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

Phase I: Task 2 – Document of Successful Practices

Submitted to

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Federal Highway Administration

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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 report is an interim outcome 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 (QMPs) 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.

Lisa Hanf, Acting Director, FHWA Resource Center

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16. Abstract

For years State Department of Transportations (DOTs) have conducted pavement surface condition surveys to use in the management of their pavement assets. These surveys involve a significant investment of time, money, and manpower. Understanding the level of reliability of the pavement condition data used in Pavement Management is important. Repeatable and reliable pavement condition data plays an important role in the development of condition indexes, performance models, understanding of how and why pavements perform better than others, and finding cost-effective solutions to pavement preservation needs. Good and reliable pavement condition data also play an important role in determining performance parameters. There are several sources of information on Quality Management (QM) standards, procedures, and best practices used to perform Quality Control (QC) and acceptance of pavement condition data. Implementing these processes improves the reliability of data to meet the needs of Pavement Management Programs (PMPs). The main goal of this project is to provide successful practices for DOTs to implement in quality management programs (QMPs) that result in increased data accuracy, precision, and reliability while maintaining a cost-effective data collection process. This report is a deliverable under Phase I: Task 2 – Document of Successful Practices.

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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
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
FWD:	Falling weight deflectometer
GIS:	Geographic information system
GPR:	Ground penetrating radar
GPS:	Global positioning systems
HPMS:	Highway Performance Monitoring System
IRI:	International Roughness Index
ISO:	International Organization of Standards
KML:	Keyhole markup language
LADAR:	Laser radar
LCMS:	Laser Crack Measurement System
LIDAR:	Light detection and ranging
LRM:	Location referencing method

LRS:	Location referencing system
LTPP:	Long-Term Pavement Performance
MDP:	Mean profile depth
MEPDG:	Mechanistic-Empirical Pavement Design Guide
MLRS:	Multi-level referencing system
MoT:	Ministry of Transportation
NCHRP:	National Cooperative Highway Research Program
NHS:	National Highway System
NIST:	National Institute of Standards and Technology
PCI:	Pavement Condition Index
PCR:	Pavement Condition Rating
PMS:	Pavement Management System
PQI:	Pavement Quality Index
PSI:	Present Serviceability Index
PSR:	Present Serviceability Rating
PWL:	Percent within limits
QC :	Quality control
QM:	Quality management
QMP:	Quality management plan
RWD:	Rolling wheel deflectometer
SHA:	State highway agency
TQM:	Total quality management
TDQM:	Total data quality management

CHAPTER 1. INTRODUCTION

PROJECT OBJECTIVE

The purpose of this project is to demonstrate successful practices and processes to State Departments of Transportation (DOT's) on implementing network-level pavement surface condition (PSC) data quality management programs. The outcome of the project should include a comprehensive report with information to assist DOT's in developing state-specific data quality management plans (QMPs). The report is intended to be a living document that gets updated periodically as appropriate as technology and standard practices evolve.

The project intends to give DOTs examples of successful practices on PSC data quality management programs that they can consider adopting and implementing to meet their specific needs. Typically, DOTs have pavement condition metrics specific to their decision-making processes. For example, many states have different definitions for cracking and record different parameters of cracking, such as type, severity, and length. State pavement management programs (PMPs) 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, International Roughness Index (IRI), and faulting data per the Highway Performance Monitoring System (HPMS) field manual definitions as required per 23 CFR 490.319(c). This project intends to address both state-specific and HPMS data metrics. However, it is not practical to include every possible metric and definition used across the nation. Therefore, DOTs should use their judgment as to which practices provided in this document best fit their data quality management needs.

DOCUMENT OBJECTIVE

The objective of this document is to report the findings of Phase 1 of the project. Phase 1 includes two tasks. Task 1 has been completed and included conducting literature research and evaluating existing DOT QMPs. Task 2 is this document that provides successful practices identified during Task 1. The goals of this document (Task 2) includes:

- Document the state of practice for PSC data collection equipment.
- Identify and document standards and protocols used to establish quality management procedures that are traceable, objective, practical, and transparent.
- Document successful practices for the set-up of control sites and ground reference.
- Document successful practices for training and certifying data collection operators, manual raters, and personnel performing data acceptance activities.
- Document effective statistical analysis procedures used to analyze the data and verify that test results are within the allowed variability.

This Task 2 report may be implemented and tested in three pilot projects in Alabama, Pennsylvania, and Washington (if Phase II is awarded). These pilot studies should be used to refine and calibrate the procedures in this document based on lessons learned.

DOCUMENT ORGANIZATION

The document includes a literature review that was completed during Task 1 of this project. The literature review includes state-of-practice for PSC data. This literature review was completed to better understand the current needs of state highway agencies (DOT) and provide successful practices that may be implemented immediately. This was accomplished by reviewing all of the latest versions of existing DOT QMPs submitted to FHWA between 2018 and 2019. This literature review also includes a summary of the on-going research under the Transportation Pooled Fund Study, TPF-5(299)/(399) Improving the Quality of Pavement Surface Distress and Transverse Profile Data Collection and Analysis and within the National Cooperative Highway Research Program (NCHRP). There are several concurrent studies evaluating topics that should affect DOT data collection and QMPs. Some of these studies include standardizing definitions of data condition metrics (e.g., faulting, cracking, and rutting), proposing standardized certification processes, and procedures for reasonable accuracy and precision statements. The Document of Successful Practices should consider the changing technology and remain a living document that can be updated as the related research is completed. The literature review completed during Task 1 is included in chapter 2 of this document.

The rest of this document (chapter 3 through chapter 7) is dedicated to the Task 2 report. It provides successful practices of data quality management and how to effectively document QMPs. This document is organized mainly by the timeline of when the quality management activity should take place. Based on the reviews of existing QMPs, this timeline was generally followed by all DOTs. This timeline is also generally followed in supplementary QMP documents, including the Practical Guide for Quality Management for Pavement Condition Data Collection (Peirce et al. 2013) and NCHRP Synthesis 401 Quality Management of Pavement Condition Data Collection. The timeline contains three main phases, including:

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

Figure 1 shows a timeline of each of the three phases with general tasks that take place during each event. Subsequent chapters 3-7 are listed in Table 1, according to which phase the chapter content should take place.

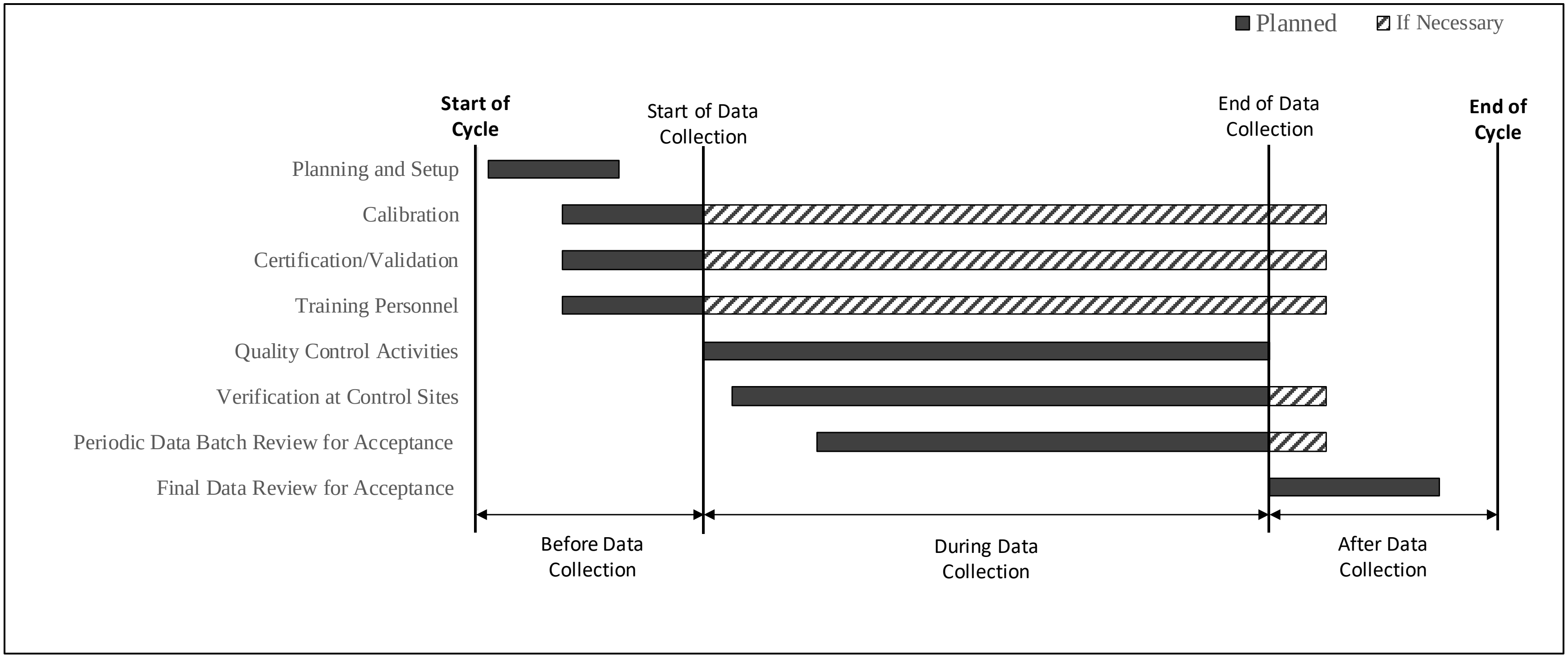


Figure 1. Chart. Timeline of each of the main data collection phases with general tasks that occur in each phase.

Table 1. General timeline and summary of document content.

Timeline of Event	Chapter Title and Content
Before data collection	Chapter 3. Planning and Setup include general planning, processes to describe data quality based on PMS needs, an overview of control sites and ground reference data, and procedures for utilizing them for different quality management activities.
Before data collection	Chapter 4. Equipment Certification and Calibration includes procedures for equipment calibration (sensor and algorithm) and certification processes for typical data collection equipment systems.
Before data collection	Chapter 5. Training includes processes for training for manual raters, the data collection team, and the data acceptance team.
During data collection	Chapter 6. Quality Control includes procedures for periodic processes and testing frequencies, reporting and record-keeping, and corrective action as it pertains to quality control.
After data collection	Chapter 7. Data Evaluation includes procedures for data evaluation after data collection.
After data collection	Chapter 8. Data Management and Improving the Process includes procedures for reporting and improving the process.
N/A	Chapter 9. Conclusions

ROUTINE DOCUMENT UPDATES

It is reiterated here that the technology associated with PSC data collection is evolving rapidly, and this document should be updated to reflect changes in the state of practice data collection. On-going TPF-5(299)/(399) research projects may affect data definitions, certification procedures, and data acceptance criteria, among other elements. DOTs should refer back to future editions of this document as technologies and protocols evolve and update their QMPs.

CHAPTER 2. TASK 1 LITERATURE REVIEW

A large number of DOTs have transitioned or are currently transitioning from manual to high-speed automated data collection methods, and from points-based to surface-based automated measurement systems (Zimmerman 2017). New data collection equipment has dramatically changed the way 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 are mature enough to collect dense data for the characterization of PSC and distresses. A variety of proprietary algorithms have been developed for calculating the fault, rut depths, crack lengths and severities, and other distresses from these high-speed devices. However, the repeatability and accuracy of those data are not easily evaluated due to the usages of a variety of technologies, and lack of certification standards. Under the TPF-5(299)/(399), efforts are devoted to improving data quality and management processes and to develop standards to certify data collection equipment and to evaluate the collected data. This chapter is organized in the following sections:

1. Summary of Practice – describes current data collection equipment technology typically used by DOTs for data collection based on reviews of literature and existing DOT QMPs.
2. Pavement Surface Condition Data – describes the data typically collected by DOTs and how it is used.
3. Fundamental Data Management Concepts – describes comprehensive data management concepts relative to PSC data.
4. Effects of Data Quality on Decision-making Processes – describes how the quality of data effects pavement related decisions.
5. FHWA Peer Exchange Reviews – describes shared challenges reported by DOTs during the peer exchanges.
6. Findings from Other Literature Reviews – describes the on-going and recently completed relevant research.

SUMMARY OF PRACTICE

The following describes the state-of-technology for modern high-speed pavement condition data collection devices.

Inertial Profiler System

Nearly all DOTs reported using a high-speed inertial profiler (HSIP) system that meets the requirements of AASHTO M328-14 Standard Specifications for Inertial Profiler in their data QMPs. The three measuring components of the HSIP system include: (1) a height sensor that measures the distance between a vehicle reference point and the pavement surface while the vehicle is traveling; (2) an accelerometer that measures the vertical acceleration of the vehicle as it moves vertically in response to the pavement profile; (3) a distance sensor that provides a location reference for the vehicle as it travels. The run-time software and post-processing software is used to combine these three measurements so that the effects of the vertical vehicle movement are eliminated, leaving the true pavement profile of the pavement. This system is used to measure the longitudinal profile and calculate IRI. There are standard processes for HSIP equipment certification, and there are many regional certification sites across the nation. Most DOTs are implementing successful practices for IRI data quality relative to other data metrics (faulting, rutting, and cracking).

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 technology. 3D technologies have become more widely used to collect faulting data (Chang et al. 2012). More information on 3D systems is described in the following section.

