reported in DOT DQMPs may be useful for other DOTs to implement if not already being carried out:

- Data collection occurs when the roadway surface is dry and, ideally, free of debris. The agency works with the data collection vendor to schedule when roads are clear of salt and sand that may have been applied as part of a winter weather treatment program. Ideally, data collection occurs after a scheduled street sweeping program (Pennsylvania Turnpike Commission, 2018).
- Daily route planning is based on different logistic and practical factors—such as forecasted weather conditions, proximity to the office, overnight survey van storage, and gas station, among others—to maximize the collected mileage for the day. Another factor typically accounted for when defining the data collection route for the day is the location and angle of the sun to minimize the front exposure of the van to the sun, as it may result in poor-quality images (excessively bright). Thus, data collection on eastbound lanes is typically planned for the afternoon, while collection on westbound lanes is typically planned for the morning (Maryland 2018).
- Data collection starts no earlier than May 15th and is completed by August 31st each year (Vermont DOT (VTrans) 2018). Note that this short timeline may not be appropriate for all DOTs, but DOTs can consider appropriate windows for their environmental condition and network size.
- Collection shall proceed without significant interruption (VTrans 2018), keeping data collection on track to meet the deadlines.
- The contractor provides the QC program before March 1st and final data deliverables by September 30th (VTrans 2018). These clear deadlines are communicated to the data collection vendor, allowing VTrans to review and accept the QC plan and perform acceptance activities.
- VTrans provides GIS Shapefiles of segments for the data collection, level of collection, and test directions. GIS Shapefile of the current linear referencing system, current and upcoming construction projects likely to be encountered, GIS Shapefile of control sites, and current relative traffic regulations and authorizations. (VTrans 2018). Sharing this information ensures the data collection team has the information they need to perform data collection route planning before the start of data collection.
- Methods for addressing impacts of adverse weather conditions, construction zones, accidents, or abnormal traffic slowdown must be addressed in the data collection QC plan (Caltrans 2018). Having a contingency plan and establishing weather thresholds that delay PSC testing is useful for ensuring data is not collected when conditions may induce data errors.

Data for the four condition metrics submitted under FHWA Rule shall be reported to the HPMS for the Interstate System by April 15 of each year for the data collected during the previous calendar year. Data for the four condition metrics submitted under FHWA Rule shall be reported to the HPMS for the non-Interstate System by June 15 of each year for the data collected during the previous calendar year.

DELINEATION OF ROLES AND RESPONSIBILITIES

Most DOTs reported the delineation of responsibilities in their DQMPs. Assigning responsibilities of specific data collection activities to analysis team members ensures adequate staffing resources. Assigning actual employee names is useful for accountability and ensuring team members know their roles.

Table 6 shows an example of project team roles and responsibilities adapted from the Connecticut Department of Transportation's (CTDOT) DQMP. Note that the terms used to describe team roles and responsibilities may be unique and not apply to all DOTs.

Table 6. Example of project team roles and responsibilities adapted from the 2018 Connecticut Department of Transportation's DQMP.

Team Role	Assigned Resource	Quality Management Responsibilities
Agency Managers	Employee Name and Company	• Set/Approve quality standards, acceptance criteria, and corrective actions. • Approve each deliverable per quality standards. • Approve resolution of quality issues. • Assess the effectiveness of the quality management (QM) procedures. • Recommend improvements to quality processes.
Quality Assurance Supervisor	Employee Name and Company	• Recommend quality standards, acceptance criteria, and corrective actions to Agency Managers. • Ensure deliverables meet a broad set of data quality requirements. • Communicate as needed with Agency Managers on any issues that may arise. • Communicate weekly with QC Supervisor. • Ensure data acceptance checks. • Ensure pavement management unit (PMU)data processing, analysis, and reporting. • Monitor schedule and report deadline adherence. • Monitor resolution of quality exceptions reported to QC Supervisor. • Ensure quality issue resolution and report results to QC Supervisor and Agency Managers. • Prepare a QM report.

Team Role	Assigned Resource	Quality Management Responsibilities
PMU Data Lead	Employee Name and Company	• Maintain acceptance log and submit quality exceptions to QA Supervisor and QC Supervisor. • Document quality audits of processed data. • Report any problems using the QC log. • Perform data & FIS video acceptance checks and document results. • Perform GIS checks and document results. • Maintain all (vendor) software, rating, classification, and rutting templates settings/distress schemes are up to date and correct. • Track reporting requirements/deadlines for the completion of pavement condition data.
Quality Control Supervisor	Employee Name and Company	• Recommend quality standards, acceptance criteria, and corrective actions to Agency Managers. • Ensure deliverables meet a broad set of data quality requirements. • Communicate as needed with Agency Managers on issues that may arise. • Communicate daily/weekly with QC Lead, Data Lead, and Field Crew Lead. • Communicate daily/weekly with QA Supervisor and PMS Data Lead. • Submit acceptance exceptions log to QC Lead, photolog unit (PLU) Data Lead, and Field Crew Lead. • Supervise manual measurement of Verification and Validation sites. • Establish reference values with the data collection team. • Monitor schedule adherence. • Ensure quality issue resolution with QC Lead and report results to QA Supervisor and Agency Managers.
QC Lead	Employee Name and Company	• Ensure QC practices are followed. • Ensure proper protocols are used. • Ensure any training addresses all personnel skill levels. • Ensure reviews by photolog data lead. • Ensure the performance of all quality activities and reporting of all data quality exceptions using a QC log. • Ensure correction of all quality issues and changes in procedures as needed. • Perform and document a final deliverables quality review as needed. • Compile documentation of all QC activities.
PLU Data Lead	Employee Name and Company	• Perform and document checks of total mileage, segment lengths, and comparison with the master route file. • Ensure and document GIS checks of segment location and completeness. • Document quality audits of uploaded and processed data. • Maintain and report any problems using the QC log. • Observe and maintain records of verification runs on validation sites; Analyze and document results. • Perform initial data & video acceptance checks and document results. • Perform GIS checks and document results.

Team Role	Assigned Resource	Quality Management Responsibilities
Field Crew Lead	Employee Name and Company	• Ensure and document initial equipment configuration, calibration, and verification. • Ensure the performance of daily and periodic equipment start-up checks, tests, inspections, and calibrations. • Ensure daily review of data logs and video samples. • Ensure real-time monitoring of data and video quality. • Ensure the performance of monthly verification runs on validation sites. • Ensure documentation of all field QM activities and report any problems using the QC log.
Field Crew	Employee Name and Company	• Perform daily and periodic equipment start-up checks, tests, inspections, and calibrations. • Perform daily review of data logs and video samples. • Perform real-time monitoring of data and video quality. • Perform daily documentation reports, including: • End-of-Day Report, QC log, and (vendor) Daily Mileage Summary.

Some DOTs self-collect PSC data using their equipment and perform the analysis in-house. Other DOTs use a vendor to collect data (Chang et al., 2020). When using vendor services, some DOTs elect to have the vendor perform some of the analysis and quality management responsibilities. DOTs can be involved in quality management activities using vendor services to ensure their data quality standards are met.

Table 7 summarizes some suggested responsibilities for DOTs relative to the three phases of data collection.

Table 7. Summary of suggested roles for DOTs to have quality management activities before, during, and after data collection.

Before Data Collection	During Data Collection	After Data Collection
• Establish a scope of work (SOW) document with general data needs, including protocols, definitions, and formatting. • Establish a schedule based on receiving data timely for use and avoiding errors due to environmental conditions. • Establish or approve control sites for use in quality management activities. • Review, approve, and keep a record of equipment calibration reports. • Establish the certification requirements and oversee certification processes based on specifications. DOTs to review, approve, and keep a record of equipment certification reports. • Review, accept, and keep a record of training programs for the data collection team and manual raters (as applicable).	• Establish requirements for the minimum frequency of QC activities and reporting based on their specifications. • Establish requirements for minimum QC activities, including frequency of verification at control sites based on their specifications. • Review, accept, and keep a record of all QC reporting. • Require periodic data submission for acceptance reviews based on their specifications. Performing all acceptance reviews at the end of the data collection season is to be avoided to reduce the possibility of systematic errors and large batches of recollected data.	• Perform final data acceptance activities. • Perform data acceptance activities based on their specifications. These may include historical (year-to-year) data comparisons, flagged data outside established thresholds, and statistical analysis methods, as further described in chapter 7. • Keep a record of all acceptance activities. • Establish error resolution and dispute resolution processes to implement and follow. After data collection, these are discussed and accepted/rejected by the data collection team. DOTs may have methods to ensure all error resolutions have been resolved, accepted, rejected/re-collected, and recorded.

ESTABLISHING DATA EVALUATION CRITERIA

DOTs can establish data evaluation or acceptance criteria for quality management activities throughout data collection. Data acceptance criteria evaluate the data's quality-related properties, including accuracy and precision.

There are several variables to consider when setting comparison tolerances or acceptance criteria between survey vehicle collected data and ground reference data. A "tiered" control site approach used by the UK Road Board is an example of how tolerances can vary depending on multiple variables. Such variables include (but are not limited to) verification needs (e.g., certification versus quality control check), data needs (e.g., critical data metrics used to trigger rehabilitation), quality of ground reference data (e.g., dense point cloud, manual measurement, or high-speed vehicle collected), and frequency of check (e.g., annually, monthly, weekly, daily). The UK Road Boards changes the tolerances for errors according to these variables as previously described in the Tiered Control Sites section.

Many DOTs report limited labor resources in their DQMPs. Therefore, using certification-level control sites and ground reference data for all verification events may be unreasonable and unfeasible. Combining solutions like lower-tiered control sites (e.g., UK Road Board's Primary, Secondary, and Daily Control Sites) and bookending may be a solution to reduce labor efforts without compromising data quality (reference chapter 2).

The acceptance criteria may consider the intended use of the data. For instance, the accuracy and precision used for network-level performance trends may differ than those used for calibrating design models for use at a project level. Another consideration when setting the acceptance criteria is the capabilities of existing state-of-the-practice measuring technologies and available methods for collecting reference data.

Evaluation criteria can change depending on how control sites are used. An example from the UK board's implementation of acceptance criteria for different levels of control sites is shown in Table 8. Table 8 is based on reporting intervals of 10 m. Note that the UK board uses the same tolerances for evaluating collected data against the reference data, but the percent within limits changes with the type of control site.

Table 8. Example of evaluation (or acceptance) criteria used by the UK board to evaluate different types of control sites at different testing frequencies (UK Roads Board 2012).

Measured Parameter	Tolerance for Certification[1]	Tolerance for Monthly Checks[2]	Tolerance for Weekly Checks[3]	Tolerance for Daily Checks[4]	All Test Surveys (Maximum)
Average rut depths	±3.0 mm	±3.0 mm	±3.0 mm	±3.0 mm	10 mm
Longitudinal Profile in each wheel path (3 m moving average and 3 m enhanced variance)[5]	±0.60	±0.60	±0.60	±0.60	N/A
Longitudinal Profile in each wheel path (10 m moving average and 10 m enhanced variance)[5]	±0.70	±0.70	±0.70	±0.70	N/A
Cracking (percent area of cracking)	See Note 6	See Note 6	See Note 6	Seen Note 6	N/A

Notes for Table 8:

1. For calibration checks, 95% of the differences should fall within the range of tolerances specified. The data should be expressed in averages or at intervals of (as appropriate), 10 m.
2. For monthly checks, 90% of the differences should fall within the range of tolerances specified. The data should be expressed in averages or at intervals of (as appropriate), 10 m.
3. For weekly checks, 80% of the differences should fall within the range of tolerances specified. The data should be expressed in averages or at intervals of (as appropriate), 10 m.
4. For daily checks, 65% of the differences should fall within the range of tolerances specified. The data should be expressed in averages or at intervals of (as appropriate), 10 m.
5. For longitudinal profile variance, the tolerances are in terms of the differences or fractional errors between the average longitudinal profile variances calculated from the measured profile and reference profile.
6. The differences in the reported levels of cracking (reported as a percent) between the two survey runs and (established ground reference) will be calculated. The distribution of these differences will be assessed. If 65% of the differences fall within 0.1%, the test shall be classified as successful.

CHAPTER 4. EQUIPMENT CALIBRATION AND CERTIFICATION

INTRODUCTION

This chapter includes procedures for equipment calibration and certification programs. Each DOT has unique data collection requirements and data needs. The information included here focuses on HPMS-defined data metrics since they have standard definitions and are collected by all DOTs. The procedures presented here can be tailored to meet DOT-specific data definitions and needs.

CONTROL SITES

Calibration and certification can be performed at qualified control sites. Different types of control sites were described in chapter 2. Many equipment vendors or manufacturers develop control sites that can be used to calibrate equipment sensors and subsystems. Certification occurs at a control site that meets certification criteria.

EQUIPMENT CALIBRATION

There are two main types of calibrations, sensor and algorithm. Calibrations are generally performed by equipment vendors or suppliers and may be reviewed and accepted by DOT personnel before certification.

Sensor calibrations are performed using vendor or manufacturer-special equipment that can make sensor adjustments to match a known standard. Sensor calibrations are performed according to the manufacturer's recommendations by a qualified party. Algorithm calibrations include modifying the vendor or manufacturer algorithms to meet DOT-specific data definitions.

Sensor and System Calibration

Each data collection vehicle integrates systems to collect pavement condition data. These systems are comprised of sensors. Each data collection vehicle often includes systems and sensors made by different manufacturers. These sensors can generally be separated into either a mapping sensor or a location sensor. The TPF-5(299)/(399) TPP final report describes mapping sensors as any sensor that acquires surface measurements in its sensor reference frame. Location sensors are described as 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 from a body-fixed reference frame to a global reference frame. Examples of mapping sensors include HSIP height sensors and 3D measurement sensors. Examples of location sensors include GPS and the Inertial Measuring Unit (IMU).

Each mapping and location sensor calibration is typically performed according to the manufacturer's recommendations by a qualified party. Most DOTs reported having the equipment sensor calibrations performed by the equipment vendor or manufacturer. At a minimum, it is suggested that calibrations be performed annually before the start of data collection. Other appropriate times to perform sensor and system calibrations are after any maintenance of data collection equipment or if data quality is questionable, as further described in chapter 7.

DOTs don't typically perform calibrations, but including calibration procedures (e.g., frequency requirements and keeping records of calibrations) in DQMPs is required under 23 CFR 490.319(c).

Table 9 shows a matrix of example data collection equipment subsystems, including the primary and supporting systems adapted from The Pennsylvania Turnpike Commission (PA Turnpike). PA Turnpike includes a "system classification" column in its matrix that classifies each system as mission-critical or ancillary. If a mission-critical component experiences technical difficulties during data collection, the field crew must immediately stop and report the issue to the field crew coordinator.

Table 10 shows example calibrations for different systems, summarized based on the DQMPs of several DOTs. A similar table can be included in every DOT DQMP to meet CFR requirements. DOTs may use different data collection methods for data metrics, and manufacturer recommendations may vary, so the examples are not one-size-fits-all.

Table 9. Example of a calibration matrix adapted from PA Turnpike 2018 DQMP detailing the primary and supporting systems used on their data collection vehicle.

System	Primary or Supporting System	Purpose	System Classification
Laser Crack Measurement System (LCMS)	Primary	Captures detailed surface distress information at highway speed, including cracking, rutting, and potholes.	Mission Critical
Inertial Profiler (IP)	Primary	Class 1 profiler used to capture IRI data	Mission Critical
Distance Measuring Instrument (DMI)	Supporting	Provides precise distance measurements to LCMS and IP systems.	Mission Critical
GPS with Inertial Measuring Unit (IMU)	Supporting	A position and orientation system providing stable GPS streams to the LCMS, IP, and LiDAR systems.	Mission Critical
Mobile LiDAR with Ladybug Imagery	Supporting	Provides panoramic ROW images.	Ancillary
Lane Departure Warning System	Supporting	Warns driver of lane wandering.	Ancillary

Table 10. Examples of calibrations for different systems.

System	Calibrations
Inertial Profiler	Perform block and bounce tests to verify the static function of equipment. Collect data from control sites for comparison to benchmark data. Calibrations should follow AASHTO R56.
3D sensor and Camera System	Static checks, cross-fall rolling tests, and dynamic repeat runs for verification. Adjust 3D images for clarity and brightness.
2D Camera System	Image quality checks and camera alignment.
Distance Measurement Instrument (DMI)	Collect data along a route with known measured length to confirm the system's accuracy.
GPS	Perform stationary signal acquisition and ensure real-time corrections are active. Collect data at control sites to validate against known data.
Roadway Cameras	Adjust alignment for left and right views and pavement-to-sky ratios. Adjust for clarity and brightness.
Inertial Measurement Units (IMU)	Static and bounce tests for grade and pitch sensors.

Annual Maintenance

Annual maintenance should be performed for sensors located on the data collection equipment according to manufacturer instructions. Maintenance procedures vary by vendor, and DOTs can consult with their data collection vendor or manufacturer to ensure all manufacturer-recommended annual maintenance is being performed. Some manufacturers may recommend that sensors get shipped back for factory preventive maintenance. Preventive maintenance ensures that the sensors operate reliably and at full sensitivity, which helps to achieve the expected performance. Sample preventive maintenance for 3D sensors (Pavemetrics 2020) includes:

- Characterization and assessment of laser power and condition.
- Adjustment of laser and camera focus.
- Realignment and recalibration of the lasers and building of new Look-Up Tables (LUT) files.
- Realignment and recalibration of the cameras.
- Validation of the inertial measurement unit (IMU) performance.
- Validation of overall performance following calibration, including checking noise level, assessing 3D accuracy, etc.
- Checking and tightening internal cables.
- Replacement of moisture absorbers.
- Testing and replacement (if necessary) of enclosure seals to ensure water tightness, and
- A firmware update (if needed).

Other manufacturers may have different preventative maintenance procedures, and DOTs can reach out to their vendors or manufacturers for more information on recommended maintenance.

Algorithm Calibrations

Distress data may be automated using computer algorithms to detect distresses, semi-automated using a combination of computer algorithms and human raters, or manual, where human raters identify distress data from computer images. The algorithms used to generate automated distress data are generally proprietary to the equipment manufacturer. Many DOTs are moving toward automated and semi-automated distress data collection. Automated or semi-automated distress algorithms are adjusted to the specific DOT data definitions to ensure the desired data is collected.

Algorithm calibration is a collaborative effort between DOT, vendors, or manufacturer personnel. Field evaluations comparing different data collection equipment vehicles in Texas shows that distress data and subsequent pavement conditions vary by manufacturers. This research reasonably predicts that the proprietary algorithms can be calibrated to reduce variability and achieve more accurate results (Serigos 2015). DOTs can include data definitions in their scope of services for vendor-collected data or work with equipment manufacturers to adjust the algorithms to fit their needs for DOT-owned and operated data collection equipment.

The TPF-5(299)/(399) project for Developing Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection and Analysis Systems and/or Services includes information to assist DOTs with algorithm calibration checks. The report recommends verifying that the proposed data collection equipment can collect adequate images for determining or verifying distress data and that distresses can be quantified to DOT-specific data definitions and needs. The proposed procedures from this project are included in the cracking certification section.

DOT Roles and Responsibilities for Equipment Calibration

Although calibrations are primarily the responsibility of the vendor or equipment manufacturer, DOTs can be familiar with the manufacturer's recommended calibrations and review and accept and keep records of calibration certificates. DOTs implementing automated or semi-automated distress data collection methods may have processes to ensure that algorithms have been calibrated to meet their specific needs.

EQUIPMENT CERTIFICATION

Based on NCHRP Synthesis 531, all DOTs use automated survey processes for IRI, rutting, and faulting. Other distress data may be calculated using automated, semi-automated, or manual processes. Many DOTs do not include complete certification processes for rutting, faulting, and cracking data. Successful certification practices have been requested by many DOTs (Orthmeyer 2018) and have been a focus of the ongoing TPF-5(299)/(399) research.

Control sites are used for equipment certification. The control site used for certification processes meets certification-level (reference chapter 2) criteria and is DOT-approved. Certification control sites meet the strictest criteria for site conditions and ground reference. DOTs can develop certification control sites relevant to each critical data metric (such as ones used to classify pavement conditions or trigger treatment strategies). Certification procedures ensure systems are functioning correctly and check that data (IRI, rutting, faulting, cracking, or other distress data) meets the accuracy and precision requirements explicitly established for DOT data needs.

Certification procedures are generally organized in this report by the two major equipment systems found on data collection equipment, HSIP systems used to collect IRI data and 3D systems. The term 3D system is described here as a system capable of collecting a transverse pavement profile and automatically extracting, at a minimum, rutting, edge/curb detection, and cross-slope parameters. Some 3D systems, paired with 2D images, can output automated or semi-automated crack detection. 3D systems can also collect longitudinal profiles and metrics associated with longitudinal profiles (IRI, faulting). As technology advances, more DOTs may begin implementing 3D systems for collecting longitudinal profiles and computing IRI. At this time, AASHTO R56 is specifically used for HSIP equipment certification, as described in the "Inertial Profiler Certification" section, as required by the CFR.

Certification for 3D systems is divided into two categories: those 3D systems used for TPP metrics (rutting, edge/curb drop-off, cross slope) and 3D systems used for automated or semi-automated crack detection. These have been separated due to the unique control site and ground reference recommendations developed under TPF-5(299)/(399). Note that DOTs are collecting other metrics with these 3D systems, and they can use judgment as to which certification method is applicable for each of their data metrics that are not explicitly included here.

According to DOT DQMPs, faulting of JCP pavement is collected using either HSIP systems or 3D systems. Ongoing research under TPF-5(299)/(399) plans to update AASHTO R36 Standard Practice for Evaluating Faulting of Concrete Pavements. Proposed updates include standardizing and clarifying the definition of faulting and providing certification procedures. AASHTO R36 currently includes an automated fault measurement procedure using HSIP data but lacks verification and certification procedures. These proposed draft certification procedures aim to apply to both HSIP and 3D systems. This research is ongoing, and it is recommended that this document include the final report's findings and recommendations upon completion.

Based on the findings of Phase I, equipment certification was identified as the most common need for improvement among all DOT DQMPs. Therefore, certification programs were piloted during Phase II at Washington State DOT (WSDOT), Pennsylvania DOT (PennDOT), and Alabama DOT (ALDOT). Pilot programs were based on applicable AASHTO Standards and research publications. The certification programs described in the following sections are based on the successes and lessons learned under the Phase II pilot certification programs.

High-Speed Inertial Profiler Certification

Background

HSIPs are commonly used to measure longitudinal pavement surface profiles. These profiles can calculate longitudinal profile metrics such as IRI. AASHTO R56 is the Standard Practice for the Certification of Inertial Profiling Systems and was explicitly developed for IRI equipment certification. AASHTO R56 certification procedures ensure repeatable and accurate surface elevation measurements based on the cross-correlation of IRI-filtered data to specific threshold values.

For data collected and reported to FHWA, 23 CFR 490.111(b)(1) requires that DOTs follow the HPMS Field Manual, which specifies AASHTO R56-14 for certifying systems used for HPMS IRI data collection.

Most DOTs referenced following AASHTO R56-14 procedures in their DQMPs. As technology advances, DOTs may elect to use 3D systems instead of HSIPs, to collect longitudinal profiles. Some vendors have reported that AASHTO R56 certification has been accomplished using 3D technology (Mandli 2020). The following sections describe how the HSIP certification processes address the above-referenced common elements of successful certification programs.

Control Site Criteria and Vendor Data Collection

Control Site

Control site criteria for HSIP certification or verification were previously summarized in Table 2. In summary, AASHTO R56 recommends the following:

- Control sites should include surface types on which the HSIP is expected to collect data in certification processes.
- Control sites should include a smooth section (30 to 75 inches/mile), a semi-smooth section (95 to 135 inches/mile), and a rough section (up to 200 inches/mile).
- Surface macrotexture(s) should be representative of each of the types of pavements in the network.
- Each test section should be at least 528 feet in length with proper lead-in distance and safe stopping distance. The total test section length should be four times the length of the longest wavelength being considered (i.e., 4 X 300 feet = 1,200 feet for IRI measurements).
- Control sites should not include significant grade or grade changes. Distresses, patches/repairs, significant horizontal curvature, or super-elevation should be avoided.

Data Collection

AASHTO R56 requires five repeat runs at each test speed, including the minimum and maximum anticipated collection speed.

Ground Reference Measurements

According to AASHTO R56, a reference profiling device that meets the repeatability and accuracy criteria for measuring IRI (specified in the Benchmark Test Evaluation Report. Karamihas, 2011) should be used to collect the reference profile data. The NCHRP 10-106 research recommends improving existing protocols to make this requirement more accessible and practical to DOTs. Also, a new Benchmark tester standard is being developed under the ASTM E17 committee.

Devices such as inclinometer-based Walking Profilers may be used to establish the reference profiles with three runs. The qualification criterium is 98% cross-correlation for repeatability of the three runs.

AASHTO R56-14 does not explicitly mention collected ground reference data during the same environmental conditions. However, this is critical, particularly for JCPs, as diurnal curling and warping can significantly affect ride quality and faulting values. DOTs can consider this when developing certification programs. Environmental effects on JCP profiles can be mitigated by collecting ground reference profiles immediately before inertial profilers make measurements.

Testing at WsDOT

Control Site

IRI certification was performed with WSDOT in August 2021. The event took place at an inactive runway near Olympia, WA. The inactive runway was chosen since it was not open to traffic. However, finding a location on the inactive runway that met the smooth, semi-smooth, and rough IRIs was challenging. The control site was rough, with some locations with IRI above 200 inches/mile, and reference profiles reported IRI as high as 500 inches/mile. IRI exceeded AASHTO R56's recommendation of up to 200 inches/mile. Therefore, the WSDOT site was not ideal for AASHTO R56 HSIP certification purposes.

Data Collection

Per AASHTO R56, the walking profiler collected three reference profiles during the WSDOT certification pilot study. Full-length chalk lines were useful to ensure the walking profiler collected the same profile at the same path each time for certification. According to a reference profiler rodeo held in May 2014, proper certification layout includes using accurate steel tape and high visibility chalk lines for the equipment to follow. (Izeppi and Toom 2014).

WsDOT and other participants drove their data collection vehicles through the control site ten times according to AASHTO R56 procedures.

Data Assessment

All data assessment for the WsDOT testing was performed using FHWA ProVAL software. ProVAL is an engineering software that views and analyzes pavement profiles and includes a certification module to implement AASHTO R56.

Three repeats of reference profiles were collected as per AASHTO R56. The repeatability score should be above 98% of cross-correlation reported by the Profiler Certification Module (PCM) of the FHWA ProVAL software. Any profile can be used as ground reference data if the three profiles meet the 98% cross-correlation requirement. Each wheel path (right and left) was evaluated separately. In this case, the WsDOT Surpro reference profiles passed for the left wheel track but failed for the right wheel track.

After the reference profile qualification, one set of reference profiles (one from each wheel path) was selected and used for vendor certification. ProVAL’s PCM module was used to compare vendor data's repeatability (comparing repeat runs) and accuracy (using the reference profiles). Vendor data was evaluated according to the recommended criteria. According to AASHTO R56, the vendor equipment should meet the following minimum requirements: Repeatability: cross-correlation of 92%; Accuracy: cross-correlation of 90%. In this case, the WsDOT HSIP passed the repeatability for both left and right wheel tracks. However, it passed the accuracy test for the right wheel track but failed for the left wheel track.

Lessons Learned

The track used for the WsDOT certification event had areas with very high roughness that did not meet the test site requirement of AASHTO R56. It is still challenging to collect qualified reference profiles, and proper certification layout and training for collecting reference profiles aid in successful DOT-operated sites.

3D System for Transverse Pavement Profiling Certification

Background

Under this project, recently published AASHTO standards were piloted for TPP certification at WSDOT, ALDOT, and PennDOT. Another project under TPF-5(299)/(399) also piloted these standards during the same timeframe with other DOTs, but those results are not reported here. The standards include the following:

- AASHTO PP106-21: Assessment of Static Performance in Transverse Pavement Profiling Systems (Static).
- AASHTO PP107-21: Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems (Body Motion Cancelation).
- AASHTO PP108-21: Assessment of Navigation Drift Mitigation in Transverse Pavement Profiling Systems (Navigation Drift).
- AASHTO PP109-21: Assessment of Highway Performance in Transverse Pavement Profiling Systems (Highway).
- AASHTO PP110-21: Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment (GRE).

AASHTO PP106. 107, 108, and 109 are used to evaluate vendor equipment, and AASHTO PP110 is used to evaluate GRE. According to the author, each standard assesses different sensor capabilities and is meant to be conducted in conjunction with each other. These standards were created explicitly for TPP metrics—i.e., rut depth, cross slope, and edge/curb detection. Each standard includes requirement statement (RS) criteria that may be used to evaluate sensors or sensor integration of high-speed data collection equipment to accurately and precisely measure each metric. There are different RS for each TPP metric. For example, the vertical measurement spacing RS for rut depth is less (more strict) than for cross-slope (since rut depth calculations are more sensitive to vertical measurement than cross-slope).

All accuracy and precision requirement statements are reported in bias and confidence intervals, where the 50% confidence interval (IQR) and the 90% confidence interval are used. 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). The percentiles chosen for evaluation (5th, 25th, 75th, and 95th) are calculated simply from the recorded data. More samples provide better estimates when taking a finite number of discrete samples from a distribution. In other words, the certainty of the estimate increases when the sample size increases. The 95th percentile can be reported for a small sample size (e.g., n = 10). However, there is little certainty in the estimate.

More information regarding the RS and tolerances for each test can be found in the TPF-5(299)/(399) final report (Altmann and Ferris 2020).

Control Site Criteria and Data Collection

AASHTO PP109 (Highway Performance) is the only standard that collects data at representative highway speeds and compares the data to ground reference data (ground reference data collection is described in the following section). AASHTO PP106 (Static), 107 (Body Motion Cancelation), and 108 (Navigation Drift) test sensor and sensor integration capabilities. These tests do not need to occur at conventional control sites but may have dimensional requirements or other considerations. The recommended criteria for the control sites or test facilities according to the AASHTO standards are as follows.

AASHTO PP109 (Highway Performance)

Control Site

- Control sites should exhibit a range of low-level rutting to high-level rutting for rut depth. For low-level rutting, the minimum rut depth is 2.0 mm (0.08 inches), and high-level rutting is classified as greater than 20 mm (0.79 inches).
- The control site should contain a cross slope of greater than 5% for cross slope.
- Bounding beams should be placed on the transverse edges of the test site for assessment of edge/curb detection (bounding beams are illustrated in Figure 7).
- The surface macrotexture should reflect the variety of the pavement surfaces to be evaluated.
- Sites should have ample length of road to allow the equipment to achieve target speed before entering the control site and come to a stop after exiting the control site. A minimum road length of 0.25 miles is recommended in the standard.

An example of a highway performance control site used during pilot testing is shown in Figure 7. The control site for highway performance is made from two sections, the ground reference section (the smaller top section) and the transverse capability section (the larger bottom section). These are described in more detail in the data assessment section.

Data Collection

Per AASHTO PP109, vendors collected data at speeds ranging from 10 mph to 65 mph in increments of 10 mph (the last increment was 5 mph). Some control sites limited speeds (e.g., the speed limit was below 65 mph). Three runs were collected at each test speed.

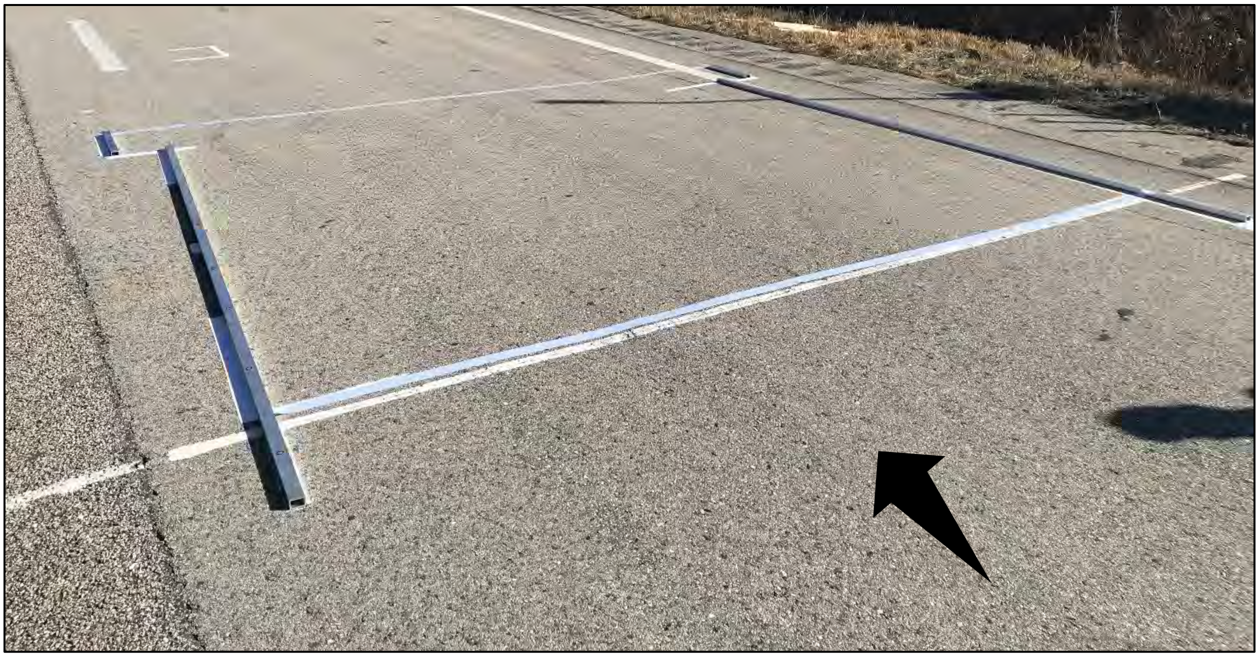


Figure 7. Photograph. Highway performance test control site (arrow indicates the direction of traffic).

AASHTO PP106 (Static)

Test Facility

- Static testing occurs while the vehicle is static (not moving).
- The test protocols include raising the vehicle, as shown in Figure 8. A straight edge is used during testing to measure sensor capabilities. Raising the vehicles offsets the height of the straight edge so that sensors are being tested at a height representative of data collection in the field. The straight edge also can be set below grade, as illustrated in Figure 9.
- Test objects are leveled under the sensors. Testing indoors in a garage is helpful but not required. Sun glare may affect the testing, which is also mitigated indoors. DOTs can check with vendors to make sure testing indoors does not affect data collection.

Figure 8. Photograph. Example of a raised test vehicle for the static test.

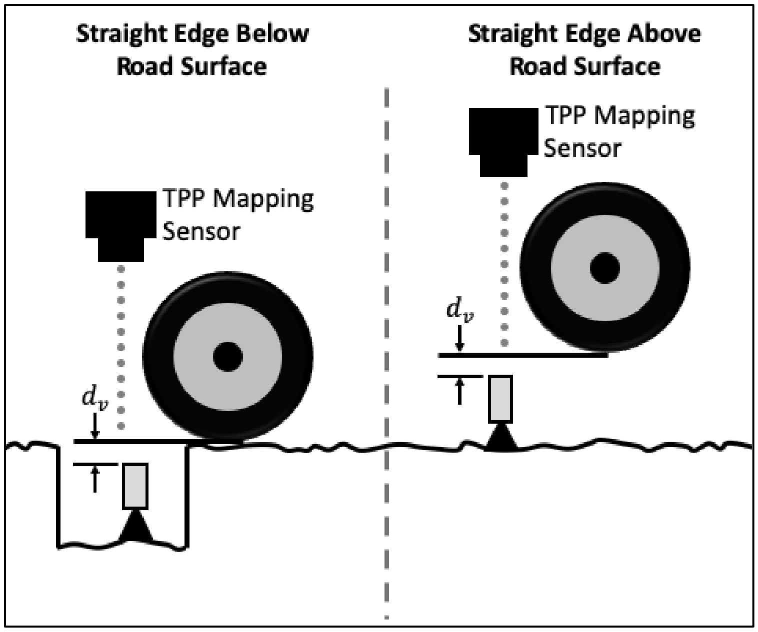


Figure 9. Illustration. Examples of lowering the straight edge or raising the vehicle to offset the height of the straightedge.

Data Collection

AASHTO PP106 states that ten scans of a leveled straight edge should be taken under the mapping sensor (equipment with multiple sensors tests each sensor individually). An additional ten scans are taken with certified gauge blocks placed on the top of the straight edge. An example of the straight edge with certified gauge blocks is shown in Figure 10.

Figure 10. Photograph. Example of the straight edge with gauge blocks under mapping sensor.

AASHTO PP107 (Body Motion Cancelation)

Test Facility

The body motion cancelation test uses certified flat plates and excitation boards to assess whether mapping and location sensor integration can remove excitation from the collected data. The setup for the test varies based on sensor location and vehicle type. The typical footprint of the test setup fits within a 14-foot by 14-foot square. Since the footprint of the test section falls outside of a standard 12-foot driving lane, it is useful to perform this test in a parking lot or similar space. The vehicle should have enough lead-in and lead-out to achieve the testing speeds before entering the test. The setup for body motion cancellation is shown in Figure 11.

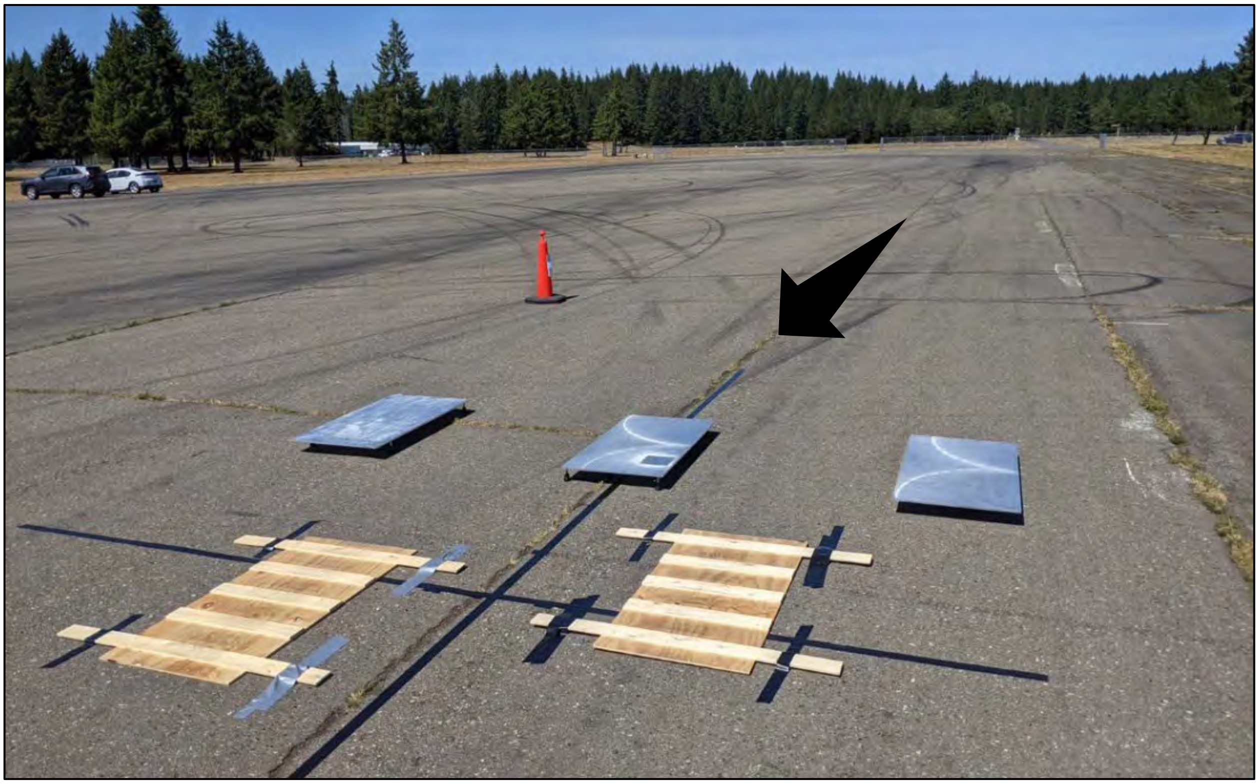


Figure 11. Photograph. Setup for body motion cancelation test (arrow indicates the direction of traffic for rear-mounted sensors).

Data Collection

Testing took place at 5, 8, and 12 mph speeds per AASHTO PP107. Two runs were collected at each speed. The excitation boards were placed uniquely to each vehicle's mapping sensor location and wheel spacing per the standard.

AASHTO PP108 (Navigation Drift)

Test Facility

The navigation drift test uses a certified object and known GPS coordinates to assess the drift of location sensors over time. The test setup for navigation drift is a figure "8" with a footprint that fits inside 178 feet by 79 feet, as shown in Figure 12. The radius for each circle is 32.8 feet (plus or minus 0.7 feet) and the center of the circles are a distance of 92.8 feet (plus or minus 1.6 feet) apart. A large parking lot or open space works well for conducting the test.

The standard uses a reference artifact as the known location. A flat plate with known dimensions was placed at the center of figure "8" for the pilot testing. The plate was leveled to 0.029 degrees, and one corner of the plate was identified as the reference point. Survey equipment meeting the tolerance criteria of the standard was used to measure a reference coordinate. Bounding beams were used to delineate the reference corner, as shown in Figure 12.

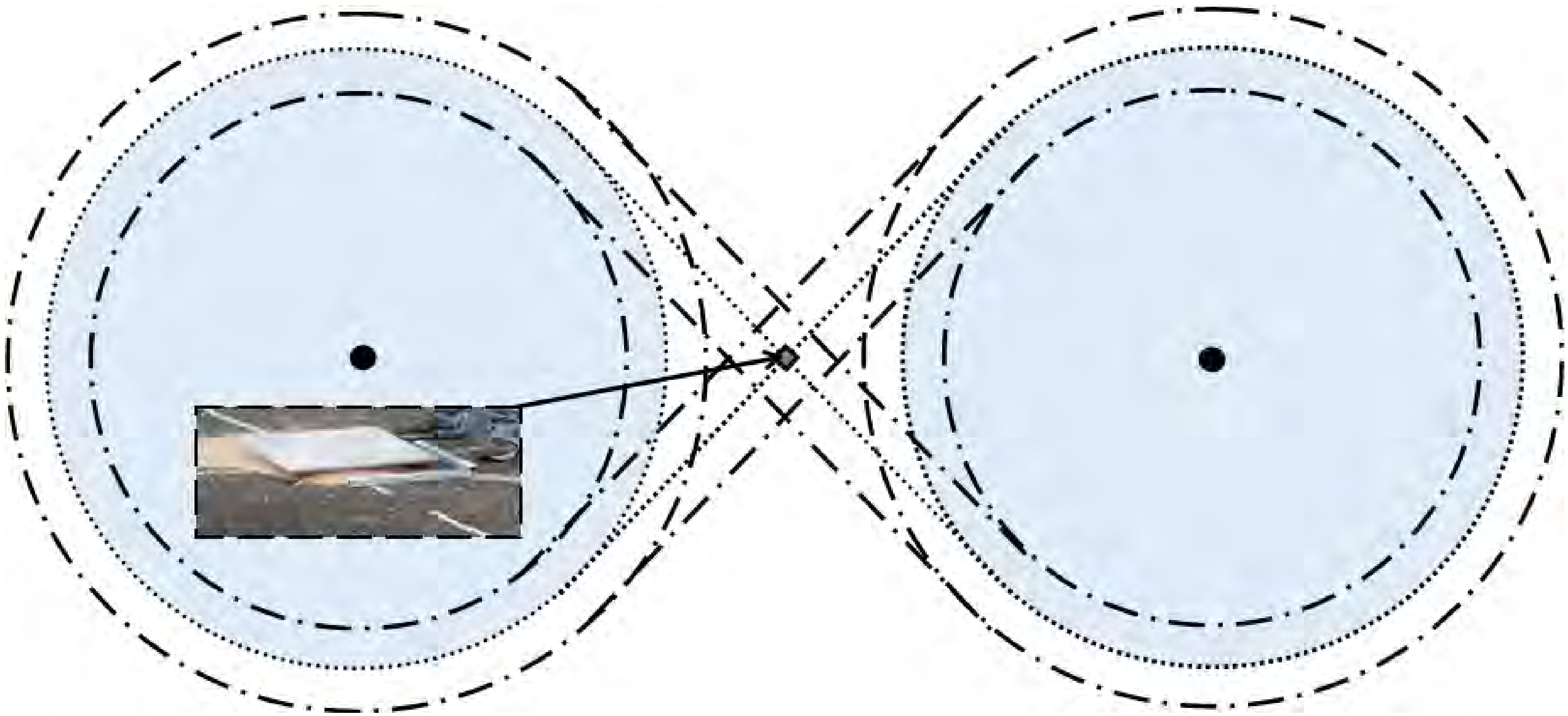


Figure 12. Illustration. Figure "8" layout for Navigation Drift.

Data Collection

Each vendor drove figure “8” a minimum of five times (passing the reference object ten times). Vendors drove according to AASHTO PP108 recommendations, targeting a speed of 8 mph and completing a full loop within 37 seconds.

AASHTO PP 110 Ground Reference Measurements

AASHTO PP110 is the standard practice for evaluating GRE used to collect ground reference data for the AASHTO PP109 (Highway Performance) test. The standard does not specify specific equipment types, and any scanning system that can complete the evaluation is considered adequate.

AASHTO PP110 (GRE) scans known certification objects (flat plates, gauge blocks, straight edges, and a square object with a 3D-printed macrotexture surface) while scanning the road surface simultaneously. During data evaluation, if the equipment successfully meets the RS for the certification objects, there is high confidence in the scanned road surface used for ground reference. An example of the certification objects is shown in Figure 13.

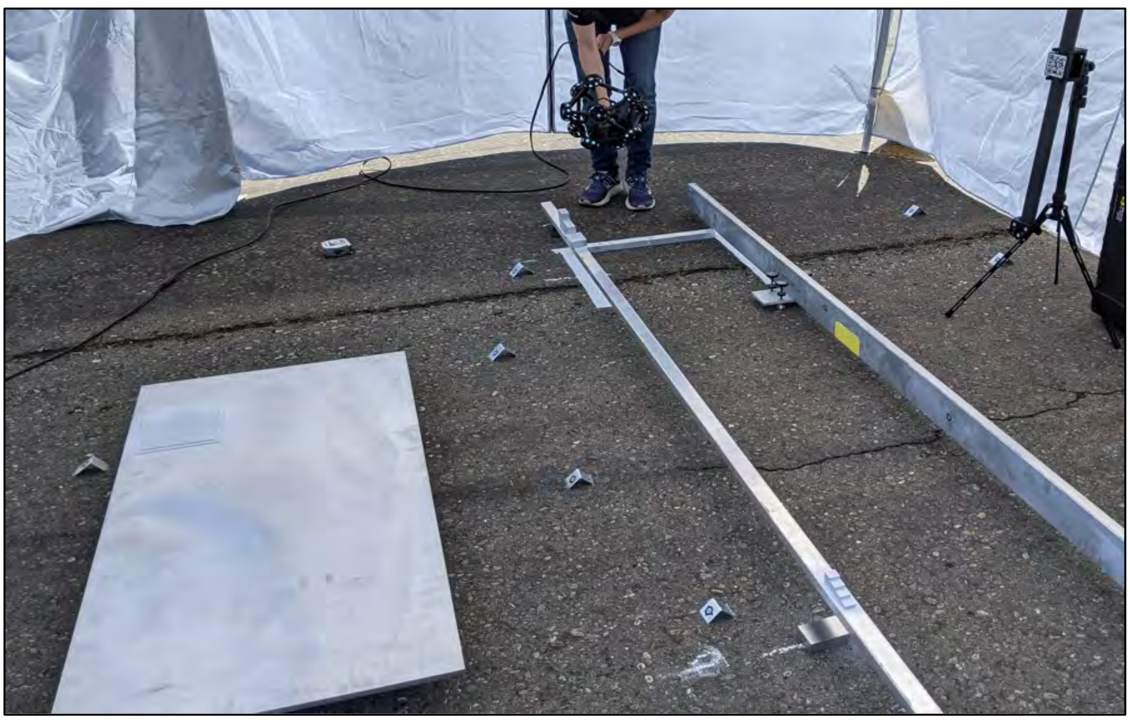


Figure 13. Photograph. Example layout of GRE certification scanning.

The same certification objects used to evaluate vendor sensors during the static test are used to evaluate the GRE equipment. The RS for GRE has smaller allowable tolerances than those used for the vendor sensors. For example, according to the criteria, the errors measured from gauge block dimensions should be smaller for GRE than for the vendor equipment. Therefore, the GRE is held to a higher standard, with more confidence in the data. An example of the GRE data along the certification object (stair-stepped gauge block) is shown in Figure 14.

Figure 14. Illustration. Example data from a GRE scan of a stair-stepped gauge block.

The GRE data is scanned in the exact location as the ground reference section of the highway performance test. Each test uses the same longitudinal bounding beams in the same location to delineate the section, as illustrated by the orange boxes in Figure 15 and Figure 16.