3D Systems

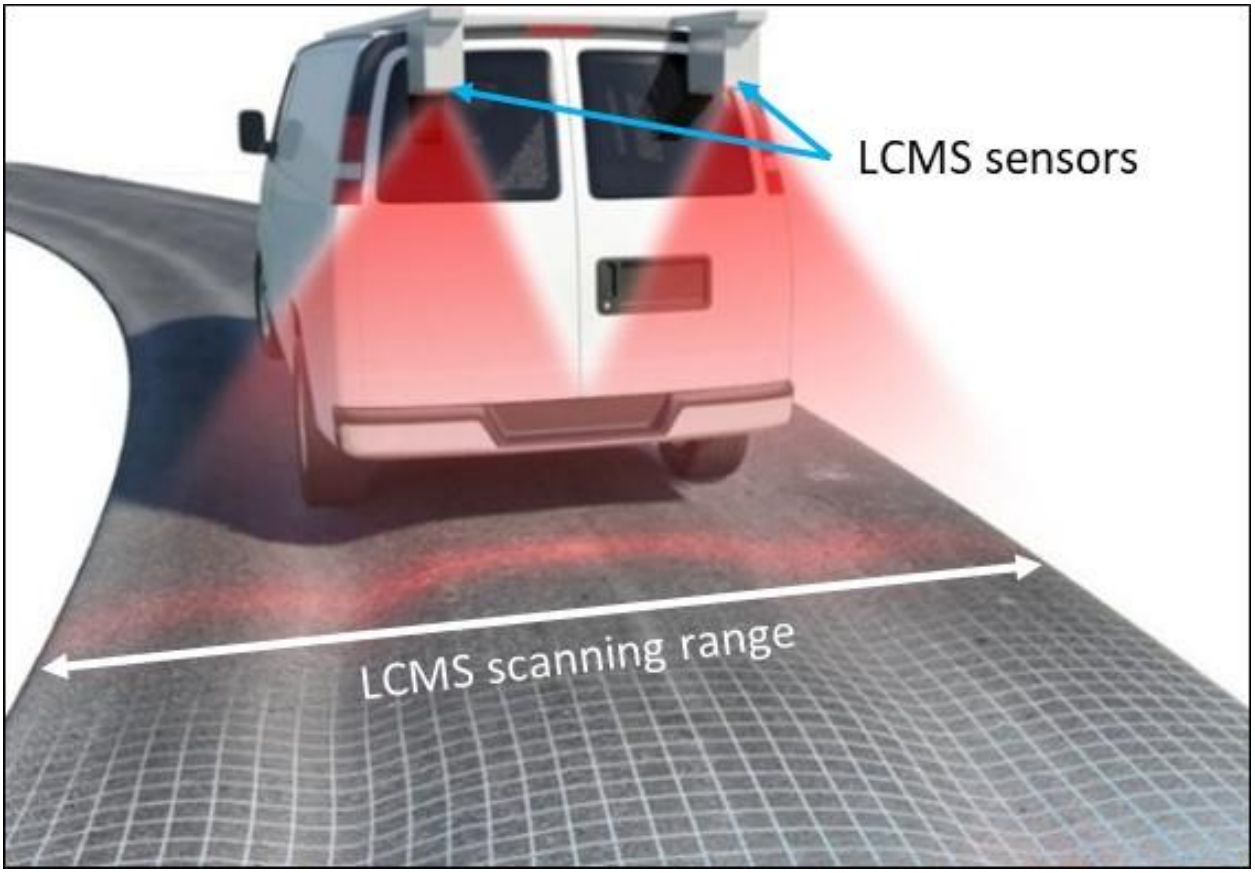
Based on information from the FHWA Standard Data Format for 2D/3D Pavement Image Data project, most users collect transverse pavement profile (TPP) data, and other data items, including horizontal and vertical curves, longitudinal grade, elevation, and cross slope with high-speed 3D survey systems in a single pass.

High-speed systems can generally collect TPPs at 4 m width. Edge drop-off can be detected automatically to avoid over-reporting rut depth. 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. Survey-grade global positioning system receivers with a local real-time kinematic (RTK) base station can position a vehicle to 1-2 cm accuracy.

There are limited 3D survey system suppliers in North America. Systems that use Pavemetrics Laser Crack Measurement System (LCMS) components in their integrated 3D survey vehicles include ICC, Dynatest, Mandli, Fugro Roadware, and ARRB Systems. Another North American supplier of the 3D system is Pathway Services. The PathRunner 3D system uses its core 3D technologies. Fugro Roadware has reported intent to provide 3D survey systems in the future. Waylink Systems Corporation provides Pave3D and CrackNet, an artificial intelligence (AI) technology solution for fully automated crack detection (WayLink Systems Corporation 2020).

A description of the LCMS technology is included in this section to demonstrate an example of 3D survey technology. It has been summarized from the information obtained from the Pavemetrics website (Pavemetrics 2020).

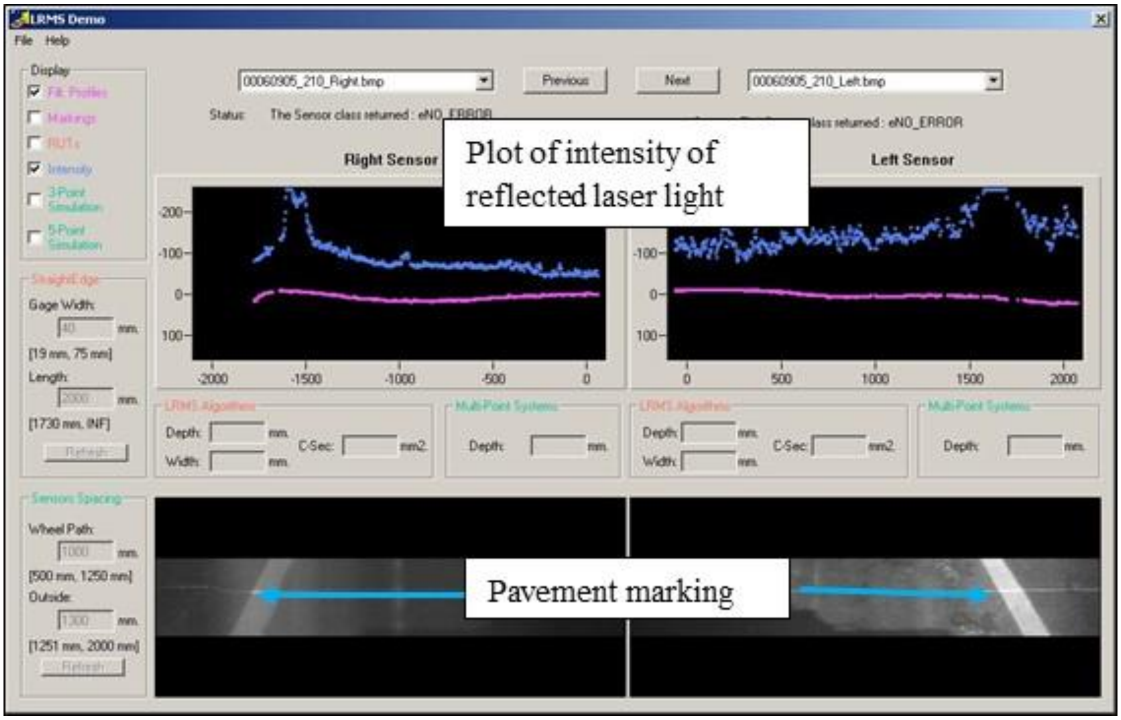
The LCMS-1 uses invisible laser line projectors and synchronized cameras to capture a four-meter (13.1 feet) wide high-resolution image and 3D range profile of the driven lane at traveling speeds up to 100 km/hr (62 miles/hr). 3D range data provides both the longitudinal profile as well as the TPP of the roadway. An example of a data collection equipment van equipped with LCMS-1 sensors and the scanning range is shown in Figure 2.



Source: Pavemetrics (2020)

Figure 2. Illustration. 3D data collection vehicle with LCMS sensors and scanning ranges.

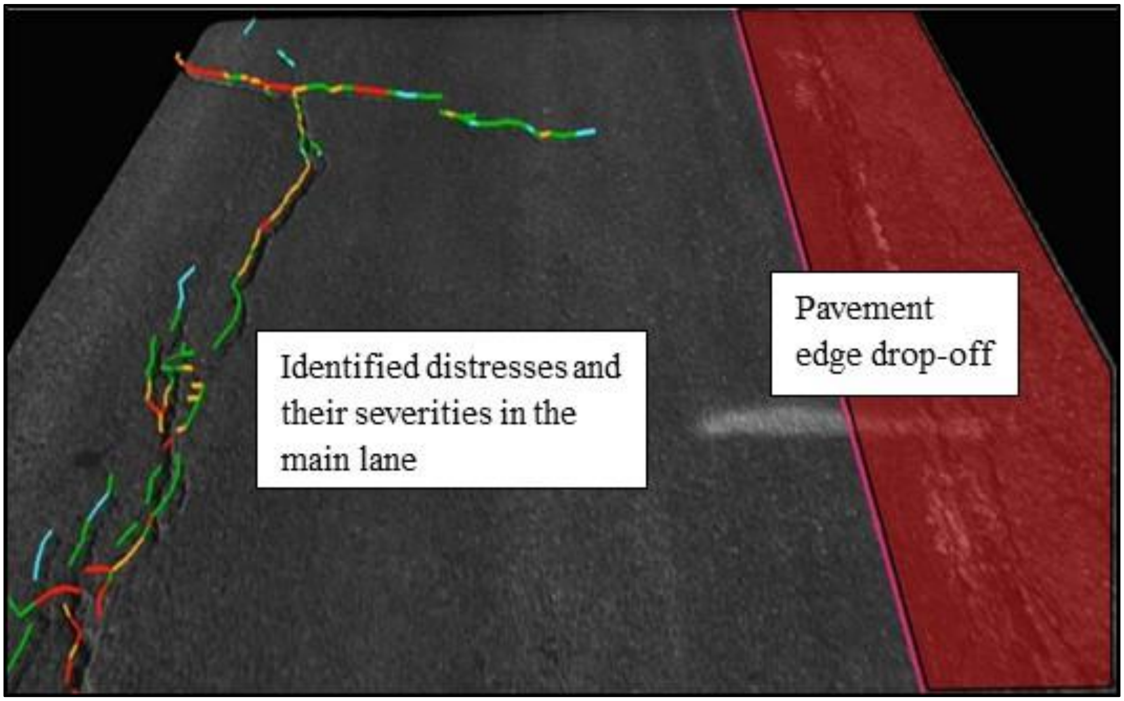
The LCMS system collects 4,000 points of measurement transversely with a vertical accuracy of plus or minus 0.5 mm per point (vertical resolution is +/- 0.25 mm) and operates at a scanning rate of up to 11,500 Hz (typically 5,600 Hz). This sampling rate permits a 5 mm longitudinal scanning resolution at speeds up to 100 km/h. The LCMS system is combined with an optical encoder that translates driving wheel revolutions into pulses, and TPPs are captured on a distance basis. The system can operate in daylight or during night-time conditions. An automated algorithm is used to detect pavement markings allowing the user to restrict distress measurements to the area between pavement stripes, as shown in Figure 3.



Source: Pavemetrics (2020)

Figure 3. Illustration. LCMS software illustrating laser sensing pavement markings.

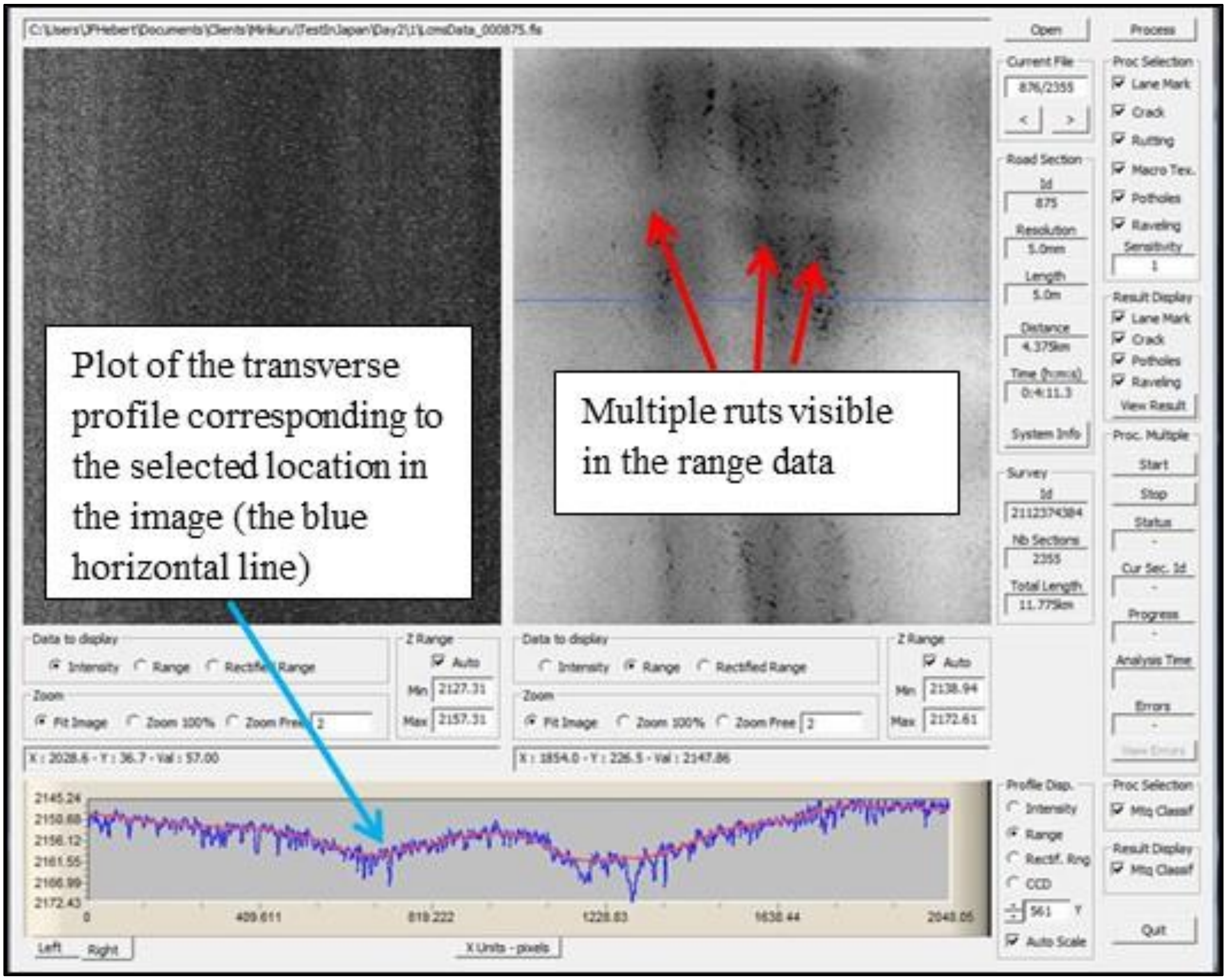
Edge drop-off can also be detected using 3D range data and the magnitude of drop-off, as shown in Figure 4.



Source: Pavemetrics (2020)

Figure 4. Illustration. LCMS 3D range data detecting edge drop-off.

The projected laser lines from the LCMS system follow the contour of the road surface and trace its TPP. High-speed cameras and frame grabbers capture a dimensionally accurate image of the projected laser lines and store them to onboard computers. Individual successive profiles are automatically stitched together to produce a continuous image as well as a 3D map of the driving lane to measure TPPs and to detect ruts, as illustrated in Figure 5.

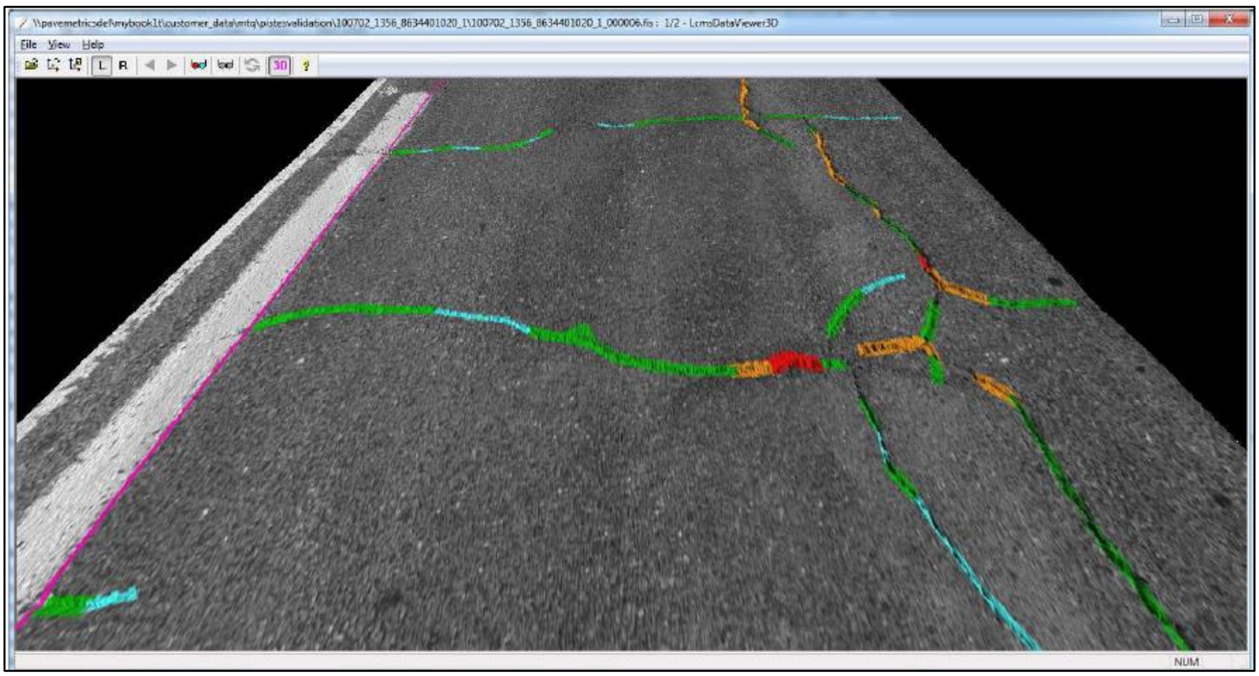


Source: Pavemetrics (2020)

Figure 5. Illustration. LCMS software measuring transverse profiles and detecting ruts.

The LCMS-1 can report rut depth, width, and type in real-time. Rut types include short radius rutting, long radius rutting, and multiple radius rutting ("double ruts"). Lane width used for rutting calculation can be automatically measured using the lane marking detection algorithm or manually defined by the user. Because the methods of measuring rut depth vary by DOT, the user may select from a list of available methods for rutting statistic generation, including straight edge or moving ruler (various lengths), string line ("taut-line"), 3-point, and 5-point measurement. Resulting rut depths can be overlaid on top of the intensity or 3D range images for reporting purposes. The recently released LCMS-2 includes several modifications, including a sampling rate of 28,000 Hz, transversal resolution of 4,160 data points, normal depth precision of ±0.25 mm, 1 mm longitudinal scanning resolution for speed up to 100 km/h, and the transversal accuracy of ±1 mm. One mm scanning resolution allows the detection of cracks with widths as low as 2 mm (Pavemetrics 2020).

Distress data can be determined from the 3D data using fully automated proprietary vendor algorithms manually by viewing images and video from a computer screen or using a semi-automated combination of both automated detection and manual post-processing. Automated detection generally uses a combination of pattern search and machine learning techniques. An example of automated distresses identification is shown in Figure 6 (Pavemetrics 2020). Automated detection of pavement cracks may be more objective than manual rating and is more efficient. Some algorithms have demonstrated certain successes, but still, have limitations. Most agencies report some level of manual verification in their data QMP. Advances are being made using deep learning methods that show an improvement in automated distress detection and should potentially provide better solutions when they are made commercially available. (Zhang et al. 2018).



Source: Pavemetrics (2020)

Figure 6. Illustration. LCMSDataViewer3D illustrates identified distresses, including cracks, potholes, and lane marking overlaid on top of 3D pavement images.

PAVEMENT SURFACE CONDITION DATA

Typically, DOTs have defined pavement condition metrics that may not match the HPMS definitions required by the CFR. For example, many states have different definitions for cracking and record different parameters of cracking, such as type, severity, and length. There are also several methods for calculating rut depth. State PMPs depend on these different data definitions for maintaining data consistency and making historical or year to year comparisons. Subsequent chapters in this report provide procedures that DOTs may implement to comply with the data quality requirements for HPMS definitions of cracking, rutting, IRI, and faulting as well as unique definitions used by DOTs.

Recent agency practices for automated pavement condition data collection based on survey results were summarized in NCHRP Synthesis 531 (Pierce et al. 2019). Fifty-seven agencies in the US, Puerto Rico, and Canada responded to the survey. The results include what type of data is typically collected and whether processes are fully automated, semi-automated, or manual. The summarized responses for asphalt, jointed plain concrete pavement (JCP), and continuously reinforced concrete pavement (CRCP) are listed in Table 2, Table 3 and, Table 4 respectively, adapted from NCHRP Synthesis 531.

Table 2. Summary of data collected for asphalt pavements and collection method (fully automated, semi-automated, or manual).

Asphalt	Fully Automated	Semi-automated	Manual	Total No. Responses
Rutting	53	0	3	56
IRI	55	0	0	55
Transverse Cracking	32	13	10	55
Alligator Cracking	29	15	10	54
Longitudinal Cracking	33	9	9	51
Potholes	14	13	9	36
Patching	10	15	11	36
Raveling	14	11	10	35
Block Cracking	16	11	7	34
Edge Cracking	19	10	4	33
Cross Slope	30	0	1	31
Bleeding	10	9	9	28
Reflection Cracking	16	7	4	27
Texture	19	1	2	22
Lane/Shoulder drop off	9	3	5	17
Depression	8	2	3	13
Shoving	5	2	6	13
Bumps and Sags	8	1	2	11
Corrugation	3	2	6	11
Weathering	0	3	7	10
Polished Aggregate	1	3	4	8
Faulting (composite)	4	0	0	4
Delamination	2	0	0	2
Wheel path cracking	1	1	0	2

Table 3. Summary of data collected for JCP pavements and collection method (fully automated, semi-automated, or manual).

JCP	Fully Automated	Semi-automated	Manual	Total No. Responses
IRI	44	0	0	44
Faulting	37	3	2	42
Cross slope	20	1	1	22
Longitudinal Cracking	20	13	7	40
Transverse cracking	16	17	6	39
Texture	12	1	2	15
Patching	8	14	7	29
Corner cracking	7	16	7	30

JCP	Fully Automated	Semi-automated	Manual	Total No. Responses
Spalling	7	15	8	30
Joint seal damage	6	7	7	20
Lane/shoulder drop off	6	4	5	15
Durability	4	9	6	19
Map cracking	4	7	2	13
Blowups	2	6	3	11
Pumping	2	3	6	11
Broken slabs/percent cracked slabs	1	3	0	4
Polished aggregate	1	3	3	7
Scaling	1	3	7	11
Shattered area/slabs	1	2	0	3
Shrinkage Cracks	0	0	2	2

Table 4. Summary of data collected for CRCP pavements and collection method (fully automated, semi-automated, or manual).

CRCP	Fully Automated	Semi-automated	Manual	Total No. Responses
IRI	19	0	0	19
Cross slope	9	0	0	9
Longitudinal Cracking	8	7	2	17
Transverse cracking	6	6	1	13
Texture	6	0	1	7
Punchout	5	8	1	14
Lane/shoulder drop off	5	1	2	8
Spalling	3	4	1	8
Patching	3	7	2	12
Durability	3	3	2	8
Scaling	1	1	1	3
Map Cracking	1	3	0	4
Polished aggregate	0	2	1	3
Blowups	0	4	2	6

The results from the synthesis show that the majority of agencies are using automated processes for collecting IRI, rutting, and faulting. Roughly half of the surveyed agencies are using automated processes for distress collection, while the other half are using manual or semi-automated methods.

Forty-eight agencies (U.S. and Canada) that use automated data collection were asked to indicate whether the agency or a vendor collects and analyzes the data. The synthesis results showed that there is an even split (16 each) between agencies who self-collect and analyze data, agencies who use a vendor to collect and analyze data, and agencies who use a combination of vendor and self-collection and analysis. Agencies who use a combination of agency and vendor collection and analysis reported that the efforts were divided as follows:

- Both the agency and the vendor collect and analyze the data (six agencies).
- A vendor collects the data, and the agency analyzes the data (five agencies).
- A vendor collects the data, and the agency and the vendor analyze the data (three agencies).

- The agency and a vendor collect the data, and the agency analyzes the data (two agencies).

It is evident, based on these results, that the roles and responsibilities between DOT personnel and vendor personnel vary among DOTs. The Practical Guide (Pierce et al. 2013) provides a detailed table with roles and quality management responsibilities. This list was referenced in many DOT data QMPs. Clarification on Quality Control (QC) versus quality assurance and data acceptance roles and responsibilities may be useful as there is some confusion on the level of involvement for DOT personnel when a vendor is doing most of the data collection and analysis (Orthmeyer 2018). Chapter 3 includes a list of roles and responsibilities for DOT personnel that may be considered in DOT QMPs.

FUNDAMENTAL DATA QUALITY MANAGEMENT CONCEPTS

Product quality management (QM) has an extensive body of literature on total quality management (TQM) with principals and techniques for improving quality in product manufacturing. The same ideas and practices can be applied to data QM. Wang (1998) relates data QM concepts to product QM concepts and presents a perspective on Total Data Quality Management (TDQM). Pierce et al. adapted the processes presented by Wang (1998) in the Practical Guide (2013) to relate specifically to pavement condition data collection. The pavement condition concepts include:

- Describe data quality – Identify the acceptable levels of resolution, accuracy, and repeatability.
- Plan and implement QC – Develop and implement a set of procedures to produce, check, and ensure data of acceptable quality.
- Perform acceptance tests and evaluate results – Perform tests to compare delivered data to acceptability metrics.
- Take corrective action – Take steps to re-collect or reprocess data to achieve data acceptance standards.
- Report on data quality – Document the data quality standards, protocols, equipment, personnel, collection and processing methods, QC, acceptance tests, and results.
- Improve the process – Use the knowledge and experience gained to modify processes to improve data quality.

These concepts resemble the five critical areas (Criteria) that are needed to be addressed in the DOT QMP per the CFR. Therefore, it is logical that most DOTs implemented these TDQM concepts to some extent in their QMPs. Each of these concepts is described below with a summary of the most common current practices reported by DOTs in their QMPs.

Describe Data Quality

Data resolution refers to the level of detail – such as IRI measured to the nearest inches/mile. There are several resources with options for data resolutions for different metrics. Table 5 is adapted from the Practical Guide (Pierce et al. 2013) and shows examples of data resolution for different metrics based on HPMS, LTPP, and AASHTO protocols. Most DOTs included data resolution requirements based on one of these protocols, or a state-specific protocol.

Table 5. Examples of data resolution requirements based on different protocols.

Data Metric	HPMS	LTPP	AASHTO
IRI	1.0 inches/mile	0.6 inches/mile	6 inches/mile
Rut Depth	0.10 inch	0.04 inch	0.04 inch
Fault Height	0.10 inch	0.04 inch	0.04 inch

Data precision is often used interchangeably with data repeatability. Data precision is how consistent results are when the one measurement system repeats measurements. Many DOTs have established thresholds for precision and reported methods to check precision during data collection. Checking data precision typically includes making repeat runs at a control site at a designated frequency throughout testing. Nearly every DOT reported checking precision throughout testing on IRI data. Fewer DOTs reported checking precision for faulting, cracking, and rutting. This practice is because there are recognized standards and procedures for certification and verification of IRI testing equipment, but not for faulting, cracking, and rutting. While most DOTs included methods to check precision throughout data collection, few DOTs gave adequate details regarding establishing control sites. Procedures for establishing control sites and collecting ground reference data are described in chapter 3.

Data accuracy refers to the closeness of a measurement to accepted ground reference data. Checking data accuracy typically includes making runs at a control site with known ground reference measurements at a designated frequency throughout testing. Nearly every DOT reported checking accuracy throughout testing on IRI data by comparing it to established ground reference data typically collected by a walking profiler. Very few DOTs reported checking accuracy for faulting, cracking, and rutting. As stated previously, this is a result of having no recognized national standards or procedures for certifying and verifying equipment, or for establishing a ground reference. Several on-going TPF projects plan to provide options for resolution, accuracy, and repeatability (precision) specific to the data collection equipment and type of data being collected. These studies should provide information for establishing ground reference data that can be used to verify the data collection equipment. Many recently completed or on-going draft research reports include procedures that are referenced in subsequent chapters.

Measuring Data Quality

Precision and Bias

Measurement errors can be divided into two components: systematic errors and random errors. Systematic errors provide a measure of *bias,* while random errors provide a measure of *precision*. ASTM E177-14 describes bias as "the difference between the expectation of the test results and an accepted reference value," and precision as "the closeness of agreement between independent test results obtained under stipulated conditions." Bias is dependent on the ground reference, while precision is not. The lower the systematic error, or bias, the higher the accuracy of the measurement method. The lower the random errors, the higher the precision, or repeatability, of the measurement method. Figure 7 shows, for illustration purposes, a generic distribution of repeated measurements along with the reference value.

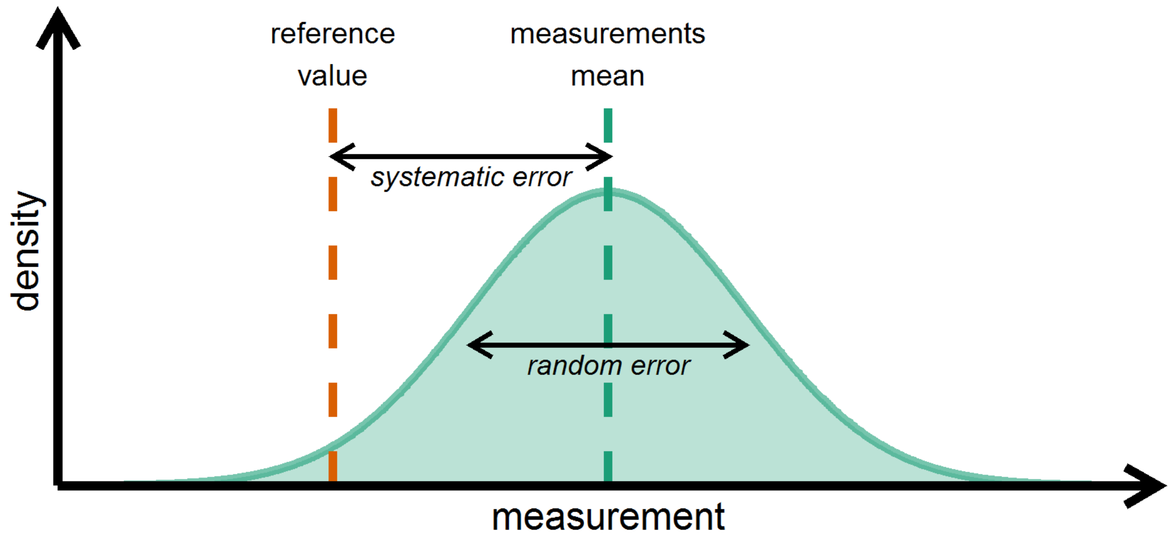


Figure 7. Graph. Generic distributions with systematic and random measurement errors.