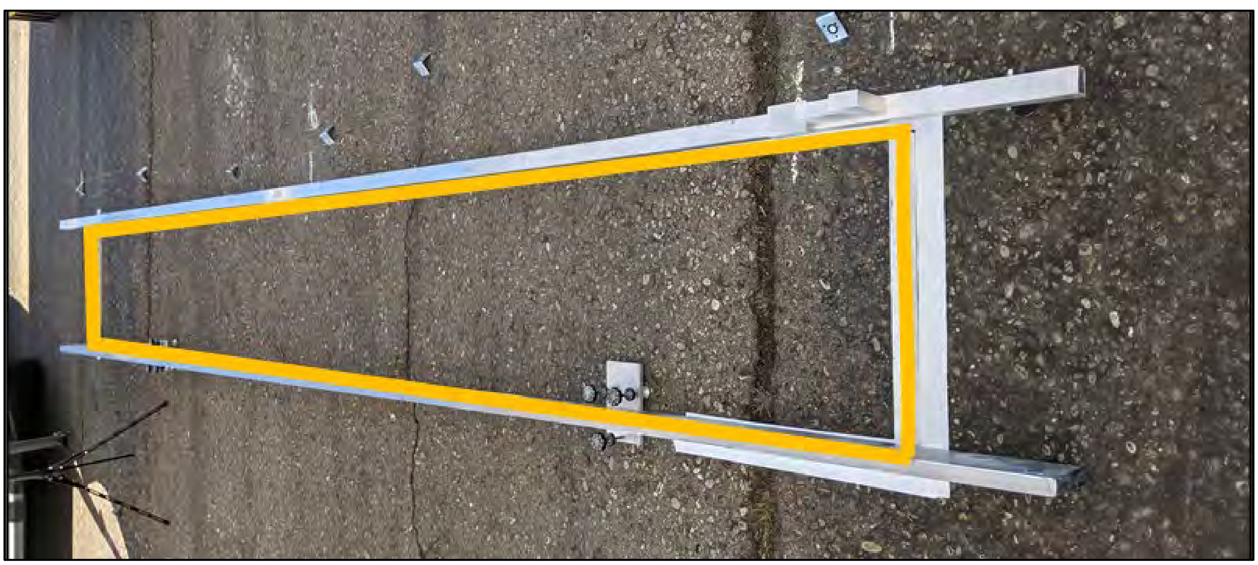


Figure 15. Photograph. GRE test section layout.

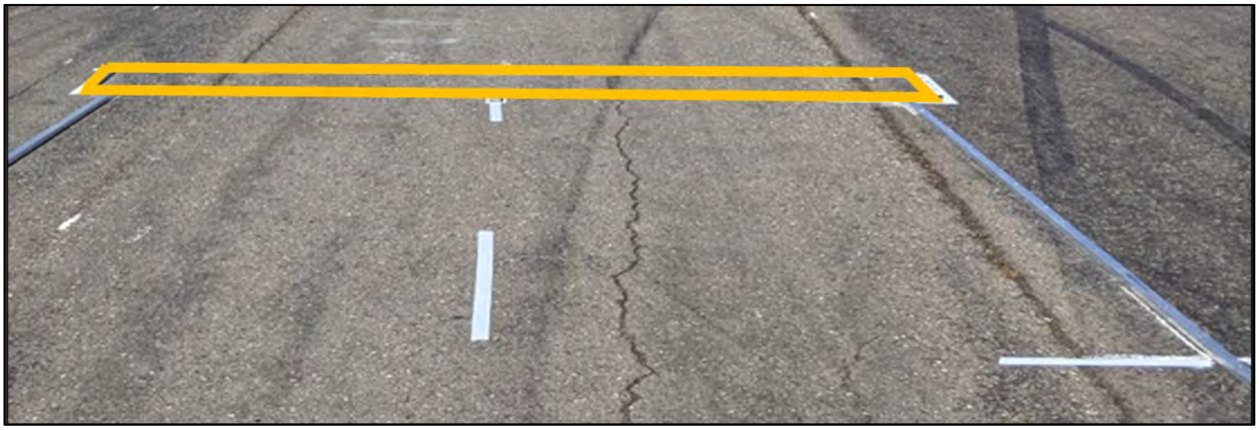


Figure 16. Photograph. Highway performance section layout.

Control Site Observations

During the pilot studies, AASHTO PP106 (static), AASHTO PP107 (body motion cancelation), and AASHTO PP108 (navigation drift) were performed on the same day. Typically these tests could be performed in a DOT parking lot or nearby facility, and it was relatively simple to find spaces to perform the tests. Each test requires some setup or layout, but all three tests were completed in a day. Some time-saving considerations for static, body-motion cancelation, and navigation drift are as follows:

- Raising vehicles for static testing can be time-consuming and dangerous if not done correctly. Facilities with lifts or curbs make the test more efficient.
- The layout for figure "8" for navigation drift can be tedious, and the permanent layout of figure "8" would greatly reduce test time.
- The body motion cancelation test setup is based on vehicle dimensions, and getting the dimensions before testing is useful.
- An anti-glare spray was used on all metallic surfaces to mitigate the effects of glare.

It was more challenging to locate sites for AASHTO PP109 (highway performance) and AASHTO PP110 (GRE). Finding safe areas that met the high-rut depth criteria was difficult. In some cases, the testing took place at facilities closed to traffic, such as the inactive runway at WSDOT or NCAT test track for ALDOT. At PennDOT, the testing took place on a roadway using lane closures. DOTs can evaluate their road networks and nearby facilities to find safe and representative control sites for highway performance testing. Completing highway performance and GRE testing typically took one day. Some time-saving considerations for highway performance and GRE are as follows:

- GRE scanning was time-consuming, and the scanning equipment used during pilot testing was sensitive to sunlight (glare). Therefore, testing took place under tents and canopies. The wind made the tent walls flap, and strong winds moved the tent. Having adequate support for temporary tents or structures mitigates the effects of wind. Other scanning devices may be less sensitive to sun/glare, which would minimize impact from the wind.
- According to AASHTO PP110, scanning certification objects can take place separately from scanning the road section as long as no settings are changed on the equipment. Time

was saved by setting up certification objects away from the roadway so that highway performance could commence after the road surface was scanned.

- There are leveling requirements for straight edges and beams for the GRE certification, and leveling equipment should work for varying cross slopes and rough road surfaces. During one of the pilot studies, the wind blew against tent walls and knocked over the certification objects. Issues from wind were mitigated on other pilot projects by using "hot glue" to glue objects in place.
- An anti-glare spray was used on all metallic surfaces to mitigate the effects of glare.

Figure 17. Photograph. Example of using hot glue to secure objects in place.

Data Assessment

The TPP certification data assessments were made in Matlab using code written to meet the AASHTO standards developed under an FHWA TPP project (Ferris and Altmann 2020). Since this process is still cumbersome, an upcoming project plans to develop a TPP certification module in ProVAL to streamline such data assessments.

Each standard evaluates several parameters. The concepts of data assessment are described at a high level in this report. For complete details on data assessment, reference the relative AASHTO standards.

AASHTO PP106 (Static)

The standard assessed the mapping sensors' capabilities in static mode. Certified leveled straight edges and gauge blocks with known dimensions are used to quantify mapping sensor errors. An example of a static profile capturing a gauge block is illustrated in Figure 18. The mapping sensor measurements are compared to the certified object measurements. The errors are quantified and presented in percentiles, as described at the beginning of the section. Each TPP metric (rut depth, cross-slope, edge/curb detection) has RS for different errors (e.g., the height of a step, width of a step, straightness of flat surface, etc.).

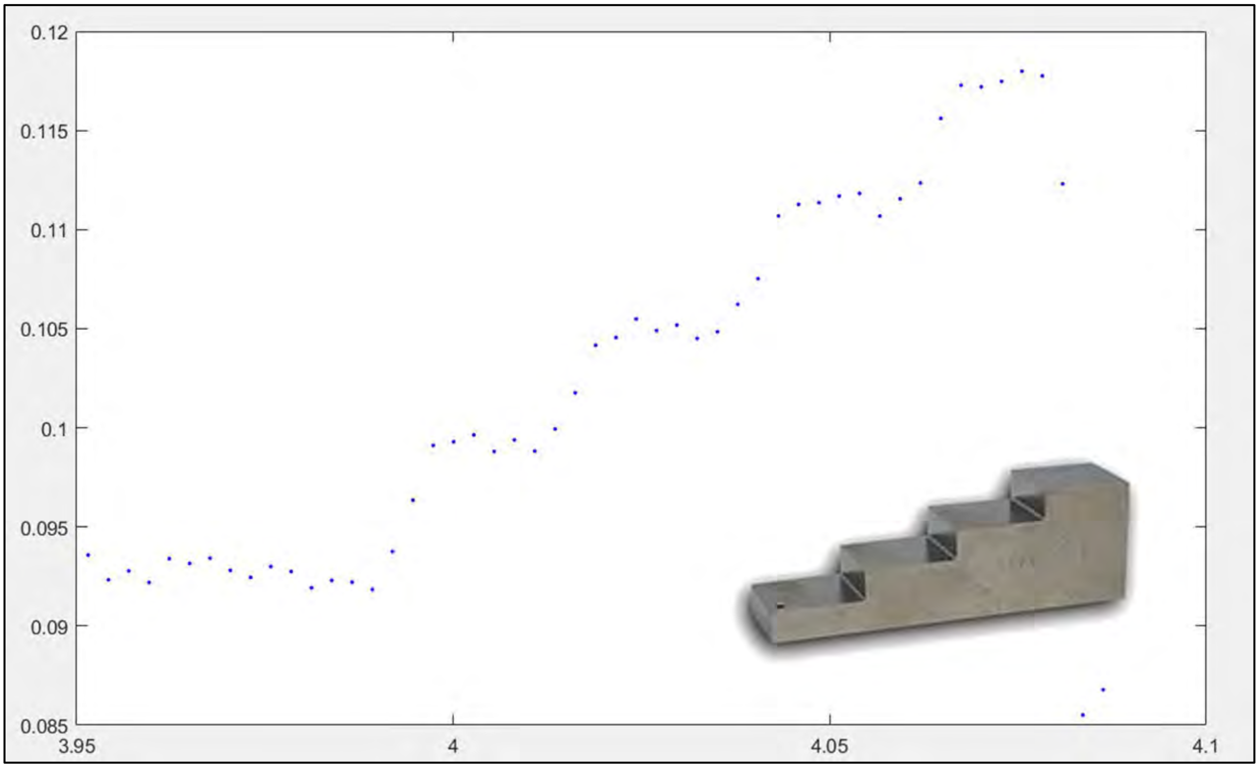
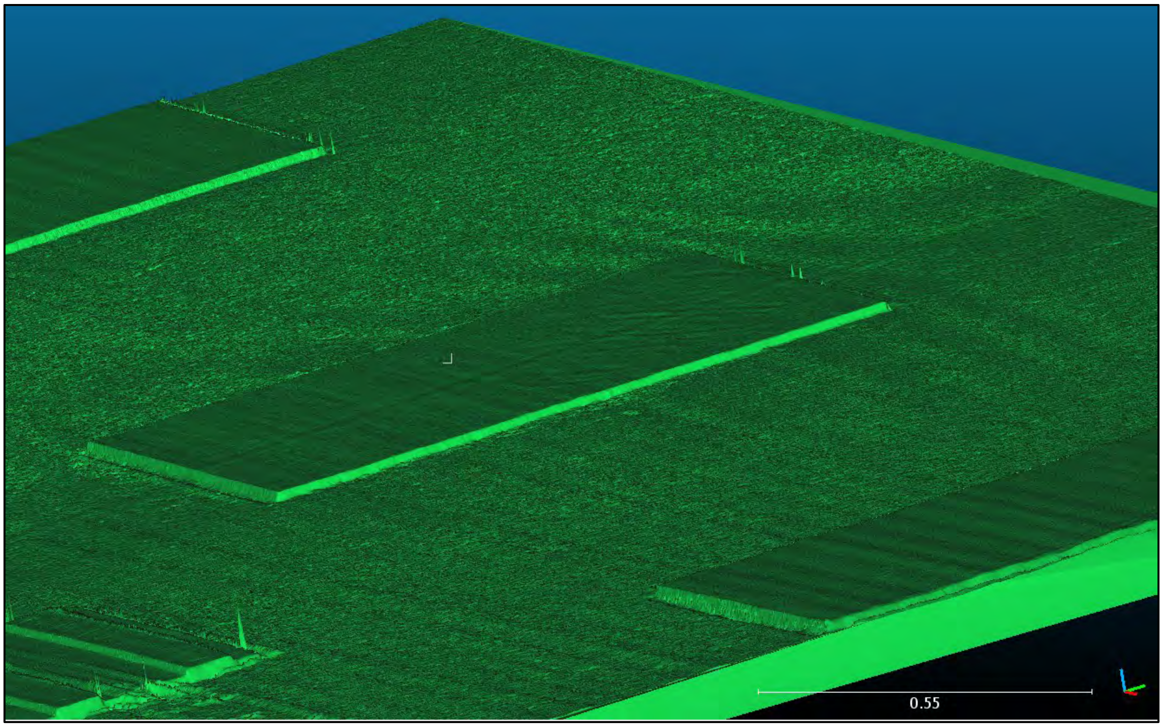


Figure 18. Illustration. Example of a static profile capturing a stair-stepped gauge block (axes are in meters).

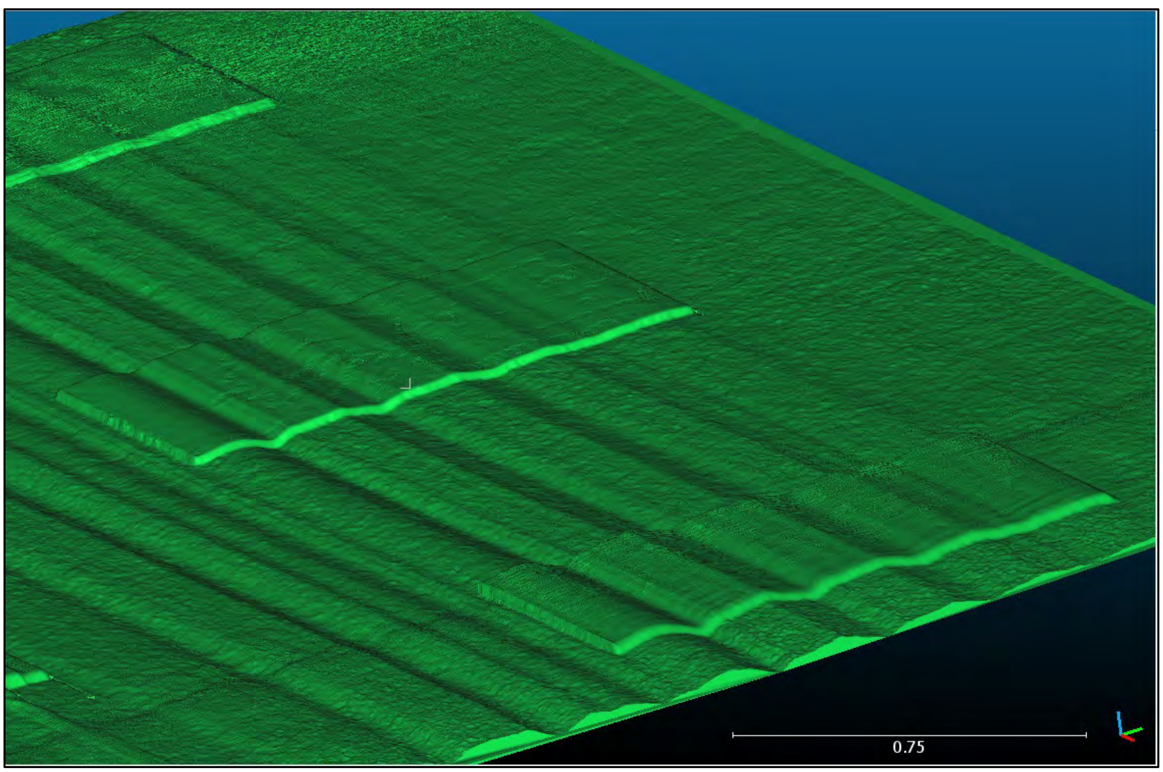
AASHTO PP107 (Body Motion Cancellation)

The standard assesses the ability of the equipment sensor integration to remove body motion from the data. The flat plates used in the test have known flatness, and the excitation boards are designed to create peak excitation in the vehicle. The data assessment compares the collected data to the flat plate to see if the excitation is adequately removed. Examples of data showing successful and unsuccessful body motion cancellation are in Figure 19 and Figure 20, respectively (photos from QES 2022).



Source: QES, 2022

Figure 19. Illustration. Example of data where body motion cancelation is successful.



Source: QES,2022

Figure 20. Illustration. Example of data where body motion cancelation is unsuccessful.

AASHTO PP108 (Navigation Drift)

The standard assesses if the location sensors drift over time. The vendor collected scans over the reference object ten times while traveling through figure "8." The GPS location of each scan was compared to the known GPS coordinate to quantify drift. An example of the navigation drift data from the pilot studies is shown in Figure 21.

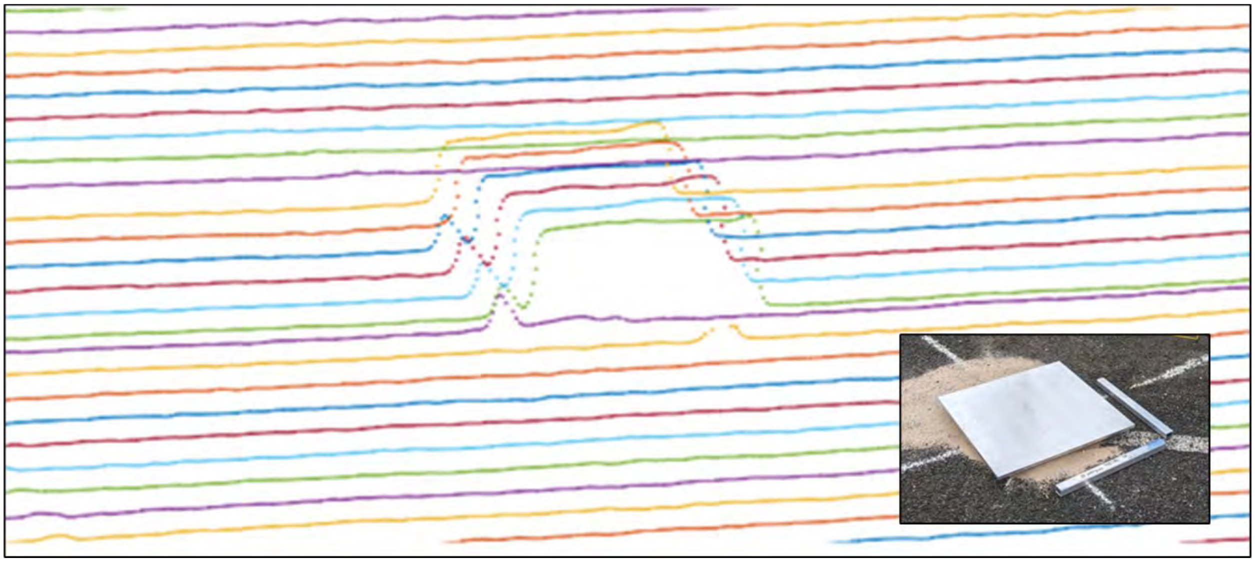


Figure 21. Illustration. Example navigation drift data.

AASHTO PP109 (Highway Performance)

The highway performance testing assessed the equipment's capability to collect TPP data at different speeds. Part of the highway performance section evaluates vendor-data-calculated rut depth, cross slope, and edge/curb detection against GRE-data-calculated rut depth, cross slope, and edge/curb detection and quantifies the errors. The assessment also quantifies transverse and longitudinal measurement spacing of data and vertical spacing errors.

The GRE data from the pilot studies produced a much denser point cloud than the vendor-supplied data. AASHTO PP109 assessments use one transverse profile from the vendor data and compare it to all the GRE data within a virtual rectangle (the width of the test section by a length of 9.8 inches). The vendor data overlaid on the GRE data, an illustration of the virtual rectangle, and the resulting profiles used for comparison are shown in the following figures (Figure 22, Figure 23, and Figure 24).

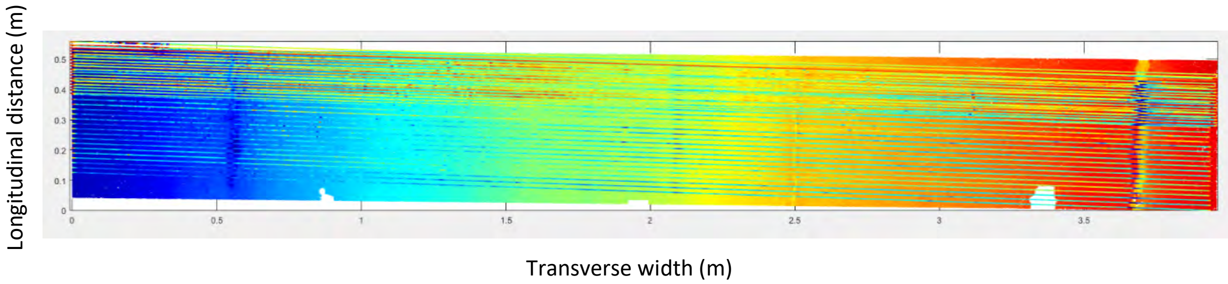


Figure 22. Illustration. Example of vendor transverse profiles overlaid on dense GRE data.

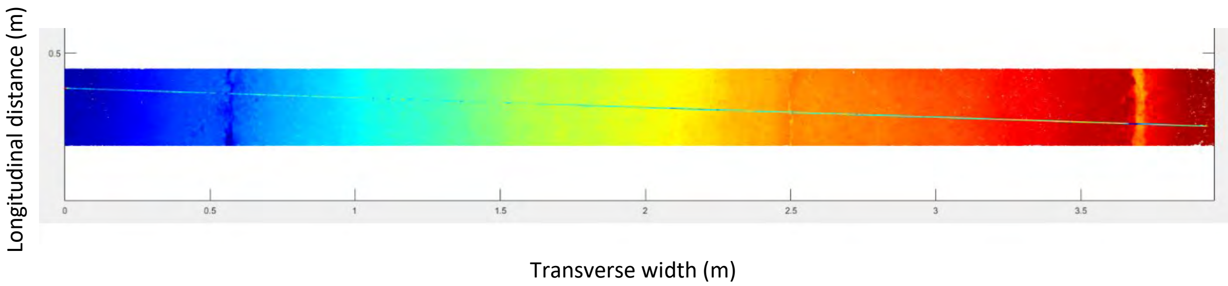


Figure 23 Illustration. Example of one vendor transverse profile extracted and overlaid on a virtual rectangle of GRE data.

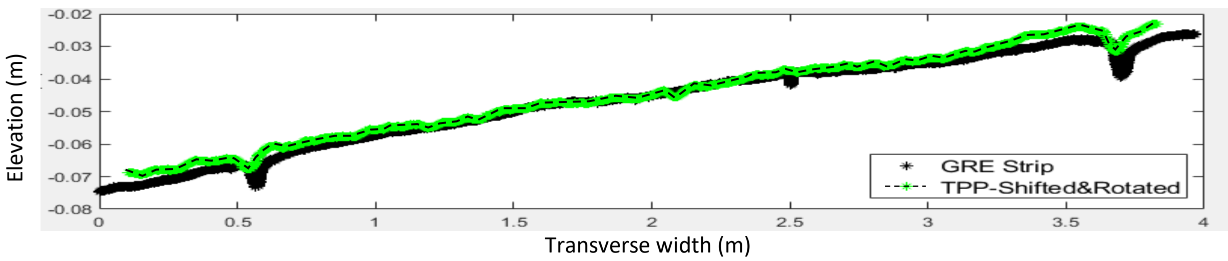


Figure 24. Illustration. Resulting profiles used for comparison.

TPP metrics of rut-depth, cross slope, and edge/curb detection from the high-speed equipment profile data were compared to the GRE profile, and errors were recorded.

AASHTO PP110 (GRE)

The GRE is assessed for capabilities to measure certified objects to produce ground reference data for the highway performance assessment. If the GRE meets the RS for certification, there is high confidence in the road surface scan used as a ground reference. Examples of certification objects include straight edges, gauge blocks, flat plates, and surfaces with known macrotexture. An example of scanned certification objects and the simultaneously scanned road surface are shown in Figure 25.

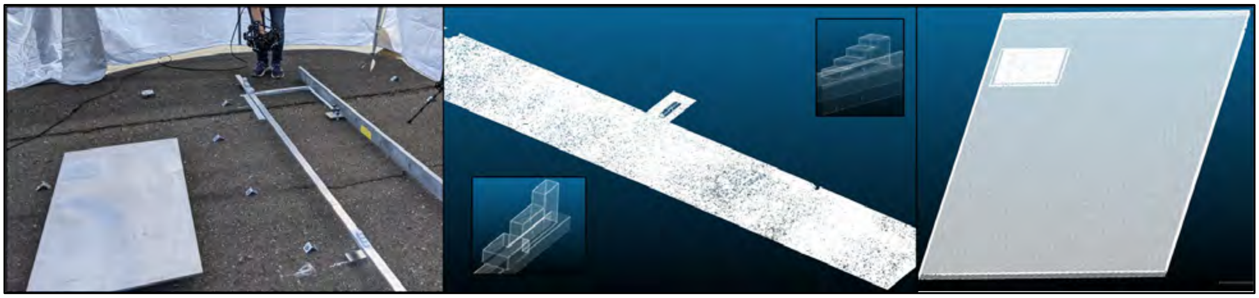


Figure 25. Photograph. Example of GRE certification object scans with roadway ground reference.