There are several different statistics used to estimate the measurement method's bias and precision from the sample set of testing observations. Measurements bias is typically computed using the sample mean, as shown in Figure 8 and Figure 9. An alternative statistic used to estimate bias includes the median of the measurement sample. Using the sample median provides a better estimate of bias when the sample set of observations has outliers.

$$\text{bias} = \bar{x} - x_{ref}$$

Figure 8. Equation. Estimate of bias in absolute terms.

$$\bar{x} = \text{mean} = \left(\sum_{i=1}^{n} \frac{x_i}{n}\right)$$

Figure 9. Equation. Median of a sample with n measurements.

Where:

$$x_{ref} = \textit{reference value}$$

Figure 8 provides an estimate of bias in absolute terms. Bias is also commonly estimated relative to the reference value, as shown in Figure 10, which allows measuring accuracy in relative terms. This way of estimating bias can be more appropriate when the measurement error is proportional to the measurement value.

$$\text{bias}_{\%} = \frac{\bar{x} - x_{ref}}{x_{ref}}$$

Figure 10. Equation. Estimate of bias in relative terms.

The precision of the measurement method is typically estimated as the standard deviation of the sample set of measurements, as shown in Figure 11, which provides a measure of precision in absolute terms, with the same units as the measurements. Robust statistics can be used for estimating the precision of the measurement method. See Maronna et al. (2018) for more information about robust statistics.

$$\text{precision} = s_x = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})}{n}}$$

Figure 11. Equation. Estimate of precision.

Where:

s_x = standard deviation of a sample with n measurements

Another commonly used statistic for estimation of precision is the coefficient of variation (CV), which measures the random errors relative to the measured value, as shown in Figure 12. CV provides an estimate of precision relative to the sample mean, which is convenient when the random error component is proportional to the measurement magnitude. This statistic is unitless, as opposed to the standard deviation, which has the units of the measurements.

$$\text{precision}_{\%} = \text{CV} = \frac{s_x}{\bar{x}}$$

Figure 12. Equation. Estimate of precision relative to sample mean.

Where:

CV = coefficient of variation of sample measurements

Other quality-related properties of measurement methods used in pavement applications include the mean squared error (MSE), which captures both the bias and precision and cross-correlation, measuring similarity between the sequence of measurements (e.g., between measured and reference profile coordinates), among others.

In addition to resolution, accuracy, and precision, there are other aspects of data quality to consider. Numerous attempts have been made to describe data quality comprehensively. Rodriguez et al. (2017) combined descriptions from several TQM studies to create a set of data quality dimensions used to evaluate TDQM processes. *These data quality dimensions can be applied to pavement condition data. Table 6 shows an adaptation of the data quality dimensions as they relate to pavement condition data.*

Table 6. Summary of data quality aspects adapted from Rodriguez (2017) relative to pavement condition data.

Data Quality Aspect	Relative Statement	Considerations
Accessibility	DOTs can easily locate and access the data.	Few DOTs give details on reporting, database, and record-keeping processes. DOTs should provide information on achieving data accessibility and provide successful case studies for good data storage and record keeping.
Consistency	The data are integrated and coordinated, if different vendors or equipment are used the information does not change.	Data consistency has proven challenging with the transition from manual data collection to high-speed data collection and the ability to collect more data than ever before. Lack of standard definitions for distresses creates challenges for data consistency. Changes in data collection vendors can cause consistency challenges. Limited existing standards may have been established for manual data collection and do not always translate to high-speed data collection equipment. The on-going TPF research should aid in data consistency as standard definitions for distresses and processes for certification, verification, and vendor selection are established.
Relevance	The data are relevant, clear, and concise, and it is processed.	DOTs have unique data requirements specific to their decision-making processes. Many vendors adjust their algorithms to provide unique definitions for each DOT. The on-going TPF research may result in standardized definitions for distress data, but it may take time for DOTs to implement them. In the meantime, DOTs should have processes to verify that the data they are receiving is relevant to their definitions and decision-making processes.
Completeness	The data that is used perform the job and make decisions is available.	Data completeness is often checked during database checks during acceptance. Some DOTs do not indicate processes for how data is checked for completeness. Successful practices for checking data completeness should be included.
Accuracy and Precision	The data received are accurate and precise.	DOTs have requested example procedures for establishing ground reference data so that data can be checked for accuracy. Many DOTs have processes for checking precision, and successful practices should be provided. Several of the on-going TPF research studies include options for accuracy and precision statements. These should be referenced as appropriate. Statistical processes for checking data accuracy and precision at appropriate sample sizes should be included.
Believability	DOTs can trust the data received.	Transparency of data collection processes and documentation, review, and record-keeping of QC activities increase data believability. Having established databases so that data can be checked year to year is also useful as there are some expectations for reasonable changes in pavement condition. Successful practices for QC and acceptance procedures and checking data year to year should be provided.
Timely for Use	The data are received on time.	Having the pavement condition data available for decision-making processes is important for DOTs. Only a few DOTs indicate schedule statements in the QMP. Successful practices of scheduling processes and having complete accepted data before decision-making processes should be included.

Plan and Implement QC

QC describes actions that are taken to measure the quality of the data to identify its compliance with the quality standard. QC refers to the product and can be part of the calibration, validation, or verification review. QC is primarily implemented by the data collection team to monitor, assess, and adjust data collection processes.

There were several successful QC plans identified during the QMP reviews. Many DOTs are using control sites as verification throughout testing every week. Some DOTs are only verifying IRI data as a result of not having established sites for rutting, faulting, and cracking. Most DOTs report having a training program for data collection teams. However, the details of the training are not often reported. Some DOTs report reviewing the data being collected in real-time and downloading and reviewing data at the end of each shift to identify suspect data. There are many successful practices for QC procedures. It is anticipated that improving control sites and collecting ground reference data for all metrics should assist DOTs with QC procedures. QC activities are further described in chapter 6.

Perform Acceptance Tests and Evaluate Results

Acceptance tests are typically performed by the agency or a third party. Acceptance testing should include database checks to identify out of range data, detect missing segments or data elements, and flag data inconsistencies. Some states reported having software programs to check and flag suspect data automatically. Acceptance testing also includes image and video checks for clarity, brightness, completeness, and proper stitching of images. Most DOTs reported database checks and image and video checks as acceptance criteria. However, not all DOTs reported their expected values and acceptable ranges for each metric. Additionally, not all DOTs give details on their methods and protocols related to performing database and image checks.

The sample size of the entire database that gets checked is not typically clearly described by DOTs. The helpful tips document provided by FHWA in 2018 states that checking all collected data and imagery is generally not practical due to the level of effort, time constraints, and costs. A summary of the procedures given in the 2018 helpful tips document is to use statistical analysis to determine a sampling size that can be evaluated for acceptance testing to determine the validity of data. For network-level pavement condition data, the sample size for acceptance tests typically ranges from 2 to 20 percent. Establishing a sample size for acceptance testing was not always reported in QMPs. Most DOTs reported checking 100 percent of the data. *Chapter 7 includes statistical analysis procedures and criteria for establishing sample sizes for data checks.*

Most DOTs reported checking data from year to year as part of the acceptance process. Some DOTs did not have an adequate database to implement year to year checks but were planning to implement it in future years. *Year-to-year checks are a successful practice and are further described in chapter 7.*

Take Corrective Action

Most DOTs report corrective action as either recollecting or re-processing the data. This is often a blanket statement that covers all stages of quality management, including QC and acceptance activities. Few DOTs have detailed corrective action plans or conflict resolution plans for discrepancies with vendor collected data. Corrective action should be included in the QMP. Troubleshooting the suspected data to determine the cause of the potential error and avoid repeat errors was addressed in a few QMPs. Successful practices include troubleshooting techniques for common data errors. The 2018 FHWA helpful tips document suggests that the pavement condition data be continuously monitored by a variety of possible methods to ensure equipment calibration and data accuracy and precision during the collection effort to avoid the submission of large batches of unsatisfactory data. *Successful practices of QC and acceptance corrective action are provided in chapters 6 and 7.*

Report on Data Quality

Reporting and record-keeping are a critical part of data management. Many DOTs mention reporting and record-keeping for one quality management activity, such as QC procedures. Fewer DOTs include processes for reporting and record-keeping on all activities, including certification, calibration, acceptance, corrective action, and error resolution. Reporting and record keeping should include the details of the database on all relative data management activities. This practice creates transparency and provides a record of quality data. Additionally, having a record of all activities related to data quality is critical for troubleshooting and improving data collection processes. *Procedures for reporting and record-keeping are included in subsequent chapters.*

Improve the Process Continuously

This report is intended to be a living document that is modified as technology and standard procedures evolve. The DOT QMPs should also remain living documents that are updated and modified with the knowledge and experiences gained by DOTs each data collection period. Several DOTs reported having annual feedback meetings to discuss ways to improve data collection processes. *Feedback meetings and evaluating practices are considered successful practices and are further described in chapter 8.*

EFFECTS OF DATA QUALITY ON DECISION-MAKING PROCESSES

The specific uses of collected data vary by agency. NCHRP Synthesis 501 (Zimmerman 2017) documents current pavement management practices in state and provincial transportation agencies to determine the extent that pavement management data are being used to support network-level agency decisions. The information was gathered from a web-based survey of practice that was distributed to 52 State transportation agencies (including Puerto Rico and the District of Columbia) and 10 Canadian provincial MOTs. Forty-one (41) DOTs and eight Canadian MOTs responded. Regarding how data is used (as of 2017), this synthesis summarizes that:

- 100% of US DOTs and 88% of Canadian MOTs have inventory and condition data for their high-volume highway networks. Fewer agencies have inventory and condition data for lower-volume systems, and significantly fewer agencies have data on frontage roads, shoulders, and ramps.
- 90% of agencies report using PMS data to predict pavement performance using some type of model.
- 87% of agencies report that treatment recommendations are generated by the PMS (treatment can be generic categories such as preservation or rehabilitation, specific such as chip seal or overlay, or both).
- 83% of agencies report using PMS data to forecast expected conditions under different funding scenarios.
- 74% of agencies report using PMS data to estimate funding to achieve performance targets.
- 64% of agencies report using PMS data to prioritize project recommendations under constrained funding.
- 76% of agencies report that the PMS recommendations and actual projects implemented in the maintenance program matched at least 40% of the time. 38% of agencies report a 70% match.
- 54% of agencies report that they use the PMS to optimize resource allocations.
- 79% of agencies reported verifying the quality of data collected, though at the time of the survey, only 49% reported having data quality management procedures.

The NCHRP Synthesis 501 report included data metrics that agencies are collecting in addition to IRI, faulting, rutting, and distress data. Roughly half of the DOTs (50%) responded that they are currently collecting network-level surface property/friction data, and seven more agencies planned to add surface texture property/friction data to network collection. Twenty percent (20%) of agencies reported collecting network-level pavement structural performance data using non-destructive testing procedures. Although this report does not include friction or structural performance data, it is worth noting that many DOTs are collecting or plan to collect this information mentioned above. As more DOTs implement these data sets into PMS systems, future versions of this report may consider implementing data quality processes for friction and structural performance data collection. The inclusion of these data elements provides information regarding friction and structural capacity to give a relatively complete evaluation of pavement condition and further assist in decision-making processes (Guerre et al. 2012).

The NCHRP Synthesis 501 report did not cover which condition and distress types are specifically used for pavement performance analysis. However, it did report that nearly half of the agencies (50%) responded to using individual distress data during analysis and performance modeling. The rest of the agencies reported that they use performance indices (based on individual distress data) during analysis and performance modeling.

The distress data that are collected and the way they are summarized into indices vary by State. For example, Texas DOT uses a pavement condition score that ranges from 1 to 100, where 1 is considered very poor, and 100 is considered very good. The condition score is based on two other scores, ride score and distress score. The ride score is computed from IRI measurements and ranges from 0.1 to 5.0. The distress score describes the level of deterioration based on distress data. The final condition score uses both of these scores, as well as traffic levels, surface types, and other highway characteristics (Serigos et al. 2015).

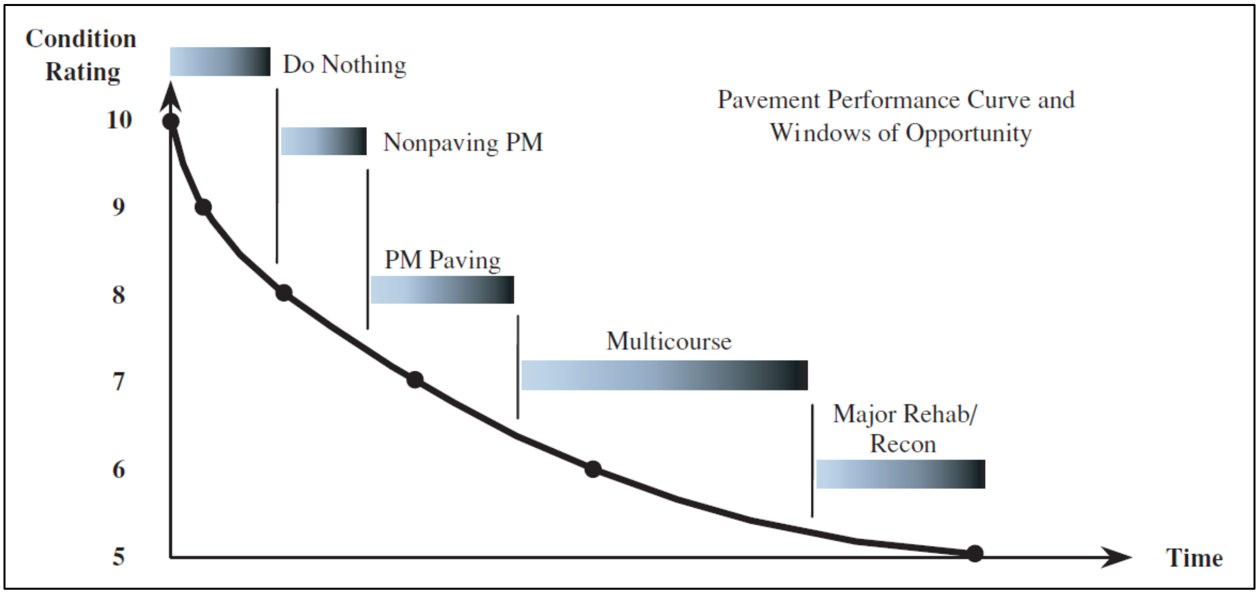
A synthesis published in 2009 summarized the pavement condition index methodology by State (Papagiannakis et al. 2009). Nearly every state had a different methodology and terminology. Some DOTs compute indices using a 5-point range, each with unique definitions for good or better pavement. Examples of these states include:

- California: 2 is good; 1 is excellent.
- Delaware: 3 to 4 is good; 4 to 5 is very good.
- Idaho: 3 to 5 is good.
- Michigan: 1.0 to 2.5 is good.
- Oregon: 2.0 to 2.9 is good; 1.0 to 1.9 is very good for non-NHS.

Twelve (12) DOTs reported evaluating pavement condition scores on a 100-point scale, and there were twelve different definitions for "good" pavement. Other terms to identify "good" pavement include excellent, very good, and acceptable. In calculating ratings and scores, there was little consistency reported among DOTs (the DOTs use a wide variety of ways to compute ratings).

As mentioned previously, 87% of agencies that responded to the NCHRP Synthesis 501 survey reported that treatment recommendations are generated by the PMS (Zimmerman 2017). The treatment recommendation processes vary by DOT. In 2011 The Second Strategic Highway Research Program (SHRP 2) report on Preservation Approaches for High-Traffic-Volume Roadways was published. Part of this report included a literature review of existing DOT decision-making processes regarding preservation treatments for high-traffic roads (Peshkin et al. 2011). Peshkin reported two approaches for identifying feasible preservation treatments based on existing pavement conditions, decision-support matrices, and decision-support trees. Both approaches rely on rules and criteria to identify appropriate preservation treatments. One of the limitations reported in this study was that the decision-making procedures used by DOTs are not always transferrable from agency to agency due to variable data definitions, indices, and other factors.

For example, the New York State DOT (NYSDOT) uses a surface condition rating on a scale of 1 to 10, where 9 to10 is very good, and anything less than 5 is poor. The condition rating is established based on the frequency and severity of pavement distresses, including cracking, patches, and potholes. They use this scale along with IRI to identify treatment candidates for preservation and rehabilitation. Figure 13 shows NYSDOT's general pavement performance curve, which illustrates different preservation and rehabilitation opportunities based on the condition rating over time. The treatment selection matrix for flexible pavements is shown in Table 7 (adapted from Peshkin et al.).



Source: Peshkin et al. 2011

Figure 13. Illustration. NYSDOT's pavement performance curve is illustrating different preservation and rehabilitation opportunities based on the condition rating over time.

Table 7. NYSDOT's preservation and maintenance selection matrix for flexible pavements.

Rating	IRI ≤ 60	IRI 61-95	IRI 96-135	IRI 136-170	IRI 170-220	IRI > 220
Rating ≥ 9	D	D	D	D	D	D
Rating 8	1	1	1	1	1	1
Rating 7	5	5A	9	9	11	11
Rating 6	9	9	9	11	12	12
Rating ≤ 5	9	9	11	12	12	13

The preservation and maintenance strategy numbers shown in Figure 13 correspond to the following treatment strategies:

- 1: Crack seal.
- 5: 6.3 mm asphalt.
- 5A: 6.3 mm asphalt mill and fill.
- 9: Mill and fill.
- 11. Mill and fill with underlying pavement repairs.
- 12: Major Rehabilitation – 2-course overlays with repairs.
- 13: Reconstruction – 3 course overlays with repairs.
- D: Defer treatment.

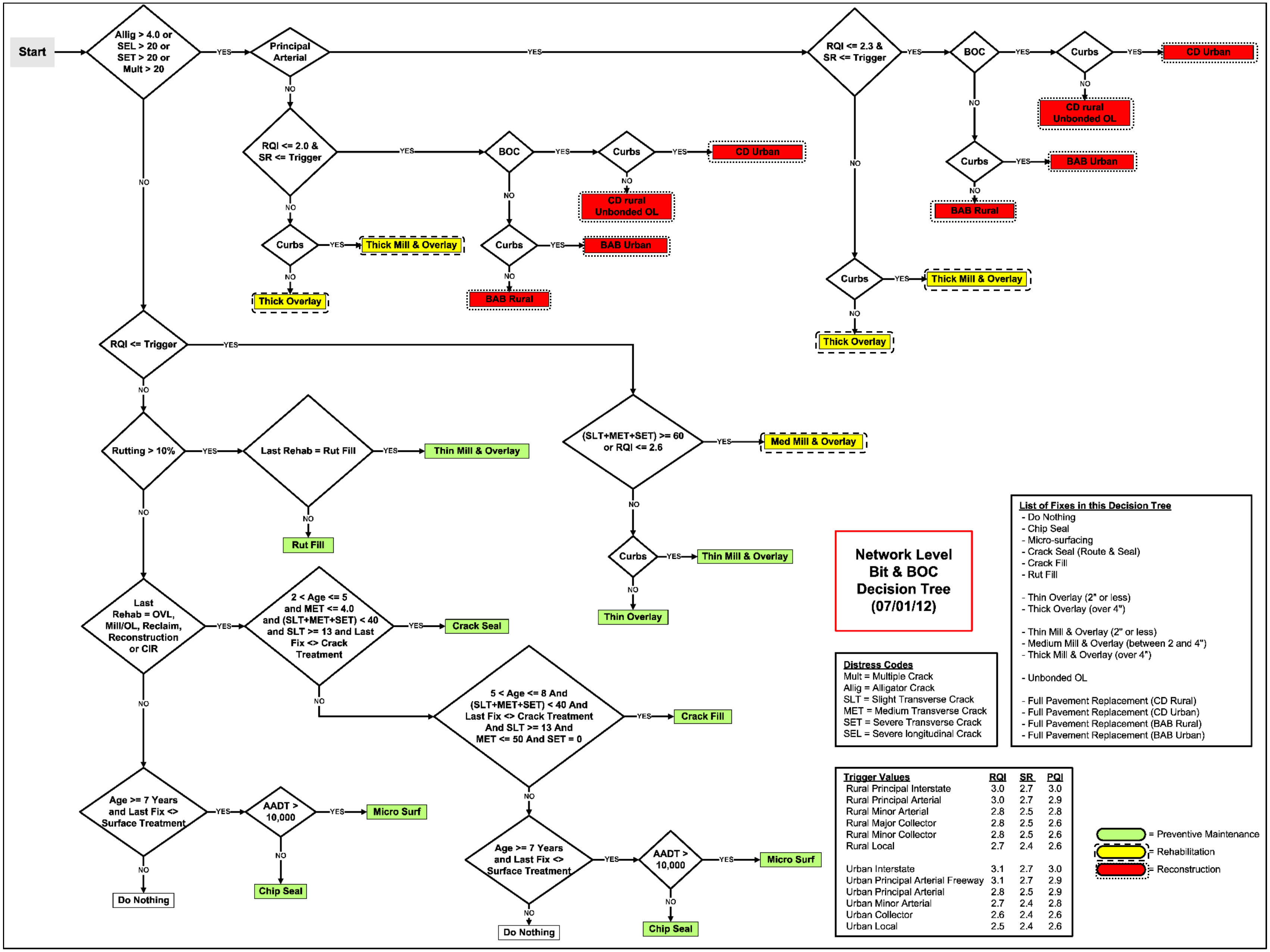
Minnesota DOT (MnDOT) uses a decision tree for selecting preservation and maintenance strategies. This decision tree considers the road type (i.e., urban, arterial, rural), age of pavement, the timing of last treatment, traffic, and a variety of individual distresses and the indices shown in Table 8 (MnDOT 2015).

Table 8. MnDOT Pavement Condition Indices

Index Name	Pavement Attribute Measured by Index	Rating Scale
Ride Quality Index (RQI)	Pavement Roughness	0.0-5.0
Surface Rating (SR)	Pavement Distress	0.0-4.0
Pavement Quality Index (PQI)	Overall Pavement Quality	0.0-4.5

RQI is calculated from IRI. SR is calculated from a variety of distresses. For bituminous surfaced pavements, these include transverse cracking, longitudinal cracking, longitudinal joint distress, multiple cracking, alligator cracking, rutting, raveling and weathering, and patching. The distresses used to determine SR for JCP and CRCP are different. The distress type, amount, and severity are manually rated for the first 500 feet of every mile, and it is assumed the remainder of the mile has the same SR. Distresses are totaled, and weight factors for each distress are applied based on severity. The SR is calculated based on total weighted distresses.

The PQI is a combination of the RQI, and SR.



Trigger Values	RQI	SR	PQI
Rural Principal Interstate	3.0	2.7	3.0
Rural Principal Arterial	3.0	2.7	2.9
Rural Minor Arterial	2.8	2.5	2.8
Rural Major Collector	2.8	2.5	2.6
Rural Minor Collector	2.8	2.5	2.6
Rural Local	2.7	2.4	2.6
Urban Interstate	3.1	2.7	3.0
Urban Principal Arterial Freeway	3.1	2.7	2.9
Urban Principal Arterial	2.8	2.5	2.9
Urban Minor Arterial	2.7	2.4	2.8
Urban Collector	2.6	2.4	2.6
Urban Local	2.5	2.4	2.6

Source: MnDOT 2015

Figure 14. Flowchart. MnDOT network-level decision tree for bituminous surfaced pavements.

The decision-making methods used by MnDOT and NYSDOT have significantly different approaches. Several other decision support matrices and trees were described in the SHRP 2 report, ranging from simple routines involving a few treatments and key distress types to complex algorithms featuring many treatments and an array of distress types, severity levels, and extents (Peshkin 2011).

The quality of data is critical in these network-level decision-making processes. Systematic and random errors can highly distort some PMS output parameters (Saliminejad, 2103). The way data quality specifically affects decision-making processes varies by DOT. This is because, and previously described, each agency has unique definitions for pavement distresses, unique methods for calculating indices and categorizing them as good, bad, or other, and unique methodologies for recommending pavement treatments.

For example, Tennessee DOT (TDOT) uses performance indices for maintenance planning. Jia et al. (2016) evaluated the influence of pavement condition variability on network-level maintenance decisions. For the PMS used in Tennessee, the variability of IRI and distress severity level were the dominant influence factors for maintenance planning. Compared to a control group, an error of +5% IRI could result in nearly 3% more maintenance decisions as opposed to a "do nothing" strategy. An error of 5% IRI corresponds to 0.92 cross-correlations, which are recommended by AASHTO R56 as the passing score for HSIP certification. Small changes in rut depth had no significant influence because TDOT's maintenance decision trees use relatively large rut depths to trigger a change in treatment.

Siabil (2016) researched the impact of accuracy in pavement condition data during the assessment of a road network in Texas. Remaining service life (RSL) was estimated based on eight (8) different indicators, including rutting and different types of distresses. RSL was predicted from raw data, and data with erroneous (suspicious) data removed. The largest difference in RSL was in the category where RSL is less than 2 years, or where rehabilitation is recommended in less than 2 years. There was a reduction of approximately 3% rehabilitation when analyzing filtered data compared to the raw data. In categories where RSL was predicted to be over eight (8) years (relatively good condition) the filtered data (erroneous data removed) only slightly increased the percent of roadway network in that category. This outcome was attributed to fewer potential errors among data in good condition. Using the RSL analysis and typical maintenance strategies, an 8-year budget was estimated for raw data and filtered data. The filtered data reduced the 8-year estimated maintenance budget for the network by 21 million dollars (1.5%). Of the 165,469 pavement sections analyzed, 12,127 were detected to have potential errors in at least one indicator. When the errors were removed from these sections, the average estimated RSL increased from 4.2 years to 11.9 years, suggesting that in this dataset errors mostly exaggerate deterioration.

A case study of Virginia DOT (Flintsch 2009) reports that when they introduced a third party to validate and verify 10% of collected data, there was an 83% reduction in pavements requiring rehabilitation, and a 22% increase in pavements requiring no rehabilitation. The overall outcome was a decrease of 18 million dollars in the recommended maintenance budget for the Virginia Interstate Highway System.

These case studies all indicate that data quality has a significant effect on decision-making and maintenance budgets. In each example, the data errors led to the exaggerated deterioration of pavements that could trigger premature pavement treatments. The monetary savings in these case studies may seem small to agencies' overall maintenance budgets, but it is a significant amount of funding. TxDOT's Unified Transportation Program (UTP), from 2019 to 2028, has a budget of over 75 billion dollars. This program addresses capacity, maintenance, and safety needs around the State. TxDOT is responsible for maintaining over 80,000 miles of road. The largest of the 12 funding categories for the UTP is preventative maintenance and rehabilitation, at 18% of the program, requiring over 13 billion dollars over the next ten years (TxDOT 2019). Several State DOT QMPs reported that their road networks were their largest asset. Making decisions using quality and accurate pavement condition data is the only way to develop accurate pavement investment budgets.

Serigos et al. initiated a pilot study in 2015 that compared two automatic distress data collection vendors with Texas DOT (TxDOT) PMS data. The PMS ground reference data was gathered using three different methods: HSIPs to collect roughness, five-point ultra-sonic sensor rut bar to collect rutting data, and manual raters for distresses. The vendor data was compared to the PMS data, or ground reference data, to identify the differences between calculated indices as well as individual distresses. Both vendors captured more distresses than the manual PMS ratings, and there were differences between vendors. This resulted in lower overall "good" or better pavement condition scores per TxDOT's calculated indices. This study concludes that based on the results and previously completed research, calibration of vendor automated distress algorithms and post-processing can reasonably be expected to achieve more accurate results. This is relevant to this project because the vendor algorithm calibrations specific to DOT definitions is a critical practice for receiving useful quality data. *This is further described in chapter 4.*

FHWA PEER EXCHANGE REVIEWS

Agencies desire data quality improvements. Every DOT that responded to the NCHRP Synthesis 501 survey reported having a plan or wanting to improve data quality (Zimmerman 2017). In 2018 FHWA conducted data QMP Peer Exchanges across the country. Lessons learned from these peer exchanges (Orthmeyer 2018) were shared in a webinar presented by FHWA. A few key topics from the feedback that are considered in subsequent chapters include:

- There is a lack of standard certification protocol for cracking, rutting, and faulting.
- There is some misunderstanding amongst DOTs on the HPMS cracking definitions. There are also issues with getting the vendors to supply the correct value for HPMS cracking.
- There was some confusion surrounding DOT involvement during the certification process. There is a conflict of interest when the vendor is solely responsible for certification. It was noted by FHWA that DOTs could identify appropriate roles for the vendor, but they should be involved in the certification process.
- There were questions on manual rating certification and how to evaluate raters. Some DOTs wanted to know if raters with many years of experience can be grandfathered into certification policies. There were questions on when manual rating applies.

- There was concern about how to obtain ground reference data. FHWA emphasized that repeatability is not enough for quality processes. Accuracy references should be established. Many DOTs are already checking repeatability/precision but are struggling with accuracy and comparisons to ground reference data.
- State DOTs are struggling with what to do with data when repeatability requirements are not met based on their specification and with the corresponding error resolution procedures.
- Staffing was a concern among many DOTs. Several agencies have contracted some of the work to third party agencies.
- Some of the best practices included the use of control sites and historical data comparison.

This feedback mirrors many of the findings from the review of the DOT data QMPs. Subsequent chapters include more information on certification for cracking, rutting, and faulting, levels of agency involvement, processes for certifying manual raters, establishing control sites with ground reference data, implementing statistical analysis methods for data acceptance, and error resolution procedures.