Lessons Learned

Each of the AASHTO standards for TPP certification and verification assessed different parameters (e.g., differences between equipment measurements and certified objects such as the width of stair-stepped gauge block, the height of stair-stepped gauge block, flatness or straightness of an object, etc.). Some vehicles met the suggested criteria of the standards, and some did not.

One of the most significant lessons learned from piloting the TPP tests was related to data submission. The raw point cloud data (data without filtering, smoothing, or elimination of outliers) is not an output that most vendors commonly use. Therefore, there was some post-processing in nearly all of the data analyzed during this project. The level of post-processing and how it affects the assessment results are not fully understood. Future research can work with vendors to communicate data needs to get the data for which the assessments were created.

Static Performance

The following items are other lessons learned and considerations for future testing:

- The data resolution between the equipment was significantly different, despite all participants meeting the RS for transverse measurement spacing. The stair-stepped gauge blocks were unidentifiable in the lowest-resolution data. Therefore, the assessment and results have low certainty since the data points for the gauge block analysis were estimated. The data resolution requirements can be clarified to participants before testing.
- The FOV of collected data may not be the same as the visual FOV seen during data collection. During data collection, the visual FOV (e.g., the actual laser lines visible [with proper protective eyewear]) captured the extent of the test section. However, the extents of the test section were not visible in the results submitted by some participants.
- Most of the data appeared to have some filtering resulting in rounded edges of gauge blocks, sloped surfaces, or both. Some data was noisy, and the steps could not be identified. The filtering could be caused by averaging many collected profiles for 10-seconds rather than collecting ten single scans. Furthermore, the data viewed on the onboard display during data collection did not reflect the output data, indicating post-processing. It is recommended that future projects continue to work with vendors on the correct data output needed to run the assessments.

Body Motion Cancelation

- The body motion cancelation test can be performed relatively quickly to check the fusion of mapping and location sensors. The placement of excitation boards and flat plates depends on the vehicle track width and sensor placement. Having these measurements in advance reduced setup time.

Navigation Drift

- The setup and data collection procedures for Navigation Drift were straightforward. However, the artifact flatness requirements made the plate expensive. If strict flatness requirements are not required, it would be cost-effective to reduce them.
- Using the corner of a reference object can be problematic because the edges of objects generally have the most outliers. Outliers at object edges were observed in several data sets. There are different solutions for addressing the outliers, such as using a reference point on the center of an object.
- Having a permanent layout of the figure "8" could greatly reduce testing efforts.

GRE

The following items are other lessons learned and considerations for future testing:

- The tent used to block the sun's glare required several “human anchors” to hold it in place during wind gusts, which was an inefficient use of resources. Other scanning technology may be less sensitive to sun glare.
- Scanning the flat plate and macrotexture surface near the Highway Performance ground reference test section was more efficient than scanning them in the ground reference test section. Scanning the flat plate and macrotexture surface in a separate area allowed the research team to simultaneously set up and start data collection for Highway Performance, saving significant time. The standard states that the flat plate should be nearby the road surface, and if a secondary scan (or file) is used to collect the measurements of the flat plate, no adjustments can be made to the equipment.

Highway Performance

The following items are other lessons learned and considerations for future testing:

- The required datasets are not standard outputs for most manufacturers. The Highway Performance testing requires raw point cloud data and gridded data for different assessments. Future research can work on clarifying these data types with vendors. Some of the data presented in this report were based on gridded data instead of (the intended) raw data.
- Multiple vendors consistently did not capture the test section extent in the transverse direction due to sensor FOV limitations or vehicle wander. Therefore, the edge/curb transverse location could not be calculated.
- Some vendors appeared to have issues with the transverse measurement spacing provided in the data headers for gridded data files. Sometimes, after the grid spacing was applied,

the measured transverse width did not meet the actual transverse width measured on-site and based on the GRE data. So although the bounding beams were visible, the transverse spacing resulted in a total transverse width that was smaller than the actual test section. Therefore, it is expected that some errors are based on the misalignment between ground reference data and vendor-collected data. Some vendors reported this as a calibration issue.

- No minimum number of profiles is required in the ground reference section, and 30 scans per second (as required in the standard) may not capture an adequate number of profiles in the short ground reference section at higher speeds. Therefore, it is recommended that the test standards indicate a minimum required number of scans in the ground reference section to ensure an adequate data sample size is collected.
- The data assessment for all TPP data was conducted in MATLAB.. The analysis procedures require manual intervention, and improvements to the analysis code may expedite the process and minimize the subjectivity of human intervention. Improved and standard analysis software may be helpful for implementation similar to the approach used for longitudinal profile based ride quality analysis using ProVal.
- There appears to be some filtering of the vendor data that removes cross-slope from the profile. None of the vendors showed accurate cross slopes.
- The ground reference test section is only 20 inches in length. There is limited space to collect profiles within that section and achieve the virtual rectangle required dimensions for ground reference comparison data. It is recommended that the ground reference section's length be increased and/or that the number of required profiles be included in the standard.
- Finding control sites to meet high rutting is challenging. Future regional certification sites (similar to the existing IRI sites) may be useful to DOTs.

3D System for Automated or Semi-automated Cracking Certification

There are many methods that DOTs reported for cracking and other surface distress detection. Some are using fully automated algorithms from the 3D system suppliers. Other DOTs reported using images taken during data collection to identify distresses from a computer screen by a manual rater. Other semi-automated processes use a combination of algorithm detections and manual raters. The certification methods proposed here apply to automated or semi-automated methods. Manual certification methods are described in chapter 5.

Most DOTs reported using manual raters for collecting ground reference data for cracking. However, in general, few details were given about the processes of the manual rater process. No other ground reference equipment was reported for establishing cracking ground reference data.

TPF-5(299)/(399) project Developing Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection/Analysis Systems and/or Services (Successful Practices for Cracking) includes verification procedures for cracking. These procedures were piloted by ALDOT.

Control Site Criteria and Vendor Data Collection

Control Site

The Successful Practices for Cracking report recommends the following for control sites (as summarized in chapter 2):

- Control sites should represent the types and severity levels of distress normally experienced by an agency for each pavement type to be evaluated.
- Control sites should consist of asphalt concrete pavements, jointed concrete pavements (JCP), and continuously reinforced concrete pavements (CRCP).
- A minimum of three sections of each pavement type should be included, although as many as six will increase statistical reliability.
- Asphalt and CRCP should be a minimum of 0.3 miles, and JCP should be a minimum of 0.5 miles or 100 slab lengths, whichever is greater.
- Additional sections may be considered for different roughness values, as roughness may affect image quality, surface textures, tined or grooved conditions, and the presence of other distresses on the pavement.
- Additional sections may be considered for different roughness values, as roughness may affect image quality, surface textures, tined or grooved conditions, and the presence of other distresses on the pavement.

ALDOT selected ten asphalt pavement control sites with ranging types and severity of cracking for certification.

Vendor Data Collection

Vendors drove each of the control sites once and submitted the distress data.

Ground Reference Measurements

ALDOT's certified manual rater made ground reference measurements according to the recommendations in the report. The Successful Practices for Cracking report recommends dividing the sections into subsections and marking wheel paths in the field to aid ground reference collection. The report includes an example of quickly subdividing and marking wheel paths using a template, as shown in Figure 26.

ALDOT rated cracking according to ALDOT definitions and calculated HPMS cracking metrics. The HPMS cracking results were used for data assessment.

Source: FHWA Morian et al. (2020).

Figure 26. Photograph. A template can be used to increase the efficiency of wheel path layout.

Control Site Observations

A preliminary investigation of the vendor data revealed that the vendor data collection equipment could detect cracks less than 5/64 inches. Based on ALDOT's past experiences, these were not typically reported by vendors in the past. Therefore, ALDOT did not perform manual ratings for cracks less than 5/64 inches. Upon this discovery, ALDOT decided to re-rate some control sites where vendors reported these "hairline" cracks to provide adequate ground reference data for comparison.

Data Assessment

Control sites can be weighted based on whether the control site is more or less important than others. For example, a site with a type of cracking that triggers a significant decision regarding maintenance or rehabilitation might be weighted more heavily than other sites. Control sites were all rated equally (by a factor of one) for this assessment.

Each control site was 0.3 miles in length. Each site was subdivided into ten equal subsections with a length of 0.03 miles (N=10). The equivalence limits varied and were set based on the mean of the subsection ground reference ratings per site, as recommended in the Guidelines for Cracking report. The report provides the following criteria for equivalence limits:

- Mean between 0 to 30 percent – equivalence limits: ± 4 percent.
- Mean greater than 30 percent – equivalence limits: ±10 percent.

The standard deviation of the difference between the ground reference rating and the vendor data was calculated for each site. For cracking verification, the Guidelines for Cracking report recommends that the power is kept above 0.80 (or 80 percent chance of correctly determining equivalence). Agencies may balance the risk and power to establish reasonable equivalence without excessive risk to the vendors. Multiple alpha values (risk of accepting a rating as equivalent when it is not) were used to develop summary tables. These tables were provided to ALDOT to assist them with vendor selection.

The assessment was performed using a standard statistical analysis software package (Minitab). More details on the assessment process and examples can be found in the Guidelines for Cracking report (Morian 2020).

Lessons Learned

- Three vendors participated in the ALDOT cracking certification pilot study, and one vendor brought two different generations of equipment. A range of alpha values was used, which significantly affected one vendor’s results but had little effect on the other three.
- Weighting the test sections is an option to place more importance on certain cracking types. For example, if a DOT's decision-making processes include rehabilitation triggers at a certain threshold of wheelpath cracking, placing more weight on control sites with comparable levels of wheelpath cracking may be useful.
- Data collection technology for cracking is improving based on the detection of 5/64 inches cracks based on the participant data.
- The pilot study used one manual rater for ground reference cracking rating. Adding more manual raters would allow for consensus ratings which, according to the Guidelines for Cracking Report, may improve the certainty of the results. However, it can be challenging to find multiple experienced raters.
- During the pilot testing, participants did not make repeat runs at each test site. Repeat runs may be used to assess repeatability.

Image Equipment and Quality

A critical component of certification of 3D systems that detect cracking and other distresses is ensuring video and image quality adequacy. Even DOTs that use fully automated procedures for cracking data collection reports using images for acceptance or quality assurance procedures. Therefore, regardless of whether a DOT uses automated, semi-automated, or manual procedures for crack and distress detection, image quality checks may be included in certification processes. The Successful Practices for Cracking report includes procedures for image equipment verification requirements and image quality checks, and DOTs can consider using these procedures in their certification program. The procedures and recommendations from the final report are described in the sections below.

It is noteworthy that data images used for distress classification typically require proprietary vendor software for viewing. AASHTO MP 47-22 was recently published as a standard 2D/3D pavement image data format that the agencies and industry may adopt.

Imaging System Clarity

Either line scan or frame-type digital cameras can be used to collect pavement images. Using frame-type cameras can result in some image distortion along the image edges. In contrast, the line scan camera produces a series of single-pixel images stitched together to provide the second dimension, similar to a fax machine, and therefore does not have this issue.

- Image size – pixels by pixels: For a 3D image, a 4,096-pixel transverse resolution theoretically supports the identification of a 1 mm wide crack. Similarly, a 1,300-pixel transverse resolution theoretically supports the identification of a 3 mm wide crack, and 2,048 pixels a 2 mm crack width. These theoretical resolution levels are best achieved when the camera is still or moving slowly. Higher-resolution cameras can identify finer cracks. For 3D pavement imaging, 16-bit images should be used. Crack identification is also affected by the 256 shade levels in an 8-bit image, making crack width identification more complex (Olsen et al. 2013), (Wang et al. 2016).
- Image dynamic range check: Dynamic range is the ratio between the brightest to darkest signal levels. It determines how many levels of difference in digital values exist in a given image. For binary (black and white) images, 8-bits (256 levels) are usually sufficient to represent visual information. Color images with a dynamic range of 24-bits are available and may be used to capture detailed features such as surface texture.
- Percent fill factor: The pixel fill factor indicates the light-gathering area of the photodetector used. The proportion of the pixel area insensitive to light is indirectly indicated. The minimum suggested fill factor is 90%, and this practice indicates that 10% of the pixel is insensitive to light. The photodetectors most commonly used are silicon chips or metal oxide semiconductors. A lower fill factor may be acceptable if the resulting image quality is sufficient to identify the desired distresses.

Image Resolution

3D line scan data collection produces higher resolution, dynamic range, and fill factor than earlier technologies. It also reduces the smearing of images of fast-moving objects. Applying the 3D range data with laser image lighting has significantly reduced image clarity issues from variable lighting conditions and improved the interpretation of low-intensity contrasts such as oil stains on the pavement surface.

Compression type and storage size requirements vendor uses to meet data delivery:

Currently, the size of the original data collection files and compression method varies from one software developer to another. However, FHWA is in the final publication phase of a report titled "Evaluation of Proposed Standard Data Format and Compression Algorithms for 2D/3D Pavement Surface Image" (Tsai 2019), which proposes a standard data format for the 2D/3D image systems. An agency may consider requiring the 2D and 3D images provided by the vendor to comply with the proposed standard data format. An example of the current minimal rules and validation procedures for standard data format based are listed in Table 11.

Table 11. Example of minimal rules and validation procedures for images.

Properties	Sub-rules	Validation Procedure
File Integrity	The file signature is present	Check if the last four bytes of the file are "psi."
File Integrity	The file trailer is present	Check if the last four bytes of the file are "@@@@."
File Integrity	The file's checksum equals the given one	If a checksum is given, calculate the checksum based on the file content and check if it equals the given checksum.
Header Correctness	The values in the header fields are valid	For each value, if the field takes only the assigned value, check if the value is in the "assigned values list." For example, the version should follow the format "X.YY," where X and YY are numbers.
Header Correctness	The size of the 2D/3D data is correct	If the data are not compressed, check if the following condition holds: "datasize = bitdepth / 8 * width * length"
Data Correctness	The data in the 2D and 3D sections can be extracted using header information	Extract and decode the 2D and 3D data using the header provided information. Check if the extracted data can fit into a width * length matrix of that given data type.

Image Capture Width

The image's width should cover the entire driven lane in the travel direction, accounting for vehicle wander, typically 13.5 to 14 feet wide.

System Capabilities

- Illumination source: The downward perspective image should be collected with uniform and consistent illumination applied to the pavement surface. The illumination should be regulated to provide sufficient contrast and crack shadows to discern cracking and patching clearly. Images bearing ambient and vehicle shadows that obscure pavement features should not be accepted.
- Data collection speed: Data should be collected at or near prevailing highway speed.
- System storage: The file size requirement is partially determined by the size of the data stream collected and the compression ratio used. For example, 1-mm resolution imaging for a 4-meter lane width needs a data flow of approximately 120 MB per second before compression (Olsen et al., 2013). Data collection systems differ regarding whether data is processed in real-time or post-processed. Therefore, storage requirements can be determined as a part of the system used, contingent upon meeting the requirements for image clarity and interpretation of the information stored in the retrieved image. The storage size is significantly affected by the requirements for full survey data vs. sample data. General requirements should include that the data storage file be self-describing and self-contained. Self-description is described as data that different systems can interpret at different points in time. Self-contained is described as data for interpretation is included within the data "container." For example, metadata should provide identifying

information such as location and date and a string of information linking the header to all the access data stored for that specific location. The acceptability of storage capacity and compression taken as a whole can be determined based on the final image quality produced by the system.

Image Quality

The Successful Practices for Cracking report references AASHTO R86-18 (formally AASHTO PP68) Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection as a reference for image quality requirements. This standard includes checks that a DOT can perform as a quality management activity, including certification. DOTs can evaluate their data definitions and criteria for additional requirements specific to their data management program. The AASHTO R86 criteria for image quality include the following statements:

- The images should provide a sufficient difference between data point values representing distressed and non-distressed areas that subsequently distress detection techniques can delineate a minimum of 33 percent of all cracks under 3 mm (0.12 inches), 60 percent of all cracks present from 3 mm (0.12 inches) and under 5 mm (0.2 inches) wide, and 85 percent of all cracks 5 mm (0.2 inches) wide or wider regardless of orientation or type. This capability should be determined by utilizing a minimum of ten 0.03-km (100-foot.) samples containing an average of at least five such cracks per sample.
- The images should be sufficiently void of erroneous differences between data point values. A section of pavement without distress, discontinuities, or pavement markings contains less than 3 m (10 ft.) total length of detected false cracking in 50 square meters (540 square feet) of pavement. The determination of this capability should be made utilizing a minimum of ten 0.03-km (100-foot.) samples of various types that meet the criteria.
- Detect average crack width for each crack detected in the previous bullet should be within 20 percent or 1 mm (0.04 inches), whichever is larger, of the actual width with at least 85 percent confidence.

Other considerations given in the Successful Practices for Cracking report include:

- The pavement surface is visible without shadows, reflection from the wet surface, or other conditions of the imaging process resulting in images that cannot be viewed.
- A crack width of 1 mm (0.04 inches) should be identifiable (for a stationary or low-speed system), with a 2 mm (0.08 inches) width identifiable when the image is collected. At the same time, the collection vehicle travels at 60 mph.
- The image size should accommodate some vehicle wander while collecting data. It is not practical to avoid vehicle wander, particularly when traveling on an active highway.

JCP Faulting Certification (Inertial Profilers and 3D Systems)

JCP faulting certification was not piloted under this project due to the lack of an AASHTO fault certification standard. The ongoing TPF-5(299)/(399) research includes a project for JCP Faulting Collection and Analysis. Draft reports from this ongoing project state that most DOTs use 3D systems to collect faulting data. Some DOTs report using HSIPs but indicated planning to change from using HSIPs to 3D systems soon. Defining, collecting, analyzing, and reporting faulting values varies by DOT. The intended outcome of this research is to address the shortcomings of current faulting practices and establish standards that quantify the accuracy and precision requirements for faulting data collection and analysis to meet DOT requirements.

Based on DQMP reviews, some DOTs certify and verify faulting data using a fault meter. For example, Flordia DOT (FDOT) selects ten random joints from their two rigid control sites to certify faulting equipment using a fault meter.

AASHTO R36-17 includes guidance on faulting verification sections (control sites) when using HSIP. These criteria can be used for equipment certification and are as follows:

- Verification Sections—Verification sections are selected with known faulting. Faulting on these sections is measured by equipment operators on a regular basis. Evaluations of these measurements provide information about the accuracy of field measurements and give insight into needed equipment calibration. The repeatability precision requirement is recommended to be between and 0.7 mm (0.03 in.) and 2 mm (0.079 in.) at a 95 percent confidence level at a single joint. Verification sections are rotated on a regular basis in order to assure that the operators are not repeating previously known faulting values during the verification. As an alternate to verification sections, remeasure and compare up to 5 percent of the data as a daily or weekly quality check.
- Repeatability, Reproducibility, and Bias for the Automated Methods—The fault magnitudes from two profiling runs on the same joint should not differ more than 0.6 mm (0.02 in.), when collected by the same HSIP, at a 95 percent confidence level. The fault magnitude from two profiling runs on the same joint should not differ more than 0.9 mm (0.04 in.), when collected by two different HSIPs, at a 95 percent confidence level. The bias of the automated fault measurements should not exceed 0.7 mm (0.03 in.) at a 95 percent confidence level.
- Quality Checks—Additional quality checks can be made by comparing the previous year's faulting statistics with current measurements. At locations where large changes occur, the pavement manager can require additional checks of the data.

ROLES AND RESPONSIBILITIES FOR EQUIPMENT CERTIFICATION

Based on DQMP reviews and the DOT comments from the FHWA peer exchanges regarding data DQMPs, setting up certification control sites and ground reference data is something that many DOTs are struggling to do. DOTs can be involved with the setup of control sites and ground reference data used for certification.

DOTs are responsible for ensuring the requirements of 23 CFR 490.319(c)(1) are met for equipment certification related to the HPMS data. They may accomplish this with their resources or a third party in an unbiased approach. If the State DOT decides to engage a third party for the calibration and certification of the equipment used to collect the data, they may do so; however, the State DOT must include this as part of their Data Quality Management Plan process. The State DOT ensures that any such work performed by third parties meets all requirements of 23 CFR 490.319(c)(1).

REPORTING AND RECORD-KEEPING FOR CALIBRATION AND CERTIFICATION

DOTs can keep records of all calibration and certification activities and results. The records can be easily accessible so DOTs can access them if any data quality issues arise.

CHAPTER 5. TRAINING

INTRODUCTION

This chapter includes successful practices for training personnel involved in automated, semi-automated, and manual data collection. This chapter considers training for data collection, data acceptance, and manual rater teams.

DATA COLLECTION TRAINING

This section includes training for the data collection team (agency or vendor). If DOTs are using vendors to collect PSC data, the training for data collection personnel is typically performed by the vendors. In this instance, DOTs still need to review and include vendor training processes in their DQMP to ensure the training is adequate for their data collection program needs.

Since HSIP and 3D equipment include complex systems that collect complex data, proper training is critical to collecting quality data. Many DOTs did not include general training requirements in their DQMPs. The following case studies highlight some of the successful training practices for data collection teams found during the DQMP reviews:

Successful Case Studies

Maine DOT (MaineDOT)

Maine DOT (2018) self-collects network PSC data and reports hosting training sessions for different data collection team members (shown in parenthesis). MaineDOT references using the Automated Road Analyzer (ARAN) data collection equipment in the 2018 DQMP. The training is hosted by the equipment supplier and includes the following topics:

- *Introduction to ARAN (ARAN Manager/Operator-Driver):* This segment covers the operational and technical theory of the ARAN data collection subsystems. Computer and subsystem hardware connections and interconnectivity are reviewed. Each subsystem is introduced and discussed in detail. The ARAN software and how it works are introduced.
- *Operator I (ARAN Manager/Operator-Driver):* This segment introduces the Operator's responsibilities and covers the vehicle checklist, recommended driving method for data collection, mapping, laser and vehicle safety, and general maintenance.
- *Operator II (ARAN Manager/Operator)* This segment provides lecture and hands-on activities for windshield rating, vehicle rating, project setup, and beginning and end of day procedures. Data collection term definitions and best practices are introduced.
- *Data Collection I (ARAN Manager/Operator)* In this segment, agency staff cover the in-depth theory of data collection for the different subsystems. Both theory and practical aspects of creating collection sessions, starting and ending files, rating, and data monitoring are studied. Data analysis and corrections are also essential parts of this segment.

- *Systems Calibrations (ARAN Manager/Operator)* This segment covers the calibration procedures for the DMI, roughness, cross fall, rutting, grade, GPS, texture, pavement imaging, Surveyor, and camera subsystems.
- *Troubleshooting (ARAN Manager/Operator)* The ARAN data collection system consists of many subsystems. This segment addresses some of the more obvious checks that can be used to address any issues encountered.
- *ARAN Database Creation (Highway Management Technician)* ARAN Database Creation enables the student to be proficient in database creation. To use the data, the data must be taken off the truck and databases created that are a usable format for the Department's data. The data is removed from the vehicle, and the data format is analyzed, then the steps for database creation are covered.
- *Vision (Highway Management Technician)* This course deals with the Vision application and associated processes. The Vision application integrates road network data with ARAN-collected data. The student has hands-on opportunities to learn how to perform functions such as routing importer, data quality checks, segmenting, viewing, Automated Crack Detection, and reporting.
- *Vision (Highway Management Assistant Engineer-Assistant Highway Management Engineer)* This course deals with the setup and administration of Vision. It also includes how to use the features and functionality of this web-based application.

Pennsylvania DOT (PennDOT)

PennDOT (2018) uses a contracted vendor to collect PSC data. PennDOT keeps a record of all vendor training for data collection equipment operators. The vendor provides a training matrix for each of the field operations technicians. These matrices include different levels of field operation technicians and the tasks that must be completed to be proficient at that level. The equipment vendor evaluates other field technicians and operator levels, and PennDOT keeps the training matrices. Reviewing and keeping detailed training records is an example of successful practice, ensuring that the data collection team is knowledgeable and capable of completing the data collection assignments. In addition to keeping detailed training records, PennDOT requires that the vendor be trained in state-specific distress definitions before data collection. An example of an operator training matrix for a Field Operations Technician Level 1 is listed below (adapted from PennDOT). Some terminologies are specific to the equipment vendor and proprietary and do not apply to all DOTs. Field Operations Technical Level 1 tasks include:

Tasks for Field Operations Technician 1:

- Has completed Quality and HSE Orientation.
- Has completed Smith Driving System Training.
- Can perform the safe operation of ARAN? Can demonstrate proper driving technique as related to ARAN data collection? Can drive consistently in the wheel path?
- Can complete ARAN daily mechanical inspection checklist in SalesForce/understands why checklist must be completed before leaving for collection or transit.
- Can complete ARAN daily generator maintenance checklist in SalesForce.
- Has completed First Aid (with CPR/AED) Qualification within the first three months.
- Has basic knowledge of ARAN sub-systems and can identify all equipment.

- Can perform generator/sub-systems startup.
- Can perform basic Sub-System troubleshooting utilizing ACS Diagnostics.
- Can navigate with New ACS polyline maps, can distinguish sections, and how to route the sections for collection by utilizing Mission Management without supervision.
- Can refer to the section collected on the Map to verify that they are collecting the correct section of the road.
- Can effectively collect a dummy section/run diagnostics and knows how to review acceptable data in the ARAN 9000 software under Review Data Tab without supervision.
- Can review data on sections of road collected, paying attention to skipped images from utilizing the end-of-day report function under Quality Video.
- Can access data file setup and systems check procedures using Diagnostics before data collection in the ARAN 9000 software without supervision.
- Can enter notes on the end-of-day report, select the type of collection, and delete sections (explaining why sections were deleted).
- Can utilize Data Management, backup data, export data, and generate End of Day Reports.
- Can access Daily Report, complete daily CSV reports, and check the quality of sample ROW video images.
- Understands the importance of Fugro Safety Policies and performs all duties safely and professionally.
- Can upload Daily Report to the FTP site effectively.
- Can perform a Field Inspection effectively and know the location of all ARAN equipment.
- Can perform the Daily Report on SalesForce.
- Can perform data shipment, hard drive inventory, and navigate through SalesForce/Saasmaint effectively without supervision.

DATA ACCEPTANCE TRAINING

This section includes training for the data acceptance team. Data acceptance can be performed by DOT personnel or a third party hired by the DOT. Very few DOTs addressed how personnel is trained to perform data acceptance activities. Training for the data acceptance team can include training on proprietary software programs, basic data management processes, including naming convention and storing, and proper documentation of data and quality management activities. DOTs may find it useful to have data acceptance personnel attend and understand basic equipment operator and field training to understand better the data collection processes and potential sources of data error. A few successful practices found during DQMP reviews are included in the following section.

Successful Case Studies

Alaska Department of Transportation and Public Facilities (AK DOT&PF)

- AK DOT&PF (2018) requires the data collection vendor to provide two full-day training sessions at Alaska DOT&PF's general office. The first session is upon delivery of the first data set (initial five percent), and the second session is when the full data set is delivered for the first year.

- Additionally, AK DOT&PF requires the data collection vendor to provide up to 80 hours of onsite technical support training at Alaska DOT&PF's discretion. Establishing these training requirements for data analysis is an example of successful practice for ensuring that data acceptance personnel get adequate support regarding software and analysis.

New Jersey DOT (NJDOT)

NJDOT (2018) office staff are trained in vendor data collection and asset management software. The training is conducted annually, and detailed topics are included in the DQMP. The training topics for vendor and asset management software are listed below. Note that these training topic terms are specific to the selected software vendors and may not be understood or applicable to all DOTs. The example shows that detailed training topics can ensure that the data acceptance team has the training and knowledge to perform their quality management tasks. The data can be processed and exported to asset management software for storing and using the data.

Office Staff should be trained for the equipment vendor (Pathway) processing and asset management software (dTIMS) processing. NJDOT uses in-house processing manuals for both software. While the manuals are comprehensive, training should be conducted annually to make sure all staff is aware of updated procedures in the following areas:

- Pathway processing topics.
  - Transferring and backing up data.
  - First/last image checks.
  - Adjusting milepost extents.
  - Running autocrack.
  - Running autoclass.
  - Evaluating downward-facing camera images.
  - Identifying pavement distress.
  - Evaluating profilograph.
  - Exporting data.
  - Accepting data.
- dTIMS processing topics.
  - updating the database.
  - updating committed projects.
  - updating sectioning.
  - updating condition.
  - processing analysis set.
  - reviewing and exporting budget analysis.

MANUAL RATER TRAINING AND CERTIFICATION

Describing Manual Raters

Few DOTs included manual rater certification procedures in their DQMPs. Many DOTs reported that manual ratings were not performed in their programs, based on using vendor algorithms to detect cracking and distresses automatically. However, many of these same DOTs reported using manual ratings for establishing ground reference data, performing manual acceptance checks of automated distress detection, or using PSR in areas with speed limits below 40 mph as allowed in the HPMS Field Manual. These activities may be considered manual ratings, and personnel performing any ground reference rating, QC, or acceptance checks can be certified specific to DOT data protocols. As discussed throughout this document, all DOTs collect different distresses to use in their decision-making processes, and the definitions of each distress vary by state.

State DOTs can collect and report Present Serviceability Rating (PSR) as an alternative to IRI, cracking, rutting, and faulting per 23 CFR 490.309 on the National Highway System (NHS) routes with speed limits less than 40 mph. To use PSR, DOTs should certify manual data collectors per the PSR manual condition rating method described in the HPMS Field Manual. A DOT may elect to use an alternative pavement condition method (e.g., PCI, PSI, etc.) to PSR. In that case, the manual data collectors must be certified for that methodology. The State DOT must have an acceptable method of converting its manual pavement condition method (e.g., PCI, PSI, PCR, etc.) to PSR, as defined in the HPMS Field Manual.

Elements of Successful Manual Certification Programs

Based on the successful practices identified in the DQMP reviews, elements of good manual certification programs include:

- Certification programs include evaluating a comprehensive understanding of manually collected HPMS metric data definitions.
- Certification programs include evaluating a comprehensive understanding of manually collected DOT-specific metric definitions.
- Evaluation methods include “hands-on” practical certification testing at control sites or using pavement images of distresses.
- Evaluation methods include either a pass or fail outcome.
- Certification records are kept and have an expiration.
- Training programs are available to prepare manual raters for certification.
- A responsible party is assigned to conduct manual rater training.

The following sections include successful practices found during the DQMP reviews of manual rater certification.

Successful Case Studies

Texas Department of Transportation (TxDOT)

TxDOT (2018) reports in their DQMP that annual training is conducted for all TxDOT operators involved with data collection for quality assurance and acceptance of automated data submitted by the service provider. All staff involved with any post-processing verifications of surface distresses from collected images must be certified annually by attending surface distress rating classes for asphalt, CRCP, and JCP pavements. Personnel must pass a written test, scoring 70%

or higher, to demonstrate an overall understanding of the surface distress rating process, procedures, and quantification. A log of certified raters is kept, which includes the rater's name, department, certification specific to pavement type, and year of certification. Note that even the vendor employees are included in this Certified Visual Raters log.

Also included in the TxDOT DQMP is their Pavement Rater's Manual. This manual includes visual evaluation procedures, a description of automated rating forms, safety information, and definitions and detailed procedures for rating state-specific distress definitions for each pavement type (Asphalt, JCP, CRCP).

South Dakota Department of Transportation (SDDOT)

The SDDOT DQMP (2018) gives the following steps for personnel certification (adapted) for personnel that is involved in manually rating cracking based on collected images:

- An instruction manual is provided to the pavement raters to guide them on how to view the images, identify the cracking in pavements, and use the crack editing software.
- A written examination is given to raters to verify their knowledge and skills to comprehend the material and use the image-viewing software. The examinee must attain a score of 80%.
- Raters recertify every three years. New Raters are required to pass the certification before data collection.
- A practical exercise on the image viewing and crack detection software, where the examinee must quantify the cracking percent on the pavement, and the examinee must attain a score of 80%.
- A list of certified raters is maintained in the SDDOT's profiler operation document folder.
- The Assistant Pavement Management Engineer is responsible for this training.

SDDOT uses a surface condition index (SCI) instead of the pavement serviceability rating (PSR) in HPMS reporting on roads meeting the criteria in the HPMS field manual. SDDOT reports successful training for raters performing these measurements. The following content is adapted from SDDOT's DQMP regarding training for visual distress surveys used to calculate SCI.

Training

Training of the five personnel is accomplished in three phases. These three phases are Introductory, Field, and Reinforcement. The purpose of the goal and the time used for each phase are listed in Table 12.

A driver is not allowed to rate the pavements; however, the driver is trained to identify and quantify the distresses. This process allows the driver to assist the rater by calling out distresses that road geometrics do not allow the rater to see.

Table 12. Summary of the purposes, goals, and timing of SCI distress rater training activities during the three phases adapted from SDDOT's DQMP.

Phase	Purpose	Goal	Timing
Introductory	Provide introduction and orientation	General employment orientation. Introduce safety procedures, day to day operations, location referencing, and The Distress Survey Manual.	Day 1 to 2
Field	Provide training on the Pavement Distresses and how they are collected	All personnel becomes proficient in identifying and quantifying Pavement Distress safely and efficiently.	Day 2 to 5
Reinforcement	Reinforce training on Distresses and how they are collected.	Evaluate the performance of the crews in a "real world" situation. Provide feedback to crews on performance and adjust as necessary	Week 2

In the Introductory Phase, all personnel performs the orientation meeting and paperwork with the Bureau of Human Resources to begin employment with the State of South Dakota. When this is accomplished, training sessions with Pavement Management staff introduce the trainees to safety procedures (including a defensive driving course), day-to-day operations like location referencing across the state, and The Distress Survey Manual.

The Field phase is where the new interns and seasonal personnel are introduced to actual distresses on roadways. The steps that are used to accomplish this are below:

1. Find and tell: the students and the instructor drive to predetermined sections of the roadway to find, observe and discuss distresses and their severity levels.
2. Stop and go (paper): the students begin to include the severity with the extent of the distresses in this phase. The instructor has a student drive a section while he/she and the other students rate on paper. At the end of each of the sections, the instructor has the driver stop the vehicle, and a discussion of the distresses found in that section takes place. If there is anything in question, the instructor can have the driver go over the section again or drive back and look at distresses in question. This process takes place until the instructor is satisfied with the student's understanding of the distresses on each of the four pavement types (AC, JCP, CRCP, and Gravel).
3. Stop and go (laptop): the final item to include is the use of a laptop to record the pavement distresses. The students gain experience in operating the Distress Survey Application. Again, this is achieved by rating a section and stopping to discuss it.
4. Full rating scenarios – this is where raters begin to rate continuously, from section to section. Usually, each section includes a full mile. After each section, the trainer stops and discusses, then continues. This process continues until the student and instructor are confident in the job being performed.

The Reinforcement Phase is the first trip out. The students become the rating team in this phase. The Black Hills of South Dakota is the area chosen for this phase of training because it is a challenging portion of the state to perform data collection. Each team is paired with an instructor and begins their week as the instructor observes the crew. The instructor is available for any questions or problems that may arise, and the instructor makes "on-the-spot" checks and corrections as the week progresses.

The lead instructor is the Assistant Pavement Management Engineer and is assisted by the Pavement Management Engineer and the Planning Data Manager.

Certification

The total training time for the rating teams is 80 hours. Once the three training phases have been completed to the satisfaction of the Instructor(s), the raters are considered certified to gather pavement distress data. This certification is subject to evaluation continuously through the time of employment. It may be revoked at any time for due cause by full-time Pavement Management personnel or the instructor. A list of certified Raters is maintained in the SDDOT's Profiler Operation document folder.

ROLES AND RESPONSIBILITIES

DOTs using vendors to collect data can still review and accept training procedures and records, and DOTs can ensure sufficient detail on vendor programs to ensure adequate training. DOTs who self-collect data can ensure proper training is provided to DOT personnel. Trainings can be performed in-house or by the equipment vendor or manufacturer.

REPORTING AND RECORD-KEEPING FOR TRAINING

DOTs may keep training records for all data collection or analysis personnel, and training records can include an expiration or a requirement for recertification. TxDOT (2018) does not mention how long the certification is valid, but they record the year certification was awarded. SDDOT (2018) mentions that manual certification is subject to evaluation but does not specify how frequently. Many DOTs' DQMPs stated that proper training is critical for data quality management, and proper record-keeping documents that training activities occur as intended.

CHAPTER 6. QC/QA ACTIVITIES DURING DATA COLLECTION

INTRODUCTION

This chapter includes successful practices of quality management activities performed during and after data collection. Based on DOT DQMP reviews, quality management activities during data collection were a common strength among DOTs. Since some DOTs use vendor services to collect data and some self-collect, QC, QA, and acceptance are hard to define. Each DOT has unique roles and relationships with data collection vendors, and the responsible party for the quality check and the terms assigned (QC, QA, acceptance) vary. The quality management activities described in this report are loosely called QC/QA. DOTs can use judgment to establish roles, responsible parties, and terms to fit their needs. In instances where DOT example practices are described, the terms used by that DOT are used.

CONTROL SITES

Verification at control sites is a common QC/QA activity referenced in DQMPs. DOTs typically did not differentiate between control sites used for certification and QC/QA activities. Certification control sites are "Certification-level," as described in chapter 2, and have the strictest requirements requiring control site criteria and ground reference. These sites may not be economical or practical for QC/QA activities. If desired, DOTs can use other types or tiers of control sites for quality activities. DOTs can use a combination of control sites to fit their data quality program needs best while remaining reasonably economical and efficient.

FREQUENCY OF QUALITY MANAGEMENT ACTIVITY

The frequency of quality activity aligns with the activity being performed. Successful practices identified in the DOT DQMPs included real-time data monitoring, daily checks for each day of data collection, and weekly or monthly checks at control sites. The frequency of quality control activity can be included in the DQMP. More examples of appropriate frequencies for quality management activities during data collection are summarized in this chapter.

ACCEPTANCE CRITERIA

The DOT or vendor may establish acceptance criteria for quality activities. DOTs can review and approve vendor acceptance criteria for QC/QA activities (when using vendor services). Different criteria may be established for different activities described in the following sections.

ELEMENTS OF SUCCESSFUL QUALITY CONTROL PROGRAMS

Many DOTs reported successful QC/QA activities and procedures. Based on the reviews, the following activities are used to summarize successful QC/QA processes:

- QC/QA procedures are written.
- Procedures include minimum testing frequencies.
- Activities include clear acceptance criteria.
- Activities include real-time data checks as data is collected for out-of-range data.

- Cross-rater checks (as applicable). Checking the difference in results between different raters is important for ensuring the data's year-to-year consistency.
- QC/QA checks during initial daily data reduction.
- Daily system equipment checks and validation of DMI, GPS, sensors, or other supporting systems.
- Procedures include verification at control sites at specified frequencies.
- Procedures include clear acceptance criteria and thresholds for classifying as pass or fail.
- Procedures include reporting, reviewing, and record-keeping procedures.
- Procedures include error resolution procedures for data not meeting QC/QA acceptance criteria.
- Procedures include a responsible role in completing QC/QA activities.

DOTs can check with their data collection equipment vendor or manufacturer for other recommended processes specific to their data collection equipment. Pavemetrics' LCMS is a commonly used 3D system for data collection equipment, and they recommend the following data QC/QA processes. Other vendors and sensor manufacturers may have similar procedures specific to their equipment and software.

3D Data Quality Tips and Tricks

The following data quality tips and tricks were adapted from a document provided by Pavemetrics (2020) regarding the usage of 3D equipment:

- Lens Cleaning:
  - Field crews should regularly clean equipment lenses to ensure they are free from dust and contaminants. Depending on road conditions, this could need daily cleaning.
- Wet Road Surfaces:
  - Data should not be collected when the pavement surface is darkened due to moisture or when standing water or potholes are filled with water. Surfaces should be allowed to dry following rainfall.
- Monitoring Images During Collection:
  - The field crew should monitor equipment intensity and range images during field data collection to ensure they appear well-exposed and sharp.
  - The field crew should review a percentage of collected equipment images daily at the end of each day to ensure that the data collected is of acceptable quality for subsequent data processing.
- Periodic Sensor Validation:
  - The field crew should periodically validate the calibration of each sensor using Pavemetrics' equipment Validation Tool software and the Pavemetrics validation object. The validation object is a triangular-shaped metal artifact. An example of data collection equipment scanning such a validation object is illustrated in Figure 27. A close-up of the equipment Validation Object shown in the intensity image is also illustrated in Figure 28. An example of the equipment Validation Tool software being used to check data quality using the equipment Validation Object is shown in Figure 29.

    - The validation procedure checks the focus of the camera, the noise level in the images as well as the accuracy of the calibration. However, it should be noted that the validation software cannot adjust the calibration. It assesses whether the sensors are still well aligned.
- Spot Checks:
    - If the field crew is uncertain whether some collected data are of good quality, a sample should be sent to the office for review and approval by the data-processing staff before leaving the project area.
- Use of Control Sites:
    - Control sites should be representative of the pavement in the network. Control sites should be located on the pavement that is not scheduled for construction improvements. So that the condition more-or-less remains constant or only slowly degrades.
    - At the start of each data collection season and monthly throughout the season, the field crew should collect data at control sites and note any apparent repairs that have been made to the pavement or significant deterioration since the last survey.
    - Field crews should process the data and output cracking (total cracking length for each section), rutting, and roughness. These results are compared to the values from the last survey. The crew should expect cracking, rutting, and roughness values that are relatively the same or moderately worse. Suppose the values show improvement or significant deterioration, and the field crew did not note any maintenance or deterioration that explains the changes. In that case, the data should be flagged, and equipment malfunction should be investigated further.
    - Before storing the equipment, data from control sites should be collected at the end of the data collection season. This process provides a measure to compare to in the spring of the next year or the next data collection cycle.

Source: Pavemetrics (2020)

Figure 27. Photograph. Example of equipment Scanning of the Validation Object.

Source: Pavemetrics (2020)

Figure 28. Photograph. An example of a Validation Object is shown in the intensity image.

Source: Pavemetrics (2020)

Figure 29. Illustration. Example of Validation Tool software being used to check data quality using the Validation Object.

CORRECTIVE ACTION AND TROUBLESHOOTING

Corrective action measures can be established, reviewed, and approved before data collection. Each QC/QA activity can have an error resolution associated with it.

Error resolution logs are established when QC/QA checks do not meet acceptance criteria. Many DOTs report having error logs, though they typically only use them for data acceptance checks. Error logs, including error resolutions, can be kept for all data quality activities. CTDOT (2018) states in their DQMP that error logs are maintained throughout the entire (data collection) process: beginning with data collection, during quality control, and during post (data) processing. Using error resolution logs is critical to ensure any data that does not meet the established acceptance criteria is tracked until it is resubmitted and accepted. Oregon DOT (2018) reports tracking and reporting errors for QC/QA and quality acceptance in logs. QC/QA logs include delivery and resolution data, as shown in Table 13. These logs are separate from quality acceptance logs, though the content in each log is similar. DOTs can receive all QC/QA error logs from data collection teams to resolve any errors appropriately.

Table 13. Example of QC/QA logs adapted from Oregon DOT 2018 DQMP.

Deliverable Name	Delivery Date	Status/Findings	Resolution	Resolution Date
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

- No Data

SUCCESSFUL CASE STUDIES

Specific case studies of DOTs implementing successful QC/QA practices are included in this section.

Maryland DOT

Maryland DOT (2018) self-collects network-level PSC data. Their DQMP includes detailed tables for quality management activities specific to data collection equipment checks, pavement condition metrics, and collected imaging, inventory, and other data. Validation and verification checks are performed at control sites. Each table includes the following elements:

- Standard procedure.
- Responsible party.
- Purpose.
- Frequency.
- Acceptance criteria.
- Error resolution.

Adaptions of these tables are shown in Table 14, Table 15, and Table 16. Other DOTs implement similar tables. The referenced vehicle and equipment are based on Maryland DOT‘s 2018 DQMP, and the responsible parties in Table 14, Table 15, and Table 16 are described as follows:

- The Data Processing Team (DPT) is responsible for the processing, updating, managing, developing, and QC/QA of construction data and post-processing routines of collected data and imagery.

- The Data Warehouse Team (DWT) is responsible for the management of PM databases and the integration of data with databases administered by others. It provides support to other PM teams to facilitate the production and processing, quality control, analysis, and reporting of data.
- The Data Analysis Team (DAT) is responsible for the analysis of pavement management data. This analysis includes the projection of the pavement network condition, the optimization of maintenance and rehabilitation strategies, as well as the reporting of pavement management data, including State-wide public reports and state reporting, and subsequent federal reporting by planning divisions.
- The Field Explorations Division (FED) is responsible for all pavement field data collection activities. Along with daily data collection, the FED handles equipment calibration, validation, verification, maintenance, and QC of the collected data.
- Pavement Management Assistant Division Chief (PM ADC).

Table 14. Summary table of procedures for the quality management of data collection equipment adapted from Maryland DOT 2018 DQMP.

Procedure	Responsible Party	Purpose	Frequency	Acceptance	Error Resolution
ARAN Preventive Maintenance Service	Manufacturer (Fugro Roadware Inc.)	Perform various preventive maintenance activities of the ARAN vans, including calibration and quality checks such as: • DMI calibration. • Inertial Profiler – Block Check. • Inertial Profiler Static/Bounce Test. • Reverse Runs to Verify Roll, Pitch, and Heading.	Once a year, before the start of the annual data collection program.	• DMI – difference between runs < 0.3 pulses per meter. • Block Check criteria from AASHTO R57. • Static/Bounce Test criteria: maximum IRI < 0.1 inches/mile during static portion and 0.5 inches/mile during bounce portion (average during bounce should be less than 0.4 inches/mile). • The difference of absolute value for pitch and roll should be within +/- 0.4%.	• DMI Calibration is repeated; if still not within tolerance, remedial actions involving inspection and possible replacement of hardware components. • HSIP's lasers investigated and possibly replaced. • Static/Bounce Test repeated until passing result achieved; accelerometers investigated and possibly replaced. • A repeat of reverse runs and adjustment of frame angles performed.
Test Loop – Before Data Collection Program	Manufacturer (Fugro Roadware Inc.), FED, DAT, DPT and PM ADC	Validation of all data elements produced by the ARAN system through analysis of data collected from 10 runs on the 45 sections of the 13.1 mile-long Test Loop. Analysis and acceptance of Test Loop Data are conducted within 5 days. Results are transmitted to all involved parties.	Once a year, before the start of the annual data collection program.	Pavement surface images: • Correct aspect ratio. • Interval is 0.004. • no overlap or gap between left and right images. • Metrics (IRI, Rut, Faulting, Cracking) within the following range: Current year's predicted value ± (last year's 95th percentile – last year's 5th percentile)/2.	• Test Loop QC Report is generated with a description of results. • An investigation into possible causes of flagged data may result in the recalibration of sub-components and repeat collection of the Test Loop. Survey van does not collect data until it passes all acceptance criteria.

Procedure	Responsible Party	Purpose	Frequency	Acceptance	Error Resolution
Test Loop - During Data Collection Program	FED, DAT, DPT and PM ADC	• Verify that ARAN system components are within calibration standards through analysis of data collected from 3 runs on the 45 sections of the 13.1 mile-long Test Loop. • Analysis and acceptance of data are conducted within 5 days of collection. Results transmitted to all involved parties.	Every 3 to 4 weeks, during the annual data collection program.	Pavement surface images: • Correct aspect ratio. • Interval is 0.004. • a. no overlap or gap between left and right images. • Metrics (IRI, Rut, Faulting, Cracking) within the following range: Current year's mean value from the initial collection of Test Loop ± (last year's 95th percentile – last year's 5th percentile)/2.	Test Loop QC Report is generated with a description of the result. An investigation into possible causes of flagged data may result in the recalibration of sub-components and repeat collection of the Test Loop. Survey van does not collect data until it passes all acceptance criteria. All data collected since the last passing Test Loop testing are subject to further review.
ARAN DMI Calibration	FED	Adjust the calibration factor on 1-mile-long calibration sites.	Every 3 to 4 weeks, during the annual data collection program.	DMI calibration factors for 3 runs must agree within 0.1 percent.	Remedial actions involving inspection and replacement, if necessary, of hardware components.
Daily QC - Before Data Collection Runs	FED	• Confirm functionality of ARAN sub-components. • Confirm appropriate environmental conditions. • Conduct a safety vehicle check. • Cleaning of apertures and lenses before starting the data collection runs for the day.	Daily, during the annual data collection program.	• Proper tire pressure. • The successful connection with all subcomponents. • Images are of acceptable quality. • Safe functioning of the vehicle. • Dry pavement surface, not excessive winds, temperatures within operational range for equipment.	Data collection of affected ARAN van is suspended until issues are resolved. Remedial actions involving the investigation of sub-components.

Procedure	Responsible Party	Purpose	Frequency	Acceptance	Error Resolution
Daily QC - During Data Collection Runs	FED	• Confirm functionality of ARAN sub-components. • Confirm appropriate environmental conditions. • QC of data elements during the data collection runs for the day.	Daily, during the annual data .collection program.	• Images of acceptable quality. • Data elements are completely populated. • Measurements within a reasonable range of value and consistent with the driven road. • Dry pavement surface, not excessive winds, temperatures within operational range for equipment.	• Data collection of affected ARAN van is suspended until issues are resolved. Remedial actions involving the investigation of sub-components. • Collected data for the day to be recollected upon the decision of FED TL.
Daily QC - After Data Collection Runs	FED	QC of ROW and pavement images, and IRI measurements collected for the day.	Daily, during the annual data collection program.	Visual inspection of data to confirm that: • GPS map indicates the correct location of collected data. • Measurements are reasonable and complete. • ROW and pavement images are of acceptable quality.	• Data collection of affected ARAN van is suspended until issues are resolved. Remedial actions involving the investigation of sub-components. • Collected data for the day to be recollected upon the decision of FED TL.