FINDINGS FROM OTHER LITERATURE REVIEW

Pavement surface data collection technology is advancing and changing rapidly. There are several concurrent studies evaluating topics that affect DOT data collection and data QMPs. Some of these studies include standardizing definitions of metrics, proposing certification processes, and establishing reasonable accuracy and precision statements. The report developed in Task 2 should consider the changing technology and remain a living document that can be updated as the relevant research is completed. This section summarizes recently completed projects and on-going projects and how it affects the Document of Successful Practices. It is anticipated that some projects have procedures that are ready for implementation. The report references as many new technologies and processes as reasonable while considering the state-of-practice. The following summaries are based on draft reports, draft standards, presentations, and updates given at industry events (e.g., RPUG/PE 2019), and updates during project meetings. Because many of these studies have not been completed, the content summarized here is subject to change based on outcomes. Table 9 is found at the end of this chapter and summarizes anticipated outcomes of the recent and on-going relevant research, as well as short-term and long-term effects on data QMP.

FHWA Calibration, Certification, and Verification of Transverse Pavement Profile Measurements Project

Measured TPPs of pavement are used to extract deformation parameters such as rut depth, cross-slope, and edge/curb drop off. The accuracy of the estimated deformation parameters depends on the measured TPP accurately representing a transverse section of the road surface. The objectives for this project are to develop calibration, certification, and verification methods and procedures to evaluate the accuracy and precision of transverse pavement profile measurements that are collected at traffic speed. This project considers the accuracy and precision statements for TPP measurements. The outcome of this study includes five AASHTO standards, including:

- Standard Practice for Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems: This practice describes the procedures to assess the accuracy and precision of the Transverse Pavement Profiler (TPP) when the system is excited at the primary ride and wheel hop excitation frequencies. The particular specifications addressed are vehicle body motion error.
- Assessment of Highway Performance in Transverse Pavement Profiling Systems: This practice describes procedures to assess the accuracy and precision of the Transverse Pavement Profiler (TPP) under typical dynamic operation. The particular specifications assessed are transverse measurement spacing, effective transverse width, longitudinal measurement spacing, and vertical measurement error. In addition to the TPP specifications, the TPP is evaluated on the following deformation parameters: rut depth, cross-slope, the vertical magnitude of an edge/curb, and transverse location of an edge/curb. Evaluations are performed by comparing the resulting TPP deformation parameters to ones calculated from ground reference data conforming to Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment.
- Assessment of Navigation Drift Mitigation in Transverse Pavement Profiling Systems: This practice describes the procedure to assess the amount of drift present in localization systems used in TPPs.
- Assessment of Static Performance in Transverse Pavement Profiling Systems: This practice describes the procedure to assess the specifications, accuracy, and precision of the sensor system used on Transverse Pavement Profilers (TPP) in static mode. The particular specifications which are assessed are transverse spacing, transverse width, vertical spacing, straightness error, vertical measurement error, and transverse measurement error.
- Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment: This practice describes the accuracy and precision options to ensure a Ground Reference Equipment (GRE) system is collecting acceptable quality ground reference data. The accuracy and precision are evaluated using four surfaces: a certified straight edge, a straight edge with gauge blocks, a road surface, and a macrotexture surface. The measures evaluated are transverse, longitudinal, and vertical measurement error; transverse, longitudinal, and vertical measurement spacing; transverse straightness; and horizontal plane flatness.

These standards have been tested in equipment rodeos and are ready for further implementation and testing. These methods are summarized in chapter 4.

FHWA Jointed Concrete Pavement Faulting Collection and Analysis

The objectives for this project are to improve the faulting data collection and analysis methods and develop certification and verification procedures to evaluate the precision and accuracy of pavement faulting measurements.

This study is on-going. Phase II of this study should evaluate the proposed verification and certification procedures and determine accuracy and repeatability statements. The proposed certification methods for 3D systems and methods for determining ground reference measurements include the methods that were developed for Calibration, Certification, and Verification of Transverse Pavement Profile Measurements Project. A pilot project evaluating these methods for jointed concrete faulting was scheduled for 2020 but was postponed. These methods are summarized in chapter 4 and will be evaluated under the Phase II project of this report if awarded.

TPF-5(299) FHWA: Developing Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection/Analysis Systems and/or Services

The objective of this project is to develop procedures that include technical assessment protocols for automated and semi-automated pavement cracking data collection and analysis systems and/or services for use in agency vendor selection contracting documents. The procedures should be applicable for automated 2D and 3D systems. The outcome of this project should be two separate documents: Guidelines for Vendor Selection (vendor data collection and analysis services) and Guidelines for Equipment and Software Purchasing (purchase equipment for DOT use). All agencies have unique distress definitions and collect cracking metrics accordingly. Each DOT may collect different types of distress data, as described in previous sections. The HPMS manual describes a standardized cracking metric collected by all DOTs. This study should specifically address the HPMS field manual reporting criteria.

The Guidelines for Vendor Selection should have image quality criteria and a cracking distress data verification criterion. This document has options for control sites, ground reference, specific image quality, reference limits, and other information that can be used by agencies not only for vendor selection but for QC and acceptance criteria. These methods are also applicable to certification procedures and are summarized in chapter 4.

TPF-5(299) FHWA: Development of Standard Data Format for 2-Dimensional and 3-Dimensional (2D/3D) Pavement Image Data used to determine Pavement Surface Condition and Profiles

This project resulted in a draft standard data format of 2D/3D pavement image data to determine PSCs and profiles to meet transportation agencies' data requirements based on their specifications. The report includes proposed compression algorithms to store and transmit 3D pavement images.

Task 2 of the project included a literature review of state-of-practice methods for storing pavement image data. Agencies are collecting a mix of 2D and 3D images. Standardized formatting allows pavement image data from various sources to be shared across different analysis software programs. Because there is no standard for storing and sharing image data, agencies rely on vendor-specific proprietary software and ad-hoc formats to process, display, and report collected data. This lack of standards can make accessing, analyzing, reporting, and referencing historical data difficult for agencies. Efficient and effective data storage and access are critical to data quality management.

Industry practices on how to compress and encode data vary greatly and are typically considered proprietary. Therefore, this study did not analyze the current methods being used for compression and encoding. The Task 3 report includes an assessment of existing data items collected, and options for data items and data formats to be considered in the proposed standard.

Task 4 resulted in a draft standard for data format. A compression method (OSU Method 2) was proposed as a method to conduct a highly compressed and lossless operation on complex and high-resolution 3D surface data. This method cannot be directly implemented in current data collection systems but may be implemented in the next couple of years with improvements in CPU and GPU performance. Other considerations include the development of software integrated with the new compression algorithm that is capable of performing compliance validation with the proposed standard data format, and possible data viewing and analysis applications. These proposed procedures would affect the data QMP processes for data image quality and formatting checks. They may lead to certification and QC /QA opportunities for agencies to implement as part of their data QMP (Wang et al. 2016). The results of this study are being evaluated as described below and are not ready to be implemented.

TPF-5(299) FHWA: The Following Contract for Independent Evaluation of Standard Data Format for 2-Dimensional and 3-Dimensional (2D/3D) Pavement Image Data used to determine Pavement Surface Condition and Profiles

This study is an ongoing independent evaluation of the proposed draft specification previously described. The goals are to verify the functionality and performance of the proposed standard data format and compression algorithm in terms of image fidelity processing speed, data storage needs, and other important parameters. This study should assess the suitability of the standard data format for use by DOTs and 2D/3D technology vendors and propose a set of rules by which a DOT can ensure compliance with the standard data format. Once this study has been completed, the proposed rules should be considered in data quality processes and implemented in future versions of this report.

NCHRP 01-57A: Standard Definitions for Comparable Pavement Cracking Data (AASHTO R 85)

This research is on-going. The objective of NCHRP project 01-57A is to develop standard, discrete definitions for common cracking types of flexible, rigid, and composite pavements. Standard definitions should aid in improving precision and bias levels of automated systems, as well as assist in reporting to national organizations, such as FHWA. As stressed throughout this report, agencies are typically using their unique variation of FHWA LTPP manual and ASTM standard definitions. These were developed primarily for manual surveys and were not intended for automated systems or network-level collection. Many DOTs have made unique distress manuals for identifying and defining cracking. This study should build on the work accomplished in AASHTO PP67 and PP 68 by defining cracking measurement terms and relevant processes for uniformity, standardization, and automation. Task 1 of the study is to evaluate and summarize the current definitions used by DOTs. Upon completion of this project, DOTs should evaluate cracking metrics in their QMPs.

NCHRP 20-05/Topic 49-15 Synthesis: Automated Pavement Condition Surveys

The results of this synthesis were published in 2019. The objective was to document agency practices, challenges, and successes in conducting automated pavement condition surveys. The results are based on a literature review of agency automated pavement condition data collection and analysis efforts, and a survey of highway transportation agencies. Specific considerations include improving staff training, standardization of equipment, methods, algorithms, and reporting; establishing regional certification facilities, improving the accuracy of crack detection; establishing protocols and staff certification for semi-automated surveys, and establishing user groups to discuss issues, successes, and resolutions (Pierce, Weitzel 2019).

FHWA Interstate Highway Pavement Sampling Quality Management Plan

This document is a QMP for the Interstate Highway Pavement Sampling Project. This document includes successful practices for implementing data quality management in network-level data collection and meets the requirements stipulated by item 23 CFR 490.319(c) of the final rule for national performance management measure regulations published by the FHWA. There are detailed procedures including but not limited to: methods for training and certifying manual raters, determination of ground reference data, equipment certification and validation, acceptance criteria, reviewing deliverables, and error resolution. Some of these methods are included in the following chapters.

NCHRP 01-60 Measuring the Characteristics of Pavement Surface Images and Developing Standard Practices for Calibration, Certification, and Verification of Imaging Systems

The objectives of this study are to identify and develop methods for measuring the characteristics of surface images used for pavement evaluation and analysis and develop standard practices for the calibration, certification, and verification of such images for consideration and adoption of AASHTO. AASHTO Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection (AASHTO PP68) addresses the collection of images. However, there are no widely accepted standard practices for calibration, certification, and verification of these images. This information should help DOTs evaluate image data collection systems and improve quality. Upon completion of this study, the new AASHTO Standards should be reviewed and considered in future versions of this report and DOT QMPs.

NCHRP 20-07/Task 411 Review and Update of AASHTO Standard Practice R 87

The goal of this study is to update the AASHTO Standard for Determining Pavement Deformation Parameters and Cross-Slope from Collected Transverse Profiles. The report for this study was released in spring/summer 2020. In the revised practice, the minimum width and longitudinal length of a rut were removed. The draft report also includes procedures for data collection, data reduction, and calculation of rut depth. The proposed revised practice provides a means for identifying the placement of a virtual 1.8-m straightedge on the pavement surface over each wheel path to calculate the rut depth using a virtual ruler extending orthogonally from that straightedge. The definition of cross slope has not changed in the revised practice, but the approach for the calculation of the cross slope includes a linear regression through the transverse profile to estimate an average slope across the lane. These changes should be further assessed for inclusion in future versions of this report and DOT QMPs.

International Efforts

The information on distress identification and management in Europe is limited. The French Institute of Science and Technology for Transport (LCPC 1998) and the Swiss Association of Road and Transport Professionals (GEC 2003) have developed a systematical approach in pavement distress identification in their procedures. Ireland has included the assessment of road pavements based only on the surface condition evaluation (TTI-PMS 2015). In Italy, it is limited to procedures recommended by the National Research Council and isolated cases (IRMP 1988). In recent years, effective pavement classification tools have emerged in many EU countries (European Commission, 2020). The technologies used in the EU are similar to those highspeed 3D laser imaging systems in North America, such as LCMS (Mathavan et al. 2015).

The UK Pavement Management System (UKPMS) is the national standard for pavement management systems for the assessment of local road network conditions and the planning of investment on paved roads within the UK. The primary use of UKPMS is to assist local authorities in the planning of maintenance on the local road network. High-speed data collection vehicle surveys, known as SCANNER surveys in the UK, are mandatory for the assessment of the classified road network. SCANNER surveys are carried out by commercial survey companies, using equipment that has passed an acceptance test and has an accreditation certificate. The UKPMS oversees the accreditation and requires an Annual Health Check to maintain the accreditation based on their specifications. The accreditation procedure includes SCANNER and visual tests specific to different countries, including England, Scotland, Northern Ireland, and Wales.

The UK Roads Liaison Group (UKRLG) brings together national and local governments from across the UK to consider road infrastructure engineering and operations. The UKRLG provides a user guide titled "Advice to Local Authorities: Procuring SCANNER Surveys." The section regarding data quality specifies that an independent auditor should be employed to perform quality audits. A user guide and specification titled "Technical Requirements for SCANNER Survey Data and Quality Assurance" includes acceptance criteria with accuracy and precision criteria. This document includes the recommended services to be provided by the independent auditor (UK Roads 2020). The auditing process includes many of the acceptance activities reported by the DOTs in their QMPs, including database checks for complete and reasonable data. The activities used for verifying the data collection equipment is based on three levels of reference standard as summarized below:

- Primary and Principal reference sites.
    - One primary reference site shall be established, and the data collection equipment shall be tested at the primary reference site once every 13 weeks (quarterly).
    - One or more principal reference sites shall be established, and the data collection equipment shall be tested at the principal reference site(s) once every month.
    - For quarterly and monthly checks, 95% of the differences between "reference data" should fall within the range of specified tolerances. The data are expressed as averages or at intervals of 10 meters.
- Secondary reference sites.
    - One or more secondary reference sites shall be established, and the data collection equipment shall be tested at the secondary reference site(s) once every week.
    - For weekly checks, 85% of the differences between "reference data" should fall within the range of specified tolerances. The data are expressed as averages or at intervals of 10 meters.
- Daily test sites.

- One or more daily reference sites shall be established, and the data collection equipment shall be tested at the daily reference site(s) once every day at the beginning and end of each day of testing.
- For daily checks, 65% of the differences between "reference data" should fall within the range of specified tolerances. The data are expressed as averages or at intervals of 10 meters.

Observations of the UK processes include (UK Boards 2020):

- The contracted data collection contractor (vendor) is responsible for establishing the control (reference) sites. This practice includes associated costs.
- There are no identified criteria for primary, principal, secondary, or daily control sites, such as type of pavement, type, and severity of distresses and smoothness. The only characteristics include being relatively flat, having a length of at least 400 meters, having no sharp bends or extremes of profile unevenness and texture, and being free from isolated defects.
- The contractor is responsible for establishing reference data using the data collection equipment. The reference data is established within seven days of passing the accreditation test. The auditor may carry out an independent survey of any of the sites.
- The auditor has the authority to suspend and revoke the accreditation of the data collection equipment if established control site requirements are not met based on their specifications.
- Contractor repeat surveys are mentioned. This is for establishing the precision of data collection vehicles. Ten repeat surveys are required per year for each survey vehicle. For repeat surveys, 65% of the differences shall fall within the range of tolerances specified in their specification. The assessment of data is carried out by the auditor over lengths of 50 meters. There repeat surveys are performed at sites different from the established control sites. Repeat survey sites are reasonably spread across different regions, different types of the local authority, and different road conditions, and are reasonably spread through the survey year.
- Auditor repeat surveys may be implemented by the auditor. These surveys compare the contractor survey equipment to auditor selected survey equipment. For auditor repeat surveys, 65% of the differences shall fall within the range of tolerances specified. The assessment of data is carried out by the auditor over lengths of 50 meters.
- Random spot checks may be implemented to ensure that the contractor surveys are being carried out acceptably. These checks include having the auditor accompany the contractor to assess the competence of drivers and operatives carrying out SCANNER surveys.

The processes for third party independent auditing in the UK appear to be relatively standardized. Ground reference data is established using contractor data collection equipment. This process may be an adequate method for establishing ground reference and checking the accuracy of the data collection equipment during QC activities. The UK technical requirements of the certification procedures should be assessed to see how they compare to the procedures in the on-going relevant research. The certification procedures in the UK, specifically control sites and ground reference data collection, should be evaluated for use in certification procedures as appropriate. Requiring or allowing that the contractor establish control sites (including costs associated) may be evaluated and proposed as an option. Third-party auditing may be evaluated and proposed as an option to carry out acceptance activities. The approach to using a variety of control sites, with different levels of acceptance criteria associated with frequency of testing (quarterly, monthly, weekly, daily), may be considered and implemented as a successful practice. This is further described in chapter 3.

Table 9. Summary of relevant research, the anticipated outcome of the research, and short-term and long-term implementations into the Document of Successful Practices.

Study/Research Reference	Anticipated Outcome of Study	Short Term Implementation	Long Term Implementation
TPF-5(299)/FHWA: Calibration, Certification, and Verification of Transverse Pavement Profile (TPP) Measurements	The objectives of the ongoing study are to determine the precision and accuracy of data collection equipment measuring TPPs to meet the needs of users, and to evaluate existing data collection equipment using established tests to see if they meet the precision and accuracy that has been established. The outcome is AASHTO methods, which can be implemented by agencies to certify the equipment. Additionally, an AASHTO method for determining ground reference data for TPPs is also proposed.	The draft AASHTO specifications have been completed and are ready for trial testing in pilot projects. The draft procedures for certification are included in chapter 4.	The specifications are being balloted by AASHTO as prevision specifications in 2020 and have been tested in limited equipment rodeos. However, they have not been widely adopted by agencies. Updates to the prevision specifications may occur during the period of this project. Therefore, some adjustments to the report may occur.
TPF-5(299)/FHWA: Jointed Concrete Pavement Faulting Collection and Analysis Standards (AASHTO R36)	The objectives of the ongoing study are to update AASHTO 36 by standardizing the definition of faulting and provide information on quantifying faulting, determine precision and accuracy options for high-speed equipment measuring faulting to meet the needs of users, and to provide procedures for certification, collection, and evaluation of fault data collected by data collection equipment. The proposed certification procedures and determination of ground reference for 2D and 3D data collection equipment should assess for application the procedures developed under the TPF TPP study and the current longitudinal HSIP certification processes.	The proposed accuracy and repeatability statements have not been completed. The proposed AASHTO methods have not been evaluated and may not be ready for trial testing in pilot projects. However, the certification procedures suggested at this time are similar to the longitudinal profiler certification procedures (2D) and TPP procedures (3D). The draft procedures for certification are included in chapter 4.	The outcome of this project should deliver a standardized definition of faulting, optional accuracy and precision statements, and information on how to establish control sites and ground reference data. Once these specifications are available, the report should be updated to reflect current successful practices.

Study/Research Reference	Anticipated Outcome of Study	Short Term Implementation	Long Term Implementation
TPF-5(299)/FHWA: Developing Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection/Analysis Systems and/or Services	The objectives of the ongoing study are to develop procedures that include technical assessment protocols for automated and semi-automated pavement cracking data collection/analysis systems for use in agency vendor selection contracting documents. The procedures should be applicable for 2D and 3D systems and should be efficient, standardized, and effective in providing contract language for agencies to use in vendor selection.	The procedures can be followed for validation, verification, quality control, and acceptance procedures, including establishing control sites and ground reference, to keep processes efficient for agencies. Manual rater training and certification procedures are addressed. The draft procedures are adapted for certification and are included in chapter 4.	The procedures are still in draft form and have not been widely tested among agencies. Updates to the draft specifications may occur. Cracking assessment technologies are changing rapidly, and the report should stay current with state-of-practice.
TPF-5(299)/FHWA: Development of Standard Data Format for 2-Dimensional and 3-Dimensional (2D/3D) Pavement Image Data used to determine Pavement Surface Condition and Profiles	This study was completed in 2018. The outcome of the study was a draft metadata/data format to determine PSCs and profiles to meet agency needs. The result was a draft AASHTO Standard Specification for File Format of 2-Dimensional and 3-Dimensional Pavement Image Data	The proposed AASHTO data format standard was evaluated and revised independently under the following project.	Please refer to the following project.
TPF-5(299)/FHWA: The following Contract for Independent Evaluation of Standard Data Format for 2-Dimensional and 3-Dimensional (2D/3D) Pavement Image Data used to determine Pavement Surface Condition and Profiles	The objectives of this ongoing study are to independently evaluate the draft AASHTO Standard Specification for File Format of 2-Dimensional and 3-Dimensional Pavement Image Data delivered under TPF/FHWA: Development of Standard Data Format for 2-Dimensional and 3-Dimensional (2D/3D) Pavement Image Data used to determine Pavement Surface Condition and Profiles, verify the functionality and performance of the proposed standard format, address the suitability for agencies and vendors, and propose a set of rules by which a DOT can confirm compliance with the standard data format.	This study does have proposed specifications or rules established and is being assessed for implementation.	This objective of this study is a standard data format for 2D and 3D pavement image data format. This may lead to verification/validation options for the pavement data image format in the data QMP.

Study/Research Reference	Anticipated Outcome of Study	Short Term Implementation	Long Term Implementation
NCHRP 01-57A: Standard Definitions for Comparable Pavement Cracking Data (AASHTO R 85)	The objective of this ongoing study is to develop standard, discrete definitions for common cracking types in flexible, rigid, and composite pavements. The standard definitions should be used to facilitate comparable measurement and interpretation of pavement cracking. The definitions should be of sufficient details to serve as the basis to meet users' needs for developing automated cracking software, and for being compatible with both existing and emerging image-based data collection technologies.	The study does not have any definitions ready for immediate implementation.	The objective of this study is to standardize cracking definitions. This could impact DOT definitions and practices for control sites, ground reference data, manual rater training, and acceptance criteria.
NCHRP Project 20-05/Topic 49-15 Synthesis: Automated Pavement Condition Surveys	The objective of this synthesis is to document agency practices, challenges, and successes in conducting automated pavement condition surveys and showcasing successful agency practices, integration of automated data into pavement management systems, and efforts for national reporting of pavement condition.	This synthesis includes state-of-practice surveys from agencies with information regarding data collection processes, budget, challenges, how data are used, and other information that can be used for structuring the report and tailoring to agency needs.	This synthesis includes state-of-practice surveys from agencies because state-of-practice is changing rapidly with changing technologies; this synthesis does not have a long-term implementation.
NCHRP Project 01-60 Measuring the Characteristics of Pavement Surface Images and Developing Standard Practices for Calibration, Certification, and Verification of Imaging Systems	The objectives of this study are to identify and develop methods for measuring the characteristics of surface images used for pavement evaluation and analysis and develop standard practices for the calibration, certification, and verification of such images for consideration and adoption of AASHTO.	The study does not have any standard practices available for short term implementation	The AASHTO standard should provide processes for calibration, certification, and verification of surface images used for analysis and pavement evaluation.
NCHRP 20-07/Task 411 Review and Update of AASHTO Standard Practice R 87	The goal of this study is to update the AASHTO R87 Standard for Determining Pavement Deformation Parameters and Cross-Slope from Collected Transverse Profiles.	This goal of this study is to update protocols for rutting and cross-slope. The proposed updates have been completed at this time.	When the AASHTO R87 update is provided in draft or final form, it should be assessed and incorporated into the data QMP report.

CHAPTER 3. BEFORE DATA COLLECTION: PLANNING AND SETUP

INTRODUCTION

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

Each DOT is required to provide certain PSC information based on HPMS standardized definitions per 23 CFR 490.319(c). Most DOTs chose to report only HPMS defined metrics within their QMPs 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.

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).

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

DESCRIBING DATA QUALITY

Data quality has been described by many industries, and there are many ways to describe data quality. This was previously discussed in chapter 2. The concepts are summarized again here as they directly relate to PSC data collection planning and setup. Table 10 provides standard data quality aspects as they related to PSC data collection adapted from Rodriguez (2017). It is essential to keep these data quality concepts in mind during the planning and setup of data quality programs.

Table 10. Summary of data quality dimensions related to PSC data collection.

Data Quality Aspects	Description
Accessibility	DOTs can easily locate and access the data. DOTs should 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 is used, the information does not change. This may be difficult for DOTs moving from manual data collection to automated data collection and should be considered during planning and setup.

Data Quality Aspects	Description
Relevance	The data is relevant, clear, and concise, and it is processed to meet DOT's unique decision-making processes. Each DOT should work with equipment vendors or manufacturers to ensure the data they are receiving is the data specific to their decision-making processes. Calibrations of algorithms are further described in chapter 4.
Completeness	The data used to make decisions is available. The data should be completely processed so that it is ready to implement 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. Data metrics with nationally recognized standards may include accuracy and precision statements. More information on establishing accuracy and precision statements can be found in chapters 4 and 7.
Believability	DOTs can trust the data received. Proper QC and acceptance activities, along with documentation on these activities, make the data believable. DOTs should be able to 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 should be accessible to DOTs before making network-level decision-making processes.

IDENTIFYING DATA METRICS AND PROTOCOLS

DOTs should consider all critical data metrics in its data collection program. A critical data metric is one that is used for classifying pavement condition or treatment types. Based on the literature review in chapter 2, the data metrics collected vary by agency. The data definitions are also unique. Under 23 CFR 490, DOTs are required to collect and report the standardized HPMS Field Manual data metrics. The HPMS field manual’s definitions may be different 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 QMPs that were submitted to FHWA, but it may be useful to develop similar plans for all data being collected.

HPMS Pavement Surface Condition Required Data

The data QMPs 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. QMPs should reference these required protocols. Many DOTs referenced these protocols in a table format in their approved QMPs. An example of a reference table meeting all of the requirements for HPMS data metric required protocols is shown in Table 11This table has been adapted from the Maryland DOT Pavement Data Quality Management Program (Maryland DOT 2018).

Table 11. 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 QMP.

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.
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 48-10, 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.

Note that the CFR specifies the years of AASHTO standards to be used during HPMS data collection and reporting. Many of these standards have been updated or are currently in the process of being updated. It is suggested that updated versions are used as long as they still meet the requirements of the version listed in the CFR. Several on-going projects are updating these standards, including:

- AASHTO Standard Practice R87: NCHRP Project 20-07/Task 411 has proposed updates for The Practice for Determining Pavement Deformation Parameters and Cross Slope from Collected Transverse Profiles. The proposed updates include a complete revision for 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 is planning to include standardized definitions for cracking in the AASHTO Standard.

DOTs should be aware that these standards are evolving and consider how their data collection programs may be affected.

Data collected and reported to meet the FHWA rule under 23 CFR 490 requires compliance with the procedures and definitions of the required protocols listed in Table 11. These procedures and data definitions may be different from DOT specific data.

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 should improve all data being collected regardless of the type of definition. For example, improving the certification processes for 3D sensor data collection equipment systems should improve all rut depth data collected, regardless of the unique rut definition being used. DOTs may consider adding all PSC data metrics that are collected during network level testing with their associated protocols similar to Table 11 as a reference. Many case studies shown in this document use the standardized HPMS defined metrics as examples, but DOTs should implement similar practices as appropriate for all critical data metrics in their network data collection.

SCHEDULING

Establishing and reporting scheduling considerations was not explicitly stated in the submitted QMPs reviewed in this project. However, scheduling is an essential factor in data quality as environmental conditions can affect PSC data. Reporting scheduling statements in a QMP may be useful to improve data quality based on environmental conditions and to ensure data is timely for use. The following successful practices on scheduling items that were reported in DOT QMPs 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 established based on different logistic and practical factors—such as forecasted weather conditions for the day, and 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 east-bound lanes is typically planned for the afternoon, while collection on west-bound direction lanes is typically planned for the morning (Maryland 2018).
- Data collection starts no earlier than May 15th and is completed by August 31st of 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). This keeps 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 upfront to the data collection vendor. This provides the time for 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). This 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 slowdown of traffic 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

This section includes considerations for the delineation of responsibilities for quality management tasks. Most DOTs reported the delineation of responsibilities in their QMPs. It is important to assign responsibilities to specific data collection or analysis team members to ensure the quality management activity is performed and confirm that staffing resources are adequate. Assigning actual employee names is useful for accountability and ensuring team members are aware of their roles. Table 12 7shows an example of project team roles and responsibilities adapted from the Connecticut Department of Transportation’s (CTDOT) QMP. Note that the terms used to describe team roles and actual responsibilities may be unique and may not apply to all DOTs.

Table 12. Example of project team roles and responsibilities adapted from the 2018 Connecticut Department of Transportation's QMP.

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 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 PMU data processing, analysis, and reporting. • Monitor schedule and reporting 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.
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 Vision software LCMS, 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, 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.

Team Role	Assigned Resource	Quality Management Responsibilities
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 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.
Field Crew Lead	Employee Name and Company	• Ensure and document initial equipment configuration, calibration, and verification. • Ensure performance of daily and/or 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 performance of monthly verification runs on validation, sites. • Ensure documentation of all field QM activities and reporting of any problems using QC log.
Field Crew	Employee Name and Company	• Perform daily and/or 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 ARAN Daily Mileage Summary.

As stated in the literature review, some DOTs self-collect PSC data using their equipment and perform the analysis in-house. Other DOTs use a vendor to perform the data collection. When using vendor services, some DOTs elect to have the vendor perform some of the analysis and quality management responsibilities. When using vendor services, DOTs should have some involvement in each of the quality management activities to ensure their data quality standards are being met.

Table 13 summarizes the suggested roles for DOTs to have in quality management programs relative to the three phases of data collection. These tasks should be performed by a DOT employee or person representing the DOT and not the data collection vendor.