Table 15. Summary table of procedures for the quality management of PSC metrics adapted from Maryland DOT 2018 DQMP.

Procedure	Responsible Party	Purpose	Frequency	Acceptance	Error Resolution
ARAN Data QA Upon Receipt	FED	• IRI completeness check. • Data collection speed check. • ARAN daily settings check.	Every data batch received (typically containing 4-5 days of data) during the annual data collection season.	• At least 85% of the IRI values are not missing for each run • Data collection speed > 35 mph • ARAN settings for each data collection date should be as expected.	Sections not passing QA checks are flagged for further investigation, possibly leading to re-collection based on factors such as mileage for re-collection, the importance of section, and others.
LCMS Processing Review	DPT	Review of processing results to check pavement image quality and reasonableness of crack length values on flexible pavements.	Every data batch received (typically containing 4-5 days of data) during the annual data collection season.	• Pavement images are of acceptable quality. • "Crack" field has minimal zero values for sections with identified cracks. • "Lane Width" field has no zero values. • "Crack Detection" values are greater than half of the "Length" values.	Data with unacceptable images or crack length values are reprocessed; if issues continue to arise, re-collection may be necessary. Re-collection requests are sent via email to FED's Pavement Testing Team Leader.
Rut Processing Review	DPT	Review of processing results to check the reasonableness of rutting values and TPPs.	Every data batch received (typically containing 4-5 days of data) during the annual data collection season.	Transverse Profile and Rut Depth values are deemed reasonable by the reviewer through visual inspection of graphs and longitudinal plots.	Data with unacceptable rutting values are reprocessed; if issues continue to arise, re-collection may be necessary. Re-collection requests are sent via email to FED's Pavement Testing Team Leader.
IRI Change in Speed Adjustment	DPT and DWT	Address IRI anomalies caused by changes in the speed of survey vans by applying correction equations.	Every data batch received (typically containing 4-5 days of data) during the annual data collection season.	If the percent adjustment from the equations < 8% of the original IRI value, the original value is reported as-is.	IRI values obtained from data collection speeds < 15 mph are rejected. If collection speed > 15 mph and percent adjustment from the equations > 8% of the original IRI value, the adjusted IRI value is reported.

Procedure	Responsible Party	Purpose	Frequency	Acceptance	Error Resolution
4 Phase Study	DAT and DWT	Flag sections with outlier IRI values and investigate sources of error.	Once a year, after all IRI data have been collected and processed.	IRI value for a section is flagged if the difference between the "3 Standard Deviation" value and the absolute difference is negative.	Flagged sections without valid explanations (e.g., recent construction activities or data collection lane changes) will be recollected. Re-collection requests are sent via email to FED's Pavement Testing Team Leader.
QA of Distress Data on Rigid Pavements	DPT	Perform QA checks on the distress data manually assessed on rigid pavement surfaces through visual inspection of images.	Once per week during the annual data collection season.	Supervisor reviews 5% of the manually assessed runs to check for: • Wrongly identified distresses or markers. • Missing distresses or markers. • Wrong assignment of surface type.	The supervisor makes corrections on the spot and resolves any significant issues with the reviewer before production resumes.
Review of Pavement Condition Metrics in HPMS data deliverables	DAT and PM ADC	Perform final QA checks on distress data elements in HPMS Sample and Full-Extent tables before delivery to MDOT DSD for further submission to FHWA.	Once a year after all data have been collected and processed.	Flag data for further investigation if: • Sections have missing data. • Rating groups have changed by> 1% compared to the previous year. • State-wide mean values for IRI, cracking percent, rutting, and faulting have changed by > ±2% in comparison to the previous year.	An investigation into possible causes to explain missing data and higher than expected differences in metrics respect to the previous year. Identified causes may result in the reprocessing of data to reduce the amount of missing or anomalous data.
ARAN Data QA Upon Receipt	FED	Check for completeness and proper quality through visual inspection of 100% of both ROW and Pavement images collected with ARAN	Every data batch received (typically containing 4-5 days of data), during the annual data collection season.	Flag sections with ROW or pavement images missing or presenting abnormalities, such as improper lighting or spots.	Sections with flagged images are to be recollected upon the decision of FED TL.

Procedure	Responsible Party	Purpose	Frequency	Acceptance	Error Resolution
QA of Inventory Location Data	DPT	Check for accuracy of starting and ending route collection points.	Every data batch received (typically containing 4-5 days of data), during the annual data collection season.	Flag starting and ending route collection points in inventory list with latitude and longitude coordinates differing by > 22.18 feet of the closest GPS coordinate collected by the ARAN vans.	Correct all flagged starting and ending route collection points in the inventory list.
Adjustment of Linear Referencing	DWT and DAT	Apply adjustment to starting and ending section points based on a comparison between collected GPS data and historical inventory data.	Once a year, after all, data have been collected and processed.	Starting and ending section coordinates with higher than expected differences concerning historical inventory data are flagged. Comparisons are performed every 4 mm.	All flagged starting and ending section coordinates are adjusted.
Business Plan Table QC	DWT	Review of the updated Business Plan Tables to confirm the accuracy and completeness of inventory data.	Once a year, after all, data have been collected and processed.	• Total lane mileage with pavement data less than 50 miles different than previous year's mileage. • Total lane mileage of treated sections is as expected, as decided by reviewer considering last year's mileage of treated sections and current year's allocated budget.	An investigation into possible causes of higher than expected differences. Identified causes may lead to the reprocessing of data.
Review of Inventory Items in HPMS Data Deliverables	DAT and PM ADC	Perform QC /QA checks on inventory data elements of HPMS Sample and Full Extent tables before delivery to MDOT DSD for further submission to FHWA.	Once a year, after all, data have been collected and processed.	Data are flagged if: • Total lane mileage by surface type has changed more than 1% in comparison to the previous year. • Total lane mileage by "last construction date" field and other inventory data types are within +/- 10 miles of the previous year.	An investigation into possible causes of higher than expected differences. Identified causes may lead to the reprocessing of data.

Table 16. Summary table of procedures for the quality management collected imaging, inventory, and other data adapted from Maryland DOT 2018 DQMP.

Procedure	Responsible Party	Purpose	Frequency	Acceptance	Error Resolution
ARAN Data QA Upon Receipt	FED	Check for completeness and proper quality through visual inspection of 100% of both ROW and Pavement images collected with ARAN.	Every data batch received (typically containing 4-5 days of data), during the annual data collection season.	Flag sections with ROW or pavement images missing or presenting abnormalities, such as improper lighting or spots.	Sections with flagged images are to be recollected upon the decision of FED TL.
QA of Inventory Location Data	DPT	Check for accuracy of starting and ending route collection points.	Every data batch received (typically containing 4-5 days of data), during the annual data collection season.	Flag starting and ending route collection points in inventory list with latitude and longitude coordinates differing by > 22.18 feet of the closest GPS coordinate collected by the ARAN vans.	Correct all flagged starting and ending route collection points in the inventory list.
Adjustment of Linear Referencing	DWT and DAT	Apply adjustment to starting and ending section points based on a comparison between collected GPS data and historical inventory data.	Once a year, after all data have been collected and processed.	Starting and ending section coordinates with higher than expected differences concerning historical inventory data are flagged. Comparisons are performed every 4 mm.	All flagged starting and ending section coordinates are adjusted.
Business Plan Table QC	DWT	Review of the updated Business Plan Tables to confirm the accuracy and completeness of inventory data.	Once a year, after all data have been collected and processed.	• Total lane mileage with pavement data less than 50 miles different than previous year's mileage. • Total lane mileage of treated sections is as expected, as decided by reviewer considering last year's mileage of treated sections and current year's allocated budget.	An investigation into possible causes of higher than expected differences. Identified causes may lead to the reprocessing of data.
Review of Inventory Items in HPMS Data Deliverables	DAT and PM ADC	Perform QC /QA checks on inventory data elements of HPMS Sample and Full Extent tables before delivery to MDOT DSD for further submission to FHWA.	Once a year, after all data have been collected and processed.	Data are flagged if: • Total lane mileage by surface type has changed more than 1% in comparison to the previous year. • Total lane mileage by "last construction date" field and other inventory data types are within +/- 10 miles of the previous year.	An investigation into possible causes of higher than expected differences. Identified causes may lead to the reprocessing of data.

Oregon DOT

Oregon DOT (2018) uses a vendor to collect PSC data. Oregon DOT assigns all QC responsibilities to the data collection vendor. However, Oregon DOT requires that the data collection vendor submit a QC work plan that includes the minimum requirements in Table 17. Establishing minimum QC requirements and requiring the data collection vendor to prepare and implement a plan that meets those requirements assures the DOT that the data is being collected according to their program needs. It is important that the DOT review QC reports throughout data collection to verify the plan is being implemented. It was not evident in the DQMP whether Oregon DOT required the contractor to include corrective action and error resolution. Note that "validation runs" occur at established control sites.

Table 17. QC requirements adapted from Oregon DOT 2018 DQMP.

Deliverable	Quality Expectations	Activity	Frequency
Vehicle Configuration	• Profiler, crack measurement system, location referencing, and cameras meet requirements. • Tire pressure check. • Bounce and block tests, crack measurement system height check, and photo imagery review.	Check	Pre-collection
Vehicle Configuration	• Inspect and clean laser apertures, windshield, and cameras. • Inspect hardware and mountings. • Verify test signals are received by the on-board computer. • Verify all components are working properly.	Check	Daily
Vehicle Configuration	• Perform calibration checks.	Check	Weekly
Vehicle Configuration	• Image lane placement. • Image focus, color, luminance quality. • Monitor collection system errors. • Data completeness.	Check	During collection
DMI Pulse Counts	• ≤ 0.1% difference (multiple runs).	Validate	Pre-deployment
IRI	• Bounce test ≤ 3 inches/mile (static) and ≤ 8 inches/mile (dynamic). • Block check ± 0.01 inch of appropriate height. • ProVAL cross-correlation repeatability score ≥ 0.92 (5 runs).	Validate	Pre-deployment and Weekly
Rutting	• ± 0.05 inch (3 runs).	Validate	Pre-deployment and monthly
Faulting	• ± 0.06 inch (3 runs).	Validate	Pre-deployment and monthly
Distress	• Std. dev. ≤ 10 percent (3 runs and/or historical average).	Validate	Pre-deployment and monthly

Deliverable	Quality Expectations	Activity	Frequency
Data Reduction	• Review sample images for clarity, color, and luminance • Review bounce test output. • Review power spectral density anomalies. • Process and review samples of the crack measurement system for anomalies. • Post-process all GPS data.	Validate	Daily
Data Reduction	• Confirm route start and stop points. • Confirm data completeness. • Confirm images meet requirements. • Adjust unacceptable images. • Check crack measurement system data for null and invalid values. • Calibrate automated distress algorithms. • Manual review and correction of automated distress extraction results when image analysis computer software is in error. • Review distress data for consistency between raters. • Perform data reasonableness checks.	Check	Daily during collection
Data Delivery	• Confirm correct LRS coding and lane. • Milepoint ± 0.03 mile of the actual location. • Confirm the correct pavement type. • Confirm images meet quality requirements. • Confirm events marked as required. • No missing values without valid exclusion and reason codes. • IRI: $20 \leq IRI \leq 800$ inches/mile. • Rutting: $0.00 \leq Rut \leq 2.00$ inches. • Faulting: $0.00 \leq Fault \leq 1.00$ inches. • Distress within range.	Check	Before data submittal

ROLES AND RESPONSIBILITIES

At a minimum, DOTs using vendor-collected PSC data can review and approve vendor QC/QA plans. They can include minimum requirements in the scope of work (SOW) documents. DOTs can review and track all QC/QA reports and error logs to ensure resolutions are completed.

REPORTING AND RECORD-KEEPING

All QC/QA activities can be recorded and submitted to DOTs for approval. The reports can include the acceptance requirements and clear results of whether the data passes or fails. Any data that fails can have an associated error resolution log. This information can be kept in a database so that it is available for troubleshooting if any issues arise during quality acceptance activities.

In addition to the more general items discussed above, the following may be included in QC/QA reports (Pierce et al., 2013):

- Equipment and personnel used during data collection.

- Documentation of initial and continuing calibration checks and maintenance for equipment.
- Equipment issues and actions taken.
- Schedule adherence and the reasons for any changes.
- Documentation of collection procedures and protocols used.
- Reporting any variances in standard operating procedures or changes in collection methods in the field.
- Reporting of all control, verification, and blind site testing and results.
- Documentation of all QC activities.
- Analysis of intra or inter-rater comparisons.
- Log all quality issues identified through QC activities and corrective actions taken.
- Copies of all correspondence.

CHAPTER 7. DATA EVALUATION, MANAGEMENT, AND REPORTING

INTRODUCTION

This section provides successful practices and examples of acceptance activities after data collection. Data evaluation after data collection can be performed by DOT, third-party personnel, or personnel independent of the data collection team.

ELEMENTS OF SUCCESSFUL DATA ACCEPTANCE PROCEDURES

DOTs have procedures established for accepting data. Based on the current DQMP reviews on the FHWA-approved DQMPs in 2018 and 2019, successful practices for data sampling, reviewing, checking, and acceptance criteria include the following procedures:

- Database checks, including proper data format, missing format, completeness, consistency, and range, and identification of expected values and allowable ranges for each collected metric and flag data outside the ranges.
- Image and video checks clarity, brightness, completeness, and proper image stitching.
- Determination of the adequate sample size of the reviewed data as a representation of the entire network.
- Identification of acceptance criteria.
- Data evaluation using statistical analysis methods to compare and verify results for acceptance.
- Corrective action when data does not meet acceptance criteria.
- Year-to-year or historical data checks.

These elements are further described in the following sections.

DATA ACCEPTANCE REVIEW CHECKS

PSC data may contain measurement errors, and the possible causes include random variation, missing values, or data formatting issues. This section provides procedures for review checks for data acceptance based on successful practices, and data acceptance can be independent of the party responsible for collecting the data.

Frequency and Sample Size for Data Evaluation

PSC data are typically delivered in partial batches throughout the data collection season. Immediate review of data upon receipt of each batch minimizes the time between batches and reduces the potential for data reprocessing or re-collection. Based on DQMP results, most DOTs receive batches of data for review daily, weekly, or somewhere in between. Many DOTs report using automated tools for data review and error resolution. DOTs can develop and use automated or semi-automated tools as much as possible to flag, report, and record data issues and their error resolution. Data errors can be communicated immediately with the data collection team to improve troubleshooting and avoid further data collection with the same potential for errors.

Many DOTs report acceptance review checks on 100 percent of the collected data using automated methods. Some DOTs report review checks of 100 percent of the collected data but do not specify if the processes are automated. Based on DQMP reviews, 100 percent checks are typically performed for IRI, rutting, and faulting metrics. DOTs that use labor-intensive acceptance review checks may find reviewing 100 percent of collected data uneconomical. The most labor-intensive checks reported in DOT DQMPs were image checks. Manual image checks typically only represent a subset of data. For instance, Maryland DOT (2018) reports using automated checks for data reasonableness on 100 percent of images. These automated checks include flagging data with zero values or crack lengths greater than the roadway length values. Alternatively, QA checks on distress data that are manually assessed have a sample size of 5 percent. DOTs can use automated processes as much as possible to maximize the sample size for review checks. For manual review checks or labor-intensive review checks, DOTs can evaluate sample size based on the following factors (FHWA 2018):

- Size of network.
- Experience with data collection vendor.
- Risk tolerance.
- Variability of surface types and distresses.
- Cost.

DOTs can include their justification of sample size in their DQMPs. Generally, the sample size for manual or labor-intensive data review checks ranges from 2 to 20 percent (FHWA 2018).

Analysis Methods for Data Acceptance Review

Review checks and acceptance criteria for collected pavement data can be developed for each data metric. Data review checks conducted by DOTs can be quantitative, such as checking that IRI values are within an acceptable range, and qualitative, such as visually checking that collected pavement surface images are not excessively bright or dark. This section focuses on quantitative data review procedures.

Based on DQMP reviews, an analysis method frequently used by DOTs for data acceptance review is the percent within limits (PWL) method. This statistical analysis method compares the percent of reported values within an acceptable range to an acceptable PWL. For example, Table 18 shows a subset of the data acceptance checks, with their respective acceptance PWL and error resolution procedure, adapted from the Oklahoma DOT’s (2018) DQMP. Note that the table describes different cracking levels specific to Oklahoma DOT’s data definitions, which may not apply to all DOTs.

Table 18. Oklahoma DOT's data acceptance checks (2018).

Deliverable and Quality Expectations	Acceptance PWL	Acceptance Testing	Action if Criteria Not Met
• **Asphalt Concrete (AC) Distress data within an acceptable range** • **Individual distresses and the sum of distresses to match section length or area**	95%	• Transverse cracking (levels 1 through 4). • Alligator cracking (levels 1 through 3 and summation of all levels). • Miscellaneous cracking (levels 1 through 3 and summation of all levels). • AC patching. • Raveling.	AC Distress data within an acceptable range
• **JCP Distress data within an acceptable range** • **Individual distresses and the sum of distresses to match section area or number of slabs or joints**	95%	• Number of joints. • Transverse cracked slabs (levels 1&2). • Longitudinally cracked slabs (levels 1&2). • Multi-cracked slabs (levels 1&2). • Total number of slabs affected by any types or level of cracking. • Joint Spalling (levels 1&2). • Joint D-cracking (levels 1&2). • Total of all types and levels of joint distress. • Patching (AC and PCC). • Corner Break (levels 1&2).	Correction or Re-Process
• **CRCP Distress data within an acceptable range** • **Individual distresses and the sum of distresses to match section length or area**	95%	• Number of Joints should be zero. • Longitudinal cracking (levels 1&2 and summation of all levels). • Punchouts (levels 1 through 3, and summation of all levels). • Patching (AC and PCC).	Correction or Re-Process
Longitudinal AC patch to be considered AC pavement with corresponding distress	100%	Maximum AC Patch Length five or more consecutive records where the AC patch area is greater than 600 square feet.	Correction
Match number of railroad crossings from Oklahoma DOT Inventory data	90%	Number of Railroad Crossings.	Correction
Match number of bridges from Oklahoma DOT Inventory data	90%	Number of Bridges.	Correction
Distress data matching pavement surface type	100%	Checks of Non-Matching Distress Types.	Correction or Re-Process

Another acceptance tool is the temporal check. This check type involves comparing the collected data against the values reported for the previous year (or years) at the corresponding pavement section (or set of sections). This check evaluates if the change in the data metric's value over time is within an acceptable range. As an example, Maryland DOT (2018) flags HPMS condition metrics data if the change in percent “Good,” “Fair,” or “Poor” (as defined by FHWA regulation) changed by more than 1% with respect to the HPMS deliverable submitted for the previous year (extracted from their DQMP). Similarly, Maryland DOT flags HPMS condition metrics data if the Statewide mean values (for IRI, cracking percent, rutting, and faulting) vary by more than 2% compared to the value from the previous year. SDDOT uses a temporal check for acceptance, detailed in the case studies below.

A possible analytical method to evaluate the temporal change of a data element accounting for the variability of the data is the t-test:

- A paired t-test is used when it is possible to identify the value reported for the previous year at the same location,
- An independent t-test is used when comparing aggregated summary statistics (e.g., at the route, regional, or state level).

T-tests were previously described in chapter 4. This analysis can be performed in standard statistical analysis software packages. Information about paired or independent t-tests for either continuous (e.g., IRI value) or proportion (e.g., percentage of Good pavements) variables can be found in Devore et al. (2015).

DOTs may use other statistical analysis methods for data evaluation and can include information regarding their methods in their DQMPs.

Analysis Criteria for Acceptance Review Checks

Setting acceptance criteria for collected pavement data is a topic of ongoing research. Acceptance criteria for the review checks of collected pavement data are typically set based on the following:

- Prior knowledge of the data—such as the expected range of values for a given metric.
- Specification requirements from data applications and deliverables—such as requirements for data submittal to FHWA’s HPMS
- Error resolution criteria—such as a large difference in surface condition measurement data between wheel paths collected using a 3D system- may indicate the two sensors having technical issues.
- The requirement is from pavement management system software or other software—such as input data format.

The acceptance criteria of measurement methods testing data can be determined—when a standard specification is unavailable–considering the data's intended use. PSC data is used in many pavement management applications—such as forecasts and budget estimations. Data not passing the acceptance criteria is subject to further investigation through error resolution procedures outlining the steps to address the issues. Outcomes from the investigation of flagged data allow for identifying the source of the data issues, such as a faulty component of the measurement equipment, differences in rating criteria among raters, or incorrect data processing procedures. Error resolution procedures (discussed at the end of this chapter) include corrective action, such as reprocessing or recollecting the rejected data.

Figure 30 shows three review checks reported in DOT DQMPs on collected pavement data, along with examples for each type of check.

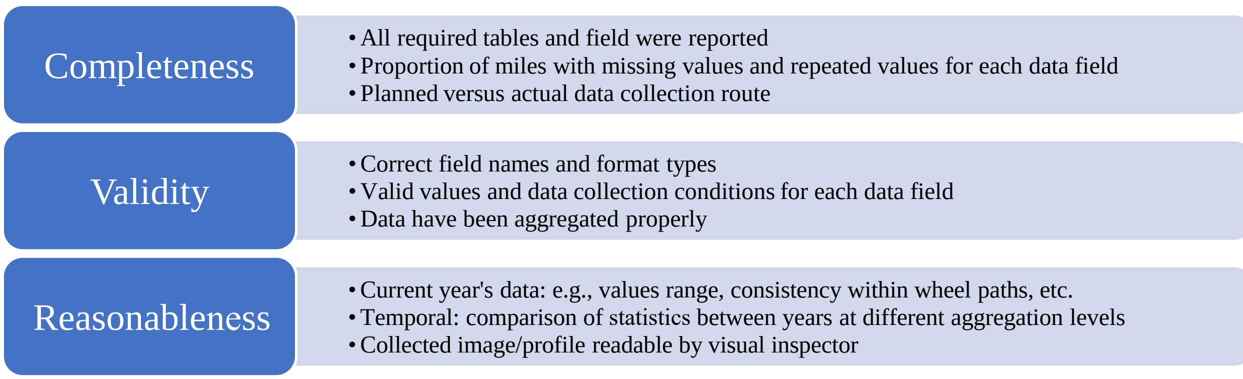


Figure 30. Chart. Typical types of review checks conducted by State agencies on collected pavement data.

The following includes details of three types of review checks and an example.

Completeness Checks

This group includes checks to detect and quantify the extent of missing values for each field in the collected pavement data. Complete datasets can be described relative to the mileage collected in the batch under review or the mileage planned for the batch. For example, suppose the batch under review contains the data collected for an entire county. In that case, the planned mileage is known, and consequently, the completeness of the batch can be estimated relative to the total mileage of the county. On the other hand, if the partial batch under review contains data collected within a period (without a planned mileage), the completeness of the batch may more conveniently be estimated relative to the total mileage in the batch. Another aspect to consider when quantifying the extent of missing data in the batch for a given field is to make the computations, including only those surface types for which the field is valid. For example, the portion of missing faulting data can be computed relative to the total mileage of JCPs only.

Validity Checks

This group includes checks to detect and quantify the extent of invalid values reported for each field in the collected pavement data. Valid values are described for each field as follows:

- formatting requirements (e.g., acceptable data collection years are four-digit numeric values).
- defined coding system (e.g., a given State agency may describe possible surface types as either “ACP,” “CRCP,” or “JCP” only).
- certain numeric limits (e.g., valid HPMS Cracking Percent values range between 0 to 100).

Consequently, a consistent way of quantifying the extent to which data values are valid is relative to the mileage with reported values. The following list provides a few examples of validity checks along with their corresponding acceptance criteria extracted from different DOT's DQMPs:

- Pavement surface data collected using a high-speed measurement system: flag data with collection speed > 35 mph for further investigation (note that DOTs may choose a more appropriate collection speed threshold specific to their network).
- Consistency of condition data by surface type: faulting is reported on jointed concrete (not asphalt) pavements only, and rutting is reported on asphalt (not concrete) pavements.
- Surface imagery: flagged if not collected in the proper lane.
- Data collection conditions: flag data if the air temperature during data collection was lower than 40° F or higher than 100° F or if the surface was wet.

Reasonableness Checks

This group includes checks to flag those reported data values that—though valid—may be outside the reasonable, or expected, set of values. Examples of reasonableness checks commonly conducted by DOTs include range checks, consistency checks, and temporal checks. These checks are conducted on the non-missing, valid data. Consequently, a consistent way of quantifying the extent to which data values are considered reasonable is relative to the mileage with reported valid values. The following list provides reasonableness checks along with their corresponding acceptance criteria extracted from different projects and State's DQMP documents:

- Reasonable roughness values: 95 percent within the limit of an IRI range of 30 to 400 inches/mile.
- Consistency across condition metrics: if IRI is low, then the cracking values are also low, and if IRI is high, then the cracking values are also high.
- Temporal changes in section-level surface condition data: flag cracking and other distresses if they present a 25 percent increase or decrease for any 0.1-mile section or pavement management section from the previous year's collection.
- Temporal changes in state-wide statistics of surface condition data: flag data if state-wide mean values for IRI, cracking percent, rutting, and faulting have changed by more than ±2% compared to the previous year.
- Temporal changes in inventory data: flag data if total lane mileage by surface type has changed more than 1% compared to the previous year.
- Location data: flag starting and ending route collection points in the inventory list with latitude and longitude coordinates differing by more than 22.18 feet from the closest GPS coordinate collected by the data collection vans.

Total mainline lane miles of missing, invalid, or unresolved sections for data submitted under the FHWA rule shall be limited to no more than five percent of the total lane miles. For each pavement section without condition metrics, DOTs shall note in the HPMS submittal with a specific code (as noted in the HPMS manual) as to why the data was not collected.

Example: FHWA Interstate Highway Pavement Sampling Project - Review Checks

This section provides an example of two review checks conducted on pavement data for acceptance of the collected batch. The data batch for these examples was collected as part of the FHWA "Interstate Highway Pavement Sampling" study (Simpson et al. 2020). This batch contained 2,425.4 miles of HPMS pavement data collected on 3 Interstate highways (I) across 13 states. The completed list and description of review checks conducted on these collected pavement data can be found in Simpson et al. (2020).

Figure 31 shows the collected mileage for different state routes. The stacked bars indicate three portions of data: 1) Yellow (and cross-hatch): reported with "events" (i.e., section marked due to either being on a bridge, lane deviations, or construction areas), 2) Green (and diagonal stripe): reported without event, and 3) Red (and polka dot): not collected. Three state-route data for this batch were completely missed, while two had a significant portion of not reported data. Furthermore, the reported data with events was relatively large for some state-route combinations, such as I10-LA and I10-TX. The flags were detected by the project team soon after receiving the data batch through an automated tool written by the project team. The results were communicated immediately to the data collection team. These flags, as well as other flags in the batch, were addressed by the contractor either by proving that flagged data was correct (e.g., images showing that sections with marked events were correctly labeled) or by reprocessing or recollection of data.

Table 19 shows the proportion of flagged data along with the label and description of different review checks—including completeness, validity, and reasonableness checks—conducted on the collected data batch, sorted by the proportion of flagged data in descending order. Data fields with less than 0.1% of flagged data were accepted—i.e., a 99.9% acceptable PWL was adopted. Consequently, seven review checks did not pass the acceptance criterion. The fields with failing review checks were related to the data collection speed, IRI, and rut depth. Each of these data flags was communicated to the data collector team, who addressed these issues by either proving that the flagged data was correct or by reprocessing and resubmitting the flagged data.

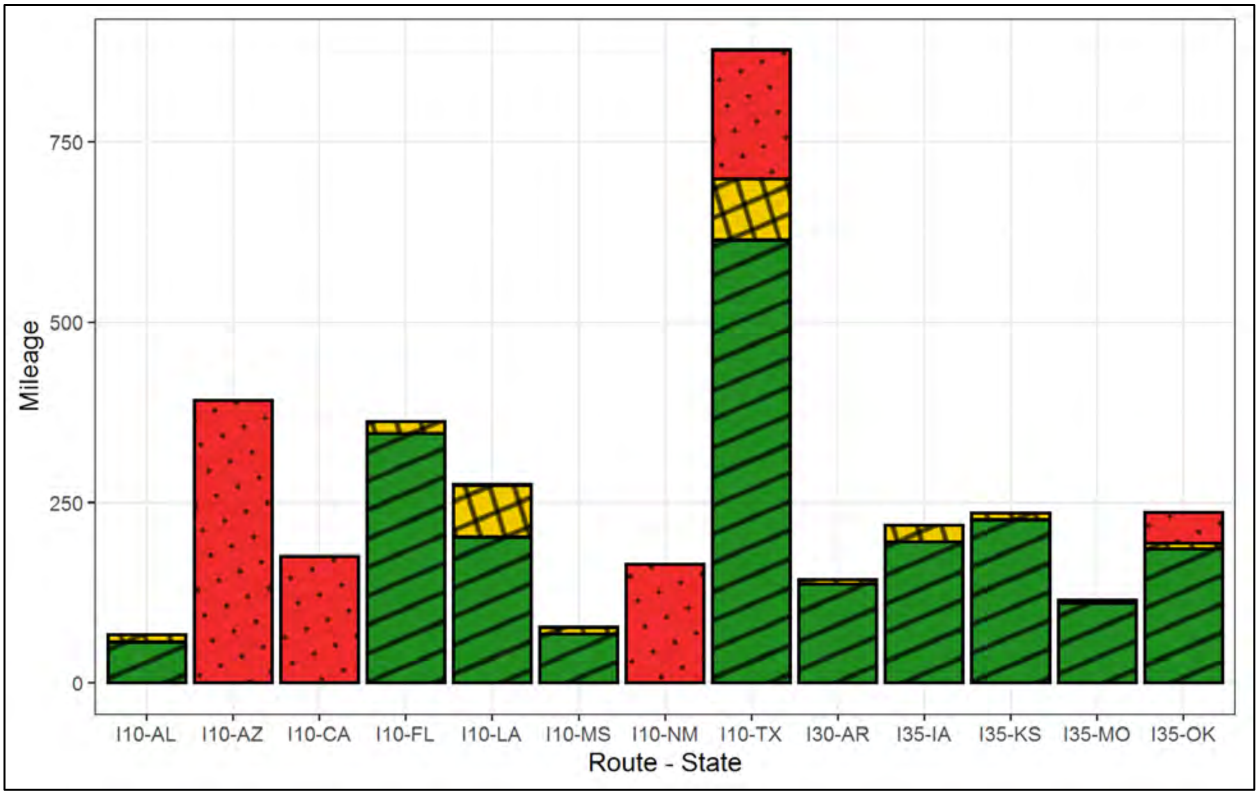


Figure 31. Chart. Collected mileage in data batch color-coded by missing, reported with, and without events.

Table 19. Results from Review of Collected Pavement Data in Partial Batch

Check Label	Percent Flagged	Check Description
Speed_QC range	50.4	data collection speed either < 40 mph or > 65 mph
IRI_any_QC range	34.9%	any IRI measure either < 40 inches/mile or > 250 inches/mile
IRI_left_QC range	26.5%	left IRI either < 40 inches/mile or > 250 inches/mile
IRI_right_QC range	24.8%	right IRI either < 40 inches/mile or > 250 inches/mile
IRI_mean_QC range	23.4%	mean IRI either < 40 inches/mile or > 250 inches/mile
IRI_QC consistency	4.9%	difference between left and right IRI ± 50 inches/mile
Rutting_QC consistency	1.5%	difference between left and right rutting ≥ 0.25 inches
Condition_QC missing	0.1%	at least one condition variable with missing values
IRI_QC missing	0.1%	missing IRI values
Fault_QC missing	0.0%	missing faulting values
Fault_QC range	0.0%	mean faulting either < 0 inches or > 1 inches for JCP

Check Label	Percent Flagged	Check Description
Crack_QC range	0.0%	cracking percent either < 0% or >60% if ACP or >100% if rigid
Rutting_any_QC range	0.0%	any rutting measure either < 0 inches or > 1 inches for ACP
Rutting_left_QC range	0.0%	left rutting either < 0 inches or > 1 inches for ACP
Rutting_right_QC range	0.0%	right rutting either < 0 inches or > 1 inches for ACP
Rutting_QC missing	0.0%	missing rutting values
Inventory_QC missing	0.0%	at least one inventory variable with missing values
Crack_QC missing	0.0%	missing cracking percent values
Rutting_Average_QC range	0.0%	mean rutting either < 0 inches or > 1 inches for ACP
Surface_type_QC range	0.0%	surface type other than ACP, JCP or CRCP
Air_temp_QC range	0.0%	air temperature either < 40˚ C or > 100˚ C
Surface_temp_QC range	0.0%	surface temperature either < 20˚ C or > 130˚ C
Fault_QC consistency	0.0%	faulting on a surface other than JCP
Rutting_surface_QC consistency	0.0%	rutting on a surface other than ACP

Image Checks for Acceptance

Acceptance processes can include image checks. Image checks were previously described in chapter 4 under certification procedures. These quality checks occur after data is collected. DOTs may use the same criteria they establish for certification but can also check for missing images, image completeness, and proper stitching of images. The following data acceptance tests and image checks are reported by South Carolina DOT (SCDOT). SCDOT (2018) reports having an Image Engineer who reviews 25% of delivered images according to the following criteria:

- Image Clarity – Images should be clear, and highway signs can be easily read. Most highway distresses should be evident in all views, and there should be minimal or no debris in the camera's viewing path.
- Image Brightness/Darkness – Images are not to be collected during hours when it is too dark (rule-of-thumb: if street lights or security lights are on, then it is too dark). It has been found that during poor lighting conditions, the images become grainy and seem out of focus, resulting in a "blackout," which can cause a control section to be rejected. Also, if the data collection occurs just before a rainstorm, the dark clouds do not allow the proper amount of light to enter the camera, and images may be of poor quality.
- Missing Images – There should be no more than 5 percent missing images.
- Image Completeness – All images were delivered relating to the collection cycle.
- Image Replay – Images should be played sequentially and in the correct order. The data collection vehicle should give the impression that it travels forward.

Successful Case Studies for Data Evaluation

Oregon DOT

Oregon DOT (2018) uses a data collection vendor and includes the following procedure in their DQMP for data sampling, review, and checking processes.

Oregon DOT conducts a rigorous review of the Contractor-submitted data and images. All data and images are subject to review for acceptance. The Contractor must submit the previous week's sensor data and images each week. Oregon DOT checks these weekly submittals for correct routing, linear reference system (LRS) coding, direction, lane, and image quality. This process ensures that all data collection vehicle (DCV) test runs meet project requirements and may be suitable for use. The timely review and feedback to the contractor ensure any unacceptable test runs can be re-collected before the DCV leaves the project.

The contractor submits the post-processed sensor and distress data and images in batches by the district. Oregon DOT performs a series of global database checks on all data submittals to ensure data is complete, within acceptable ranges, and missing data is coded correctly and accounted for. Each data submittal is loaded into Oregon DOT's quality assurance database, which has numerous data queries and checking routines to ensure that data is complete and fit for use. Oregon DOT conducts independent range checks on collected data as part of the process. The 0.1-mile segment data is also aggregated and averaged to PMS sections of uniform condition, history, and traffic to allow for time series comparisons of current-year data with historical trends and windshield ratings. When PMS section averages fall outside expected values that cannot be explained by the construction or maintenance history, all 0.1-mile segment data within the PMS section are flagged and reviewed for potential issues. After all batch deliveries have been reviewed and issues resolved, the contractor must submit a pre-final delivery with all data for acceptance. If widespread issues remain in the final delivery, a subsequent delivery may be requested to ensure the data is corrected as agreed upon between Oregon DOT and the contractor. Table 20 summarizes the data and image acceptance criteria.

Table 20. Acceptance Criteria (adapted from Oregon DOT 2018 DQMP).

Deliverable (& Frequency)	Acceptance	Checks Performed	Action If Criteria Not Met
Route, lane, direction, LRS (Weekly)	100 percent	Review the previous week's images for correct routing, LRS coding, lane, and begin and end mile locations.	Reject deliverable; Re-collect route.
Images - Forward and pavement (Weekly)	Max. 5 of 100 consecutive images with inferior quality.	Review the previous week's images for coverage and quality (lighting, exposure, obstructions, focus).	Reject deliverable; Re-collect route.
Pavement Type (By District)	100 percent	Check for discrepancies against Agency provided pavement type. No more than two 0.1-mile segments within any 1-mile section.	Resolve all discrepancies before the final distress rating.

Deliverable (& Frequency)	Acceptance	Checks Performed	Action If Criteria Not Met
Data Completeness (By District)	99 percent	Total collection miles (excludes areas closed due to construction, behind gates, or where access cannot be reasonably achieved).	Reject deliverable; re-collect route.
Data Completeness (By District)	100 percent	No blank distress data fields without exclusion code and reason.	Return deliverable for correction.
Data Completeness (By District)	100 percent	No data outside the allowable ranges.	Return deliverable for correction.
Data Completeness (By District)	90 percent	Bridge events, construction detours, and lane deviations marked correctly.	Return deliverable for correction.
Sensor data - IRI, rut, and faulting (By District)	100 percent	Compliant with Control site and Verification testing requirements.	Reject all data since last passing verification; Re-calibrate DCV and re-collect affected routes.
Sensor data - IRI, rut, and faulting (By District))	95 percent	Data within expected values based on year-over-year time series checks: IRI ± 10 percent from the previous Rut ± 0.10 inch from the previous Fault ± 0.05 inch from previous.	Flag discrepancies and investigate; Re-collect if wet weather or traffic congestion creates issues that can reasonably be avoided; Accept data on a case-by-case basis if differences are due to construction/ maintenance or deterioration more than expected or where data appears reasonable based on visual observation of road surface.
Sensor data - IRI, rut, and faulting (By District)	95 percent	Comparison with ODOT's DCV on a sample of routes: IRI ± 20 percent. Rut ± 0.20 inch.	Flag discrepancies and investigate; Approve data on a case-by-case basis if differences can be reasonably explained; When significant differences exist and the cause cannot be reasonably determined, verify calibrations for all DCV's, review data for systematic errors, re-collect if equipment issues are found.
Distress ratings (By District)	100 percent	Compliant with Control site testing requirements.	Return deliverable for re-evaluation.
Distress ratings (By District)	Interstate: 95 percent Non-Interstate: 90 percent All Routes: No more than 10 percent of 0.1-mile segments within a PMS section rated incorrectly.	Compare current year versus previous year (considering recent construction and maintenance) and flag: Good/fair/poor category changes Sections where current year overall index difference exceeds +5 or -15 points from previous year Compare overall index with windshield rating and flag: Sections with ± 10 points difference.	Flag discrepancies and investigate; Compare distress quantities and review severities, check distresses are within lane limits, check distress length and area measurements marked on pavement images and summarized in shell table; Report incorrect distress ratings and return deliverable for correction; Accept the data if the current year distress ratings appear valid, regardless of previous year's ratings.

South Dakota DOT

SDDOT (2018) uses the following procedures for weekly data acceptance reviews for HPMS-defined metrics.

IRI

All of the collected data is compared to historical results. The results of every week's data collection are reviewed within the following two weeks and are retained in the SDDOT's Profiler Operation document folder. The data uploaded, processed by the routing segment, and compared to the previous year's historical data. Data is checked for completeness to ensure at least 90% of the segment is represented.

A segment is flagged for review if any of the following conditions happen:

- the left and right wheel path IRI values are more than 25% different from the previous year,
- the difference between the right and left IRI is more than 25%,
- more than 5% of IRI data is less than 25 inches/mile, or more than 1% of IRI data is greater than 400 inches/mile.

Any flagged segment is reviewed to determine if the issue can be explained (e.g., new overlay, accelerated deterioration of pavement, segment limits changed, distress in one wheel path, etc.). If the flagged data cannot be explained, the segment is scheduled to be recollected.

The above review process is repeated for all recollected segments. The Pavement Condition Engineer is responsible for performing the acceptance reviews and identifying any segments for re-collection.

Rutting

All of the collected data is compared to historical results. The results of every week's data collection are reviewed within the following two weeks and are retained in the SDDOT's Profiler Operation document folder. The data is uploaded, processed by the routing segment, and compared to the previous year's historical data. Data is checked for completeness to ensure at least 90% of the segment is represented.

Left and right wheel path rut data are flagged for review if the value is more than 0.08 inches different from the previous year. The segment is reviewed to determine if the difference can be explained (ex., new overlay, accelerated pavement deterioration, segment limits changed, distress in one wheel path, etc.). If the flagged data cannot be explained, the segment is scheduled to be recollected. The review process is repeated for any recollected segments. The Pavement Condition Engineer performs the acceptance reviews and identifies segment re-collection.

Faulting

All of the collected data is compared to historical results. The results of every week's data collection are reviewed within the following two weeks and are retained in the SDDOT's Profiler

Operation document folder. The data is uploaded, processed by the routing segment, and compared to the previous year's historical data. Data is checked for completeness to ensure at least 90% of the segment is represented.

Left and right faulting data are flagged for review if the value is more than 0.08 inches different from the previous year. The segment is reviewed to determine if the difference can be explained (ex., new overlay, accelerated pavement deterioration, segment limits changed, distress in one wheel path, etc.). If the flagged data cannot be explained, the segment is scheduled to be recollected. The review process is repeated for any recollected segments. The Pavement Condition Engineer performs the acceptance reviews and identifies segment re-collection.

Asphalt Pavement Cracking (automated)

All of the collected data is compared to historical results. The results of every week's data collection are reviewed within the following two weeks and will be retained in the SDDOT's Profiler Operation document folder. The data is uploaded, processed by the routing segment, and compared to the previous year's historical data. Data is checked for completeness to ensure at least 90% of the segment is represented.

The asphalt cracking percent is flagged if the value is outside a tolerance of ±5% and within ±7.5%. If one value is more than ±7.5% or two consecutive results are more than ±5%, data collection is stopped until issues are resolved. The segment is reviewed to determine if the difference can be explained (ex., new overlay, accelerated pavement deterioration, segment limits changed, distress in one wheel path, etc.). If the flagged data cannot be explained, the segment is scheduled to be recollected. The review process is repeated for any recollected segments.

JCP cracking (manual)

JCP cracking is performed by manual raters using collected images. SDDOT does not explicitly describe data acceptance procedures. However, the following QC checks are performed to ensure data quality:

- Images – Images from selected areas, two miles in length, will be viewed to ensure clarity on jointed PCC pavements. This process will be accomplished before the rater uses the images to locate and quantify cracked slabs. Images are checked as follows:
  - Image clarity—all images should be clear, allowing most highway signs to be read. Most highway distresses should be evident in all views with 1/8 inch wide cracks visible. There should be minimal or no debris in the cameras' viewing path.
  - Image brightness/darkness—images are not to be collected during hours when it is raining, or rain is imminent, the dark clouds may not allow the proper amount of light to enter the camera, and the subsequent image(s) will be of poor quality.
  - Dry pavement—pavement should be dry (no visible water during testing); otherwise, the section will be rejected. As a result, data collection should be halted during a rainstorm. If raindrops are allowed to accumulate on the protective glass, the images will be of poor quality due to the lack of clarity and sharpness.

- Missing images—there should be minimal missing images. Any section that is determined to have an insufficient representation of the image will be scheduled for re-collection.

- Cracking data – Sample pavement segments, two miles in length, will be visually observed on-site for the location of cracked slabs. The cracks located by the rater using images will be compared to those located by visual observation. This process should be done at the beginning, at a random time, during, and after the survey is complete. If less than 85% of the cracks visually observed are located by the rater using the pavement images, the following steps will be taken to mitigate this issue.
  - The Assistant Pavement Management Engineer will rate the section as the rater would and compare it with the visually observed segments.
    - If less than 85% are located by the Assistant Pavement Management Engineer, the images should be recollected, the visual observation recollected, and the process started again.
    - If greater than 85% are located by the Assistant Pavement Management Engineer, the rater will need to be retrained or replaced.

CRCP Cracking (manual)

CRCP cracking is performed by manual raters using collected images. SDDOT does not specifically describe data acceptance procedures. However, the following QC checks are performed to ensure data quality:

- Images – Images from selected areas, two miles in length, will be viewed to ensure clarity on CRC pavements. This will be accomplished before the rater uses the images to locate and edit cracking data. Images are checked to the same criteria as JCP images.
- Cracking data – Three to five sample pavement segments, 528 feet in length, are visually observed (on-site) for the location of longitudinal cracks, punch-outs, and patched areas. The percentage of cracking for the visually observed area is calculated per the HPMS Field Manual. The calculated cracking percent located by the rater using automated data and edited images is compared to the cracking percent calculated by the visual observation. This process should be done at the beginning, at a random time, during, and after the survey is complete. If less than 85% of the calculated cracking percent from the visually observed area is accounted for by the rater using the pavement images, the following steps are taken to mitigate this issue:
  - The Assistant Pavement Management Engineer rates the section as the rater would and compare it with the visually observed segments.
    - If less than 85% of the calculated cracking percent from the visual observations is accounted for by the Assistant Pavement Management Engineer, the images should be recollected, the visual observations recollected, and the process should start again.
    - If greater than 85% of the calculated cracking percent from the visual observations is accounted for by the Assistant Pavement Management Engineer, the rater is retrained or replaced.

CORRECTIVE ACTION, ERROR RESOLUTION, AND TROUBLESHOOTING

Corrective action measures are established before data collection. Each acceptance activity can have a corrective action associated with it so that when acceptance criteria are not met, a plan is established to correct it. The following includes corrective action commonly referenced in the DOT DQMPs:

- Reject the data and recollect.
- Reprocess the data.
- Recalibrate the data collection equipment.
- Adjust data collection procedures.
- Retrain the data collection team.

DOT DQMPs can identify what type of corrective action best resolves data errors. Error resolution logs are established when acceptance checks do not meet established criteria. Data collection personnel can be notified immediately if a corrective action and error resolution have been assigned to a batch of data that did not meet acceptance requirements. Keeping a good error resolution log ensures that the current data meet DOT requirements and provides a database of errors and resolutions as a tool to identify and fix data errors in the future or, ideally, prevent them from happening.

Oregon DOT (2018) reports tracking and reporting errors for QC and quality acceptance in logs. Quality acceptance logs are similar to the QC logs used by Oregon DOT (previously referenced in Table 13) but include a review date. An example of the Oregon DOT quality acceptance log is shown in Table 21. Tracking all data quality issues and error resolutions ensure that the data collection team can identify the cause of the error, resolve the issues on already collected data, and prevent the issue from reoccurring in future data.

Table 21. Example of quality acceptance logs adapted from Oregon DOT 2018 DQMP.

Deliverable Name	Delivery Date	Review Data	Status/Findings	Resolution	Resolution Date
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-

- No data

Dispute Resolution with Vendor Collected Data

DOTs using vendor services to collect PSC data can establish written error resolution processes agreed upon by the DOT and vendor before data collection. These processes may include data errors that trigger data reprocessing and recollection. Acceptance checks may frequently occur throughout data collection so that any data errors can be resolved as soon as possible to avoid having to recollect large amounts of data.

Successful Case Studies for Corrective Action, Error Resolution, and Troubleshooting

Michigan DOT

Michigan DOT (2018) uses a vendor to collect PSC data. Michigan DOT staff performs acceptance reviews and checks of submitted data weekly. Michigan DOT has a database (PaveMaPP) where automated database checks are performed. PaveMaPP includes collection logs that require corrective action by the data collection vendor. A report can be generated that shows outstanding collection issues. Michigan DOT establishes this report weekly and sends it to the data collection vendor. An example of this report is shown in Table 22 where BMP is the beginning measure point and EMP is the end measure point.

Table 22. Example of an outstanding issues report sent weekly to the data collection vendor (adapted from Michigan DOT 2018).

Route Name	Set	BMP	EMP	Issue Description	Notes to Contractor	Re-collect Required
M97	2018	0	14.27	Not-surveyed section required	Construction	No
M3	2021	0.011	0.136	Incorrect route collected	No comment	Yes
M85	2025	0.127	2.656	Not-surveyed section required	Swayed too far to the right at MP 0.012, 0.031	No
ALLEN RD	2028	0	8.82	Collection Problem – down view issue	No comment	Yes
BRENN/AN ST	2028	0	0.189	Not-surveyed section required	No comment	No
MACK AVE	2032	0	0.864	Collection started early	No comment	No
WARREN AVE	2032	9.487	1.786	Collection started late	No comment	No
VERNOR HWY	2032	0.153	0	Incorrect route collected	Should start at Vernor Hwy W (Northbound)	Yes

Colorado DOT

Colorado DOT (2018) reports requiring an in-person kickoff meeting with the data collection vendor to ensure that all internal and external project stakeholders have a clear and thorough understanding of the project requirements and acceptance criteria before the commencement of any data collection or data processing. During this meeting, all of the following items are discussed:

- All deliverables are defined and clarified.
- Any questions from the Internal Project Setup process are discussed.
- Schedules for all tasks and deliverables are presented, clarified, and agreed to.
- Control site schedule, locations, and benchmarks.

Additionally, Colorado DOT reports requiring pilot data to ensure that their vendor meets Colorado DOT requirements. This process is a useful practice used to ensure data is being collected per DOT-specific data definitions. The following describes Colorado DOT’s pilot data delivery requirements, as referenced from their DQMP.

To meet Colorado DOT's requirements, the data collection vendor should process and deliver a pilot dataset as soon as a representative sample of the network has been collected. The pilot data allows Colorado DOT (and the data collection vendor) to follow their typical end-to-end process using real data. This practice ensures that all procedures, software, and configurations work as designed. Additionally, DOT personnel can evaluate the final reports and change any process step before data collection begins.