Table 13. 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
• DOTs should establish a scope of work (SOW) documents with general data needs, including protocols, definitions, formatting. • DOTs should establish a schedule based on receiving data timely for use and trying to avoid data error due to environmental conditions. • DOTs should establish or approve control sites for use in quality management activities. • DOTs should review, approve, and keep a record of equipment calibration reports. • DOTs should establish the certification requirements and oversee certification processes based on their specifications. DOTs should review, approve, and keep a record of equipment certification reports. • DOTs should review, accept, and keep a record of training programs for the data collection team and manual raters (as applicable).	• DOTs should establish requirements for the minimum frequency of QC activities and QC reporting based on their specifications. • DOTs should establish requirements for minimum QC activities, including frequency of verification at control sites based on their specifications. • DOTs should review, accept, and keep a record of all QC reporting. • DOTs should require periodic data submission for acceptance reviews based on their specifications. Performing all acceptance reviews at the end of the data collection season should be avoided to reduce the possibility of systematic errors and large batches of data that are recollected.	• DOTs should perform final data acceptance activities. • DOTs should have data acceptance requirements that are performed separately from QA 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 6. • DOTs should keep a record of all acceptance activities. • DOTs should establish error resolution and dispute resolution processes to implement and follow. These should be discussed and accepted/rejected by the data collection team after data collection. DOTs should have methods in place to ensure all error resolutions have been resolved, accepted, rejected/re-collected, and recorded.

ESTABLISHING CONTROL SITES AND GROUND REFERENCE

This section provides an overview and summary of the different ways that control sites and ground reference can be used before data collection, during data collection, and possibly after data collection (for troubleshooting, error resolution, or error dispute processes). Control sites and ground reference data are critical for successful quality management programs and are described throughout this document. This section describes general control site concepts that DOTs may consider for use in their QMPs. More detailed criteria for control sites specific to data quality activities are included in subsequent chapters.

Control Site Types

The purpose of data quality management is to give the DOT, national, and local governments confidence that the data and results provided by the data collection team are consistent and suitable for decision-making processes. Proper setup and routine use of control sites can be an efficient way to perform quality management activities. Based on the review of DOT QMPs, most DOTs are using control sites during quality management activities, including calibration, certification, quality control, and quality acceptance activities. The methods for establishing these sites vary among DOTs, and some DOTs provided little detail regarding control sites. Using different types of control sites may be useful, as efforts dedicated to setting up a control site and ground reference data for certification procedures may be uneconomical and impractical for daily, weekly, or monthly quality checks. This section provides several types and levels of control site and ground reference data collection. These control site and ground reference levels are adapted from the 2012 Edition of the User Guide and Specification Volume 4 Technical Requirements for SCANNER Survey Data and Quality Assurance provided by the UK Roads Board (UK Roads 2020). These concepts are partially being used among DOTs, but few DOTs provide sufficient details for control site criteria and ground reference data in their QMPs. Differentiating the types of control sites in QMPs is useful to ensure that the quality management activity occurs at a suitable control site. Four types of control sites are described here:

- Vendor (or Manufacturer) Control Site
- Top Tier Control Site (optional for blind control site)
- Middle Tier Control Site (optional for blind control site)
- Bottom Tier Control Site

DOTs should evaluate these types of control sites and use a combination of these sites in their quality management program to meet their specific data quality needs. DOTs may find that they already use a combination of these control sites but may consider the addition of a Top Tier control site to their QMP for certification purposes. Control sites should be identified and detailed in DOT QMPs.

Vendor (or Manufacturer) Control Site

Intended Use

The Vendor (or Manufacturer) Control Sites are used mainly for calibration of the sensors, subsystems, and algorithms of the data collection equipment and should be established per manufacturer-specific criteria. This control site may also be used to monitor long term data trends. DOTs may be involved with the development of this control site. DOTs should review and accept the calibration processes, including the use of control sites, to ensure the data collection equipment meets the needs of their data program.

Frequency of Use

The frequency of use is dependent on the manufacturer’s recommendations. In general, the minimum frequency for calibration is before data collection begins, after any data collection maintenance is performed, or if there is suspicion in the data collection equipment.

Criteria

The criteria should come from the data collection vendor or equipment manufacturer. The DOT should participate in the calibration of algorithms to ensure that their data definition needs are met.

Ground Reference Data

This control site is mostly the responsibility of the vendor or equipment manufacturer, although DOTs may be involved with the development of this control site. The ground reference data collected here should be following the manufacturer's recommendations. The DOT should understand, review, and approve the methods to ensure their data needs are met.

Top Tier Control Site

Suggested Use

Top Tier control sites have the strictest criteria for site conditions and ground reference. Therefore, the Top Tier control sites are intended for certification purposes. A sufficient amount of Top Tier control sites should be established for certification of data collection equipment. Specific criteria for different data metrics are further described in chapter 4. This control site should be independent of the vendor and manufacturer control site to verify and/or validate calibrations of sensors and algorithms. While these control sites are appropriate for any quality management activity, these are the most time intensive and use the most resources to establish, and it may not be economical to use Top Tier sites for all quality management activities. Top Tier control sites may be used as blind control sites, as described below.

Frequency of Use

The frequency of use is dependent on DOT certification frequency policies. In general, minimum requirements by DOTs are (1) before data collection begins, (2) after any data collection maintenance is performed, (3) if there is suspicion in the data collection equipment, (4) if the vendor or manufacturer has made significant changes to the data collection equipment, or (5) if there has been a significant time gap in the testing schedule.

Criteria

Top Tier control sites should meet the following minimum criteria:

- Pavement types should represent the pavement types found in the network (asphalt, jointed concrete pavement (JCP), continuously reinforced concrete pavement (CRCP).
- There should be a range of pavement smoothness representative of the smoothness found in the network and a range of type and severity of distresses representative of the network.
- Control site/s should have known lengths and Top Tier ground reference data.
- Control site/s should have a clear written testing plan including testing procedures and acceptance criteria with allowable tolerances between ground reference and data collected using the high-speed vehicle, and precision statements for repeat runs.
- The control site/s location should be selected conveniently so that DOT representatives can perform or oversee certification processes.
- Control sites should meet additional criteria specific to different equipment systems, as further described in chapter 4.

Ground Reference Data

The ground reference data should be collected separately from the data collection equipment in a manner that is representative of the DOTs data collection needs and decision-making processes. Ground reference data is specific to each metric collected and used in DOT data management processes. Chapter 4 summarizes some of the ground reference equipment that DOT stated using in their QMPs but may not be exhaustive. Many DOTs do not reference ground reference equipment for all data metrics. In this instance, ground reference equipment meeting the draft AASHTO procedures developed during ongoing TPF-5(299)/(399) is suggested. The DOT should be responsible for collecting or overseeing the collection of ground reference data for Top Tier control sites. Environmental conditions between Top Tier control site data collection and ground reference data establishment should be similar to avoid differences in data based on climate (curling and warping, the difference in crack widths, and other).

Middle Tier Control Site

Suggested Use

Middle Tier control sites may have more lenient criteria for control site conditions and ground reference. The Middle Tier control sites are intended mainly for QC and data acceptance activities. This practice allows for Middle Tier control sites to be set up throughout the road network in convenient locations, and testing may be at a frequency of weekly, or biweekly, or other. Middle Tier control sites should be used at an increased frequency to verify and/or validate the data collection equipment. Middle Tier control sites may be used as blind control sites, as described below.

Frequency of Use

The frequency of use is dependent on DOTs quality management procedures. Many DOT QMPs referenced using control sites as QC or acceptance tool at a weekly frequency.

Criteria

Middle Tier control sites should meet the following minimum criteria:

- Pavement types should represent the pavement types found in the area/region where data is being collected (asphalt, jointed concrete pavement (JCP), continuously reinforced concrete pavement (CRCP).
- There should be a range of pavement smoothness representative of the smoothness found in the area/region being tested and a range of type and severity of distresses representative of the area/area being tested.
- Control site/s should have known lengths and Middle Tier ground reference data.
- Control site/s should have a clear written testing plan including testing procedures and acceptance criteria with allowable tolerances between ground reference and data collected using the high-speed vehicle, and precision statements for repeat runs.
- The control site/s should be conveniently located so that the data collection team can perform checks at the specified frequency.

Ground Reference Data

The ground reference data should be collected economically and efficiently while still ensuring data quality. An efficient method for collecting ground reference equipment for Middle Tier control sites may include using high-speed data collection equipment to collect ground reference data, as long as the equipment has passed certification within a specified period. This may be the equipment used for network collection or separate equipment. The following statements have been adapted from the UK Boards (2000) regarding establishing ground reference at Middle Tier control sites that are used for "weekly" checks:

- The data collection team surveys the control sites using high-speed data collection equipment within seven days of meeting certification.
- The contractor may carry out more than one survey over each site as a measure of consistency and repeatability.

DOTs may elect to classify their existing control sites that do not meet Top Tier criteria as Middle Tier.

Bottom Tier Control Site

Suggested Use

Bottom Tier control sites have the least criteria for site conditions. The Bottom Tier control sites are intended to be used frequently to verify and validate the data collection equipment for QC checks. Bottom Tier control sites should be selected in a convenient location for carrying out checks before and after each day of work or data collection segment. These sites are useful for quickly checking data quality but should not be a standalone QC procedure.

Frequency of Use

These sites should be used twice daily, or at the start and stop of a data collection shift or segment. The intent is to collect data on the same section of pavement two times: (1) once at the beginning of a collection shift or segment and (2) again at the end of a collection shift or segment. If the data is reasonably the same, according to DOT requirements, the data collected between the two tests is likely valid. This practice is a good daily check if the data collection equipment is starting and stopping at the same location on the same day. Proper route planning can ensure that Bottom Tier control sites occur at the desired frequency.

Criteria

Bottom Tier control sites should meet the following minimum criteria:

- Pavement types should represent the pavement being tested (asphalt, jointed concrete pavement (JCP), continuously reinforced concrete pavement (CRCP).
- Control site/s should have a clear written testing plan including testing procedures and acceptance criteria with allowable tolerances between the start of shift and end of shift profiles.

- The control site/s location should be selected conveniently to the overnight storage of the data collection vehicle when being used daily or at the storage location at the end of a data collection route.

Ground Reference Data

Ground reference data is not collected for Bottom Tier control sites. The data collection team should collect data in the designated site as close as possible to the beginning of the data collection shift or segment and perform another survey at the same site as close as possible to the end of the data collection shift or segment. The data from the start and end of the shift should be compared to ensure established precision tolerances are met. The initial set of data becomes reference data.

Note that an example of using a Bottom Tier QC site for QC testing is included in chapter 6 under the section regarding "LCMS Data Quality Tips and Tricks" item number 6.

Option for Blind Control Site

Suggested Use

Blind control sites may be used as QC or quality acceptance tools. Blind control site locations are not disclosed to the data collection team before data collection. The location of blind control sites is disclosed after testing has taken place. The data collection equipment team should submit the data collected from the blind sites to the DOT for review and approval. Blind control sites largely check the accuracy of data, 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.

Frequency of Use

If a DOT elects to use blind control sites, the frequency depends on other QC and acceptance measures that take place. For example, a DOT using a blind control site as an acceptance tool may want to perform blind control site checks at a regular frequency to ensure data being collected meets their requirements. This prevents large amounts of data reprocessing or re-collection.

Criteria

Blind control sites should meet the following minimum criteria:

- The control site/s location should be randomly generated but encompass all pavement types in the network.
- Control site/s should have a clear written testing plan, including testing procedures and acceptance criteria, with allowable tolerances between ground reference and data

collected using the high-speed vehicle. The data collection team should be made aware of the details regarding blind test sites except for the location.

Ground Reference Data

Ground reference data may be collected the same way that ground reference data is collected for top tier or middle tier control sites, depending on the DOT's blind control site data evaluation criteria.

Successful Case Study

The following is an example of Pennsylvania DOT's (Pennsylvania DOT 2018) use of blind verification sites as a QC tool. Note that the use of blind verification sites is only one part of their three-part QC program.

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.

ESTABLISHING DATA EVALUATION CRITERIA

Evaluating Quality Management Activities, Technologies, and Environmental Controls

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

Acceptance criteria should be established for each data element and each quality activity. These criteria are typically quantitative (e.g., a coefficient of variation of repeated IRI measurements from verification testing of HSIPs lower than 5%), and it can include qualitative checks (e.g., visual inspection of pavement surface image quality). Examples of acceptance criteria for different pavement data types and testing types extracted from multiple State DOT data QMP documents include:

- Validation of measurement system's rut depth measurement: sample means of repeated measurements within ± 0.05 inches of reference for accuracy and maximum difference between repeated rut depth measurements within ± 0.05 inches for precision.
- Calibration of a distance measuring instrument (DMI): repeated measurement of 0.33-mile long calibration site within ± 0.5% of the calibration standard.

- Daily verification of HSIP: bounce test static values less than 3 inches/mile and bounce values less than 8 inches/mile, and block checks should be within 0.0001 inches of the designated block height (1 and 2 in. height).
- Daily verification of pavement surface images: visual check of image quality (e.g., flag excessively bright images), correct aspect ratio, the interval between images, and no overlap or gap between left and right images.

Currently, some data metrics have national standards that include acceptance criteria for their measurement method (e.g., AASHTO R 56-14 for acceptance of HSIPs). Acceptance criteria for metrics without a standard specification should be based on the agency's purposes and limitations. This section discusses aspects to consider when setting acceptance criteria for the analysis of testing data.

The acceptance criteria should consider the intended use of the data. For instance, the accuracy and precision used for network-level performance trends are typically not as high as calibrating design models for use at a project level. Another important consideration when setting the acceptance criteria is the capabilities of existing state-of-the-practice measuring technologies and available methods for the collection of reference data. As an example, DOTs acceptance criteria for IRI measurements are typically more stringent than those set for surface cracking data as a consequence of the challenges associated with developing cracking ground reference measurements, the variability of cracking definitions, and the current differences in technology and maturity levels among the available measuring systems.

Different acceptance criteria may be considered for different quality management activities. Many QC and quality acceptance activities, including certification, verification, and validation testing occur at control sites. DOTs may have different types of control sites for different types of activities, as previously described in this chapter. Table 14 summarizes these control sites and summarizes how the ground reference data and environmental controls should affect the acceptance criteria. These concepts are further described with an example from the UK board's implementation of acceptance criteria for different levels of control sites is shown in Table 15. These tables have been adapted to include the naming conventions used in this document. Table 15 is based on reporting intervals of 10 m. Note that the UK board uses the same tolerance for evaluating collected data against the reference data, but the percent within limits changes with the type of control site.

Table 14. Examples of how ground reference data and environmental controls may affect tolerances for acceptance criteria.

Control Site Type	Primary Use	Ground Reference Data	Environmental Controls	Tolerances for Acceptance Criteria
Top Tier	Certification	• IRI: SurPRO walking profiler or other. • 3D Systems and Faulting: Scanning equipment capable of creating a point cloud with a higher density than the data point cloud. • Cracking: Manual rating that takes place closed to traffic by a trained rater.	Strict environmental controls are suggested. Similar ambient conditions between the ground reference data collection and the data collection vehicle are suggested.	Strict tolerances for acceptance criteria are suggested because of the quality of ground reference