Colorado DOT uses the following procedure for communicating identified issues and corrective action with the data collection vendor. The following procedure has been adapted from the Colorado DOT DQMP.

Communication

If for any reason, the integrity of data delivered to Colorado DOT (by the vendor) is found to be questionable or unsatisfactory, the following steps are performed:

- An email is sent to the vendor's Project Manager by Colorado DOT, including the following:
    - A clear description of the problem(s).
    - Colorado DOT's network locators, e.g., District, CSECT, etc.
    - File Name (if possible).
    - Chainage.
    - Direction.
    - Length.
- Creation of a case ticket for Colorado DOT tracking by the vendor Project Manager.
- Activation of the Corrective Action process, if necessary, by the Quality Manager.
- Verification of the problem by the vendor's Project Manager and Processing Team.
- The vendor employs appropriate corrective action.

Corrective Action

When the QC or QA process reveals errors in the data, the data must be appropriately reprocessed and a Corrective Action record created. This reprocessed data must also be documented as part of the QC/QA report. The vendor can discover errors during the QC process or Colorado DOT during the QA process. In addition, Colorado DOT staff may identify problems before accepting the final deliverables.

All sections failing the vendor's internal quality review are corrected before forwarding the deliverable to Colorado DOT. The vendor provides documentation of these checks, identifying any management sections which require re-rating and identifying the potential source of the original errors. If the errors are identified as systematic, all similar roadways rated by the individual identified as being in error are reviewed and corrected as appropriate. This process includes data from previous deliverables as well. Upon identification of errors, additional clarification or training is provided.

As the QA review identifies differences between the vendor ratings and Colorado DOT's ground reference ratings, these differences are scrutinized to determine the magnitude and the cause of the errors. The entire deliverable is accepted when errors are discovered in 10% or less of the deliverable checked. However, if more than 10% of the data checked during QA falls outside of the allowable limits, then the entire deliverable is returned to the vendor for correction.

Arkansas DOT

Arkansas DOT (ARDOT 2018) describes the following step-by-step process for dispute resolution between the ARDOT project management (PM) and data collection vendor in their DQMP:

- The issue or disagreement shall be identified by the ARDOT PM and Data Collection Contractor's PM.
- A review of the project contract and initial project plan is conducted by the Data Collection Contractor's PM and reviewed by the ARDOT PM. If the contract or project plan addresses the issue, the Data Collection Contractor's PM and the ARDOT PM must acknowledge the fact before proceeding to the next step.
- The first tier of resolution options to be explored are those that do not negatively impact the project contract, budget, or schedule. The second tier of resolution options to be explored may impact schedules, contracts, and budgets. All resolution options are reviewed and discussed to ensure all parties are clear on each option's impact on the project deliverables, timelines, and budget.
- After all resolution options have been presented, and all ARDOT questions have been answered to their satisfaction, the ARDOT PM commits to an option that resolves the issue with minimal impact. Upon identification of an acceptable resolution option, the Data Collection Contractor's PM adjusts the project plan to reflect the changes.

New Mexico DOT

New Mexico DOT (NMDOT 2018) includes the following procedure for using independent verification. This procedure is one part of their data acceptance process, and this example mainly addresses manual checks of distress based on images. However, NMDOT reported that they are developing procedures for verifying production testing profile data (IRI, faulting, and rutting).

Independent verification testing is conducted by an independent consultant using qualified and trained pavement distress raters visually reviewing and noting distress type, severity, and extent on the digital images, and checks and verifies windshield and pavement image quality for each verification site. The independent verification Consultant also reviews and compares the profile results (IRI, faulting, and rut depth) for each verification site. Verification sites are roadway segments whose pavement condition is based on the data collection contractor's results. Verification sites consist of 0.10- to 1-mile pavement segments that the NMDOT randomly selects during production data collection. Verification sites include a two percent sample of the annual mileage collected during the automated condition survey. They are provided to the independent verification contractor for review and comparison to the data collection contractors' results. The independent verification vendor manually identifies and quantifies distress type and severity based on the pavement surface images. Images are used to perform independent analysis checks and other data quality checks.

The independent verification results for each verification site are compared with the data collection contractor results and should meet the criteria shown in Table 23.

Table 23. Independent verification criteria adapted from NMDOT 2018 DQMP.

Distress	Unit of Measure	Description	Criteria
Alligator Cracking (Flexible Pavement)	Area (square feet)	Both wheel paths	± 10% area per severity
Bleeding (Flexible Pavement)	Area (%)	All severity levels	± 10% area per severity
Block Cracking (Flexible Pavement)	Area (square feet)	All severity levels	± 10% area per severity
Edge Cracking (Flexible Pavement)	Lineal foot	Within 1 foot of either side of the fog stripe	± 15% length per severity
IRI (Flexible Pavement)	inches/mile	Average both wheel paths < 300 inches/mile	± 0.67 Std dev.
Longitudinal Cracking (Flexible Pavement)	Lineal foot	Non-wheel path All severity levels	± 15% length per severity
Patching (Flexible Pavement)	Lineal foot	All severity levels	± 10% area per severity
Raveling/Weathering (Flexible Pavement)	Lineal foot	Most prevalent severity	± 10% area per severity
Rut Depth (Flexible Pavement)	inch	Both wheel paths Categorize by severity	± 0.67 Std dev.
Transverse Cracking (Flexible Pavement)	Lineal foot	All severity levels	± 10 counts per severity
Corner Break Rigid (Rigid Pavement)	Count	Categorize by severity	± 2 counts per severity
Cracking (Rigid Pavement)	Percent	Percent of cracked slabs	± 5% total area
Faulting (NMDOT) (Rigid Pavement)	inch	Average for each severity level	± 0.05 inch per severity
Faulting (HPMS) (Rigid Pavement)	inch	Average over section length	± 0.05 inch
IRI (Rigid Pavement)	inches/mile	Average both wheel paths < 300 inches/mile	± 0.67 Std dev.

According to NMDOT, corrective action and error resolution procedures should accompany verification testing or other acceptable activity.

ROLES AND RESPONSIBILITIES

DOTs can have acceptance criteria and data-checking processes performed independently from the data collection team. If the data is self-collected by the DOT, a unit or person separate from the data collection unit or person can verify the data. Verification examples include database and image checks and reviewing the QC test results and reports completed by the data collection team. Additional useful acceptance checks may include verification at control sites, including blind control sites. DOTs can establish a reasonable sample size of data to review that represents the pavement in their network, as previously described. According to DQMPs, some DOTs elect to use a third party for independent verification. An example of using independent verification is described in the following section.

REPORTING AND RECORD-KEEPING

Few DOTs gave complete details on how their data quality management activities are reported and recorded. Most DOTs include general QC reporting requirements, and some DOTs include partial reporting and keeping specific tasks' records, including calibration, certification, and data acceptance. DQMPs can include complete record-keeping and reporting processes of all quality management activities to ensure that data quality management methods are transparent, traceable, and objective. Keeping adequate data quality management records ensures that the collected data is believable and trustworthy. Elements to include in data acceptance reports may include (Pierce et al. 2013):

- A description of quality standards and acceptance criteria.
- A description of control, verification, blind sites, and reference values were used.
- An analysis of control, verification, and blind site testing results.
- Documentation of all global database checks performed and the results.
- Documentation of all sampling checks and the results.
- Documentation of all other acceptance checks and the results.
- A log of all quality issues identified through acceptance checks and corrective actions.
- Recommendations for improvements.

An effective pavement management system depends on reliable, accurate, and complete information. Quality pavement condition data is directly linked to the ability of the pavement management system to produce reasonable, timely, and reliable information regarding an agency's pavement network (Pierce et al., 2013). Reporting is a critical part of the quality management process, allowing DOTs to create a timeline of data quality. This timeline is valuable for identifying timeframes of when data quality may have been compromised, keeping track of data quality issues, and preventing them from reoccurring.

The reporting and record-keeping process is critical and was previously addressed in relevant sections specific to calibration and certification, training, quality management activities during data collection, and evaluation after data collection. The content to consider in data quality reporting is summarized in Table 24.

Table 24. Summary of content for data quality management reporting and record-keeping.

Calibration and Certification	Training	Quality Management Activities (Quality Control) during data collection	Data Evaluation after data collection
• Reviewed and approved vendor or manufacturer calibration records identifying that the elements pass calibration criteria. • Reviewed and approved certification records that identify that system passed certification criteria. • Reviewed calibration and certification expiration date specific to all data collection vehicles and operators.	• Reviewed and approved training records for all personnel associated with data collection or analysis activities. • Record of expiration date or requirement for recertification.	• List of personnel and equipment used in data collection. • Documentation of initial and continuing calibration checks and maintenance for equipment. • Equipment issues were reported, and corrective actions were taken. • Schedule adherence and the reasons for any changes. • Documentation of collection procedures and protocols used. • Reporting any variances in standard operating procedures or changes in collection methods in the field. • Reporting of all control, verification, and blind site testing and results. • Documentation of all QC activities. • Analysis of intra or inter-rater comparisons. • Log of all quality issues identified through QC activities and corrective actions are taken. • Copies of all correspondence.	• A description of quality standards and acceptance criteria. • A description of control, verification, blind sites, and reference values were used. • An analysis of control, verification, and blind site testing results. • Documentation of all global database checks performed and the results. • Documentation of all sampling checks and the results. • Documentation of all other acceptance checks and the results. • A log of all quality issues identified through acceptance checks and corrective actions are taken. • Suggestions for improvements.

Successful Case Studies for Reporting and Record-Keeping

Pennsylvania Turnpike Commission (Pennsylvania DOT 2018)

The following is the quality management reporting in the PA Turnpike Commission DQMP.

All steps in the data review must be documented as per the quality assurance plan (QAP). The office QAP describes office-wide planned processes and systematic actions, quality practices, and resources to be undertaken and which vendor (is responsible) to deliver quality data products. It requires that all client deliverables be reviewed by the person executing the task, a qualified colleague, (and) the project manager. All reviews must be documented office-wide (data quality management software). Under this plan, required forms must be completed that document that all required items were reviewed and any corrective actions. This plan holds each party responsible for their part in (data) quality (management) and serves as an archive of QC measures completed for each project. These standard procedures are applied to all steps in the Pavement Management Projects (PMP) review.

DATA QUALITY MANAGEMENT TOOLS

DOTs can take time to establish standardized report templates, formatted file structures, and other streamlined tools to aid in implementing and enforcing data quality management. Some additional tools that can be useful are described below (Pierce et al., 2013).

Automated Software Data Checks

Many agencies perform a series of quality checks on the entire database. This quality check is typically performed using a set of queries stored in the database. Because of the multitude of queries to be run and the large size of most condition databases, a few agencies have automated the process either entirely or partially. For example, the Colorado DOT (2012) uses a computer program to check for duplicate records, missing segments, incorrect pavement types, and other errors. The Oklahoma DOT uses a Microsoft Access-based tool that enables the user to execute the queries in a logical sequence against smaller subsets (i.e., field districts) of the database (Pierce et al., 2013).

Geographic Information Systems

GIS, as used in asset management, is a tool designed to integrate data and cartography. GIS software provides a platform for examining, visualizing, and managing pavement data. The condition survey data elements can be visualized on a map as long as the data has been located geographically. For example, GIS can plot the collected data on a road network shapefile to check the segmentation process's accuracy and the collected latitude and longitude data. If a segment has been missed, a faulty beginning point assigned, or the data otherwise improperly segmented, it is often readily apparent by visualizing the data using the GIS. Examining the data is useful in many ways, such as comparing data from each side of a divided highway or comparing the radius of curvature with the map display of the location.

A newer development using GIS as a QM data tool involves creating keyhole markup language (KML) files from the condition and inventory data and importing them with a browser-based GIS such as Google Earth™ mapping service. Using an internet application to display pavement data on the road network and satellite images is very helpful in checking the data (Pierce et al. 2013).

Quality Management Tracking Software

Some DOTs reported using automated software for tracking quality issues. The software is capable of creating a ticket and tracking the error resolution. Some of these programs were reported to automatically email appropriate parties and notify them of data quality issues or can easily generate reports that can be sent to the data collection team. One such program is implemented by Michigan DOT and was described in chapter 6.

IMPROVE THE PROCESS

Similar to this report, DOT DQMPs are intended to be a living document updated continuously as technology and procedures advance and evolve. The power of data quality management stems from the continued application of the quality cycle each time data are collected. Even wellconstructed DQMPs are only effective when they are well-maintained (Pierce et al., 2013). DOTs can consistently work towards improving data quality management processes. Several DOTs include methods to improve data quality management processes in their DQMPs. Several DOTs included plans to include control sites or improve current control sites used for data quality management activities. A few examples are described in the following section.

Successful Case Studies for Improving the Process

South Dakota DOT

SDDOT includes the following post-processing feedback processes in their DQMP (specific to manual distress ratings). The following processes take place between data collection seasons:

- SDDOT Region Fall Inspections – The distress data is compiled and processed for a preliminary analysis run for the Pavement Management System (PMS). SDDOT then takes this data on the road to each of the four SDDOT Regions and the 12 subordinate Areas. On these inspection trips, SDDOT takes each candidate project generated by the Pavement Management System and, along with the regional staff, checks that the collected data reflects what is seen in the field.
- State Transportation Improvement Program (STIP) meeting – A large meeting occurs after the PMS has selected candidate projects for inclusion into the STIP. Personnel from the Planning and Engineering Division and the Operations Division come together to plan the inclusion of new projects and discuss the time of current projects in the STIP. Comments and questions on the validity of the data often occur, and with (proper data quality management and current technologies), SDDOT can address these.

California DOT

California DOT (Caltrans 2018) includes a section regarding lessons learned in their DQMP. Lessons learned can be very useful training tools to reduce repeat issues with data quality. The lessons learned in the Caltrans DQMP specifically relate to uploading PSC data into the pavement management software. It is important to note that even this last step of importing network-collected data into pavement management software has potential room for error. DOTs might find that keeping the lessons learned document for all data collection processes is a useful quality management tool.

Montana DOT

Montana DOT (2018) includes that the final quality management reporting includes a section with recommendations for improvement. The recommendations for improvement are based on the input from the data collection team, including the corrective action log and error resolution and documentation of other problems that were not reported.

CHAPTER 8. SUMMARY

This document provides successful practices for DOT DQMPs based on the literature research, evaluation of existing DOT DQMPs, recently completed or ongoing research/specifications, and lessons learned from piloted studies relative to PSC data quality. This document covers all relevant data quality management elements and activities during three chronological phases: *before, during, and after data collection*. However, readers may jump into any topic and chapter they are interested in, looking up information that can help improve their DQMPs. The structure of this report is meant to work as a standard template for DQMPs.

Many DOTs have successful elements and quality management activities reported in their DQMPs based on the thorough reviews under this project. Still, DOTs are encouraged to review their existing DQMPs against this document and add any processes or procedures that their existing plans might lack. DOTs are not expected to adopt all procedures and tools reported here but to select the ones that best improve their existing plans. One area where many DOTs could improve their DQMPs is equipment certification. It is suggested that DOTs consider using the tools and processes provided in chapter 4 to improve their certification processes.

Reporting and record keeping were not typically documented in DOT DQMPs but are critical parts of quality management and can be included in written plans and procedures. Receiving the full benefits of a quality management program without proper record-keeping is challenging.

Many DOTs only included HPMS-defined metrics required for submittal under 23 CFR 490.319(c). DOTs can also consider expanding their existing DQMPs to include all data metrics used in their decision-making processes. Documentation of data quality procedures is critical for enforcing implementation and assigning accountability to all the personnel involved in data quality activities. Having written plans and procedures increase consistency and ensures quality during employee turnover, new employee training, selection of new data collection vendors, and other changes occurring between data collection seasons or cycles.

Some of the information provided in this document, particularly regarding the transverse pavement profile (TPP) certification processes, has not been widely adopted. These procedures are subject to change and evolve as the research and procedures are further tested and validated. There are still some other critical specifications that are lacking. Therefore, this document may be updated periodically as technology and certification/data process procedures advance and evolve.

GLOSSARY

Acceptance: The process whereby all factors used by the agency (i.e., sampling, testing, and inspection) are evaluated to determine the degree of compliance with contract requirements and to determine the corresponding value for a given product (AASHTO 2011).

Acceptance testing: The activities required to determine the degree of compliance of the pavement data collected with contract requirements (Flintsch and McGhee 2009).

Accuracy: The degree to which a measurement, or the mean of a distribution of measurements, tends to coincide with the true population mean (AASHTO 2011).

Automated data collection: Process of collecting pavement condition data by the use of imaging technologies or other sensor equipment (Flintsch and McGhee 2009).

Automated data processing: The reduction of pavement condition (surface distresses, such as cracking and patching, or pavement condition indices, such as IRI) from images or other sensors. The process is considered fully automated if the pavement condition (e.g., distress) is identified and quantified through techniques that require either no or very minimal human intervention (e.g., using digital recognition software capable of recognizing and quantifying cracks on a pavement surface) (Flintsch and McGhee 2009).

Bias: An error, constant in direction, that causes a measurement, or the mean of a distribution of measurements, to be offset from the true population mean (AASHTO 2011).

Blind Site: Reference "Control Site."

Calibration: A set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or between values represented by a material measure or a reference material, and the corresponding values realized by standards (AASHTO 2011).

Control site testing: The use of reference measurements on specific pavement sections (with well-defined locations) to assess the quality of a pavement condition data collection process. If the location of the session is not known to the data collection team, these are referred to as blind control sites or segments (Flintsch and McGhee 2009).

Certification: procedure to evaluate the data collected by the equipment and operators in accordance with a nationally recognized standard or test procedure to check the accuracy and precision of the collected data with respect to reference measurements. Certification of the equipment and operators is conducted prior to the start of the data collection program.

Corrective action: The improvements/adjustments to an organization's processes taken to eliminate causes of nonconformities or other undesirable situations. Specifically, they are actions to resolve discovered problems with calibration, defective equipment, data errors, or missing data.

Crack measurement system: A system consisting of high-speed cameras, optics, and laser line projects to capture 2D images and 3D profiles. Used for automatic detection of cracks, macrotexture, and other surface features.

Cross-rating: Also called inter-rating, it means that two or more competent raters are evaluated using the same protocols on the same sample sections to determine the difference, if any, between results (Pierce et al. 2013).

Error resolution: Activities taken if the outcomes from the data collection and processing do not meet the acceptance criteria.

Faulting: the difference in elevation across a concrete pavement joint or crack (Pierce et al. 2019)

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

Ground Reference: Commonly referred to as "ground truth". A value that serves as an agreed-upon reference for comparison, and which is derived as a theoretical or established value, based on scientific principles, an assigned or certified value, based on experimental work of some national or international organization, or a consensus or certified value, based on collaborative experimental work under the auspices of a scientific or engineering group (AASHTO 2011).

Ground Truth: Reference "Ground Reference"

Independent verification: A management tool that requires a third party, not directly responsible for process control or acceptance, to provide an independent assessment of a product or service and/or the reliability of test results obtained from process control and acceptance testing (Flintsch and McGhee 2009).

HSIP: A high-speed inertial pavement profiling system that collects real-time continuous measurements of longitudinal profile elevations, IRI, and faulting (Pierce et al. 2019).

International Roughness Index (IRI): A statistic used to estimate the amount of roughness in a measured longitudinal profile. The IRI is computed from a single longitudinal profile using a quarter-car simulation (AASHTO 2017).

Linear reference system (LRS): A set of procedures for determining and maintaining a record of specific points along a highway. Typical methods used are mile point, milepost, reference point, and link-node (FHWA 2016).

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 from a body-fixed frame to a global reference frame (Ferris et al. 2019).

Longitudinal profile: The elevation profiles of the traveled surface typically along the vehicle's wheel tracks. (ASTM E950).

Manual data collection: Pavement condition data collection through processes where people are directly involved in the observation or measurement of pavement properties without the benefit of automated equipment (e.g., visual surveys and fault meters) (Flintsch and McGhee 2009).

Manufacturer: a person or company that makes the sensors and systems used on data collection vehicles.

Mapping sensor: Any sensor which acquires measurements of a surface in its sensor reference frame (Ferris et al. 2019).

Mean profile depth (MPD): "The measured profile is divided into segments having a length of 4 inches (100 mm). The slope of each segment is suppressed by subtracting a linear regression of the segment. This also provides a zero mean profile, i.e., the area above the reference height is equal to the area below it. The segment is then divided in half, and the height of the highest peak in each half segment is determined. The average of these two peak heights is the mean segment depth. The average value of the mean segment depths for all segments making up the measured profile is reported as the MPD." (ASTM 2015).

Metric: a quantifiable indicator of the performance or condition of the pavement. In terms of the HPMS, a metric refers to the reported values for IRI, rutting, faulting, cracking percent, or present serviceability rating (PSR) for a section of the mainline highway (FHWA 2018).

Measure: an expression based on a metric that is used to establish targets and assess progress toward meeting the established targets. In terms of the HPMS, measures refer to percentages of network lane miles in good or poor condition, computed using the reported "metrics" (FWHA 2018).

Pavement condition: An evaluation of the degree of deterioration and/or quality of service of an existing pavement section at a particular point in time, either from an engineering or user (driver) perspective. The condition as it is perceived by the user is often referred to as a functional condition. The estimated ability of the pavement to carry the load is referred to as structural condition (Flintsch and McGhee 2009).

Pavement condition indicator: A measure of the condition of an existing pavement section at a particular point in time. This indicator may be a specific measure of a pavement condition characteristic (e.g., smoothens or cracking severity and/or extent) or an index defined for a single dis- tress (e.g., cracking), for multiple distresses (e.g., Pavement Condition Index), or for the overall pavement condition (Flintsch and McGhee 2009).

Pavement performance: The history of pavement condition indicators over time or with increasing axle load applications (Flintsch and McGhee 2009).

Percent within limits (PWL): The percentage of the lot falling above the lower specification limit (LSL), beneath the upper specification limit (USL), or between the USL and LSL (AASHTO 2011).

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 project 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.

Precision: The degree of agreement among a randomly selected series of measurements; or the degree to which tests or measurements on identical samples tend to produce the same results (AASHTO 2011).

Quality acceptance: Those planned and systematic actions necessary to verify that the data meet the quality requirements before they are accepted and used to support pavement management decisions. These actions govern the acceptance of the pavement condition data collected using either a service provider or in-house resources. Quality acceptance is often referred to as quality assurance in the pavement engineering and management field (Flintsch and McGhee 2009).

Quality assurance: Planned and systematic actions are taken to ensure that the data collection processes are followed, as required so that the resulting data meets the specified quality requirements. QA refers to the testing performed on the production processes and can be part of the calibration, validation, or verification review.

Quality control: The system used by a contractor to monitor, assess, and adjust its production or placement processes to ensure that the final product meets the specified level of quality. QC includes sampling, testing, inspection, and corrective action (where required) to maintain continuous control of a production or placement process (AASHTO 2011).

Quality management: The overarching system of policies and procedures that govern the performance of QC and acceptance activities; that is, the totality of the effort to ensure quality in the pavement condition data.

Repeatability: Degree of variation among the results obtained by the same operator repeating a test on the same material. The term repeatability is therefore used to designate test precision under a single operator (AASHTO 2011).

Reproducibility: Degree of variation among the test results obtained by different operators performing the same test on the same material (AASHTO 2011).

Required Protocol: Standards, guidelines, processes, and references required by direct or indirect reference in 23 CFR Part 490.319 for HPMS-defined metrics.

Resolution: The smallest change in a quantity being measured that causes a perceptible change in the corresponding indication (ICO 2008).

Row Image: A digital image record of the roadway right-of-way and adjacent visible surrounding area.

Rutting: The longitudinal surface depressions in the wheel path. A rut is more specifically defined as broad longitudinal depressing in the wheel path of the pavement surface with a depth of at least 0.080 inches, a width of at least 1.0 ft, and a longitudinal length of at least 100 ft (Pierce et al. 2019).

Semi-automated data collection/processing: Process of collecting pavement condition data using imaging technologies or other sensor equipment but involving significant human input during the processing and/or recording of the data (Flintsch and McGhee 2009).

TPP: The vertical deviations of the pavement surface from a level horizontal reference perpendicular to the lane direction of travel.

Validation: The mathematical comparison of two independently obtained sets of data (e.g., agency acceptance data vs. contractor data) to determine whether it can be assumed they came from the same population (AASHTO 2011).

Vendor: A private firm hired to collect, process, and deliver pavement condition data and images in accordance with the agency-specified scope of work.

Verification: The process of determining or testing the truth or accuracy of pavement condition data collection by examining the data and/or providing objective evidence. Verification sampling and testing may be part of an independent assurance program (to verify QC and acceptance testing) or part of a pavement condition data collection acceptance program (Flintsch and McGhee 2009).

Wheel path: A longitudinal strip of pavement 39 inches wide. The inner edges of both wheel paths are offset from the center of the lane by 14.75 inches and, therefore, 29.5 inches apart. (Pierce et al. 2019). Note that DOTs may have their own unique definition of wheel path.

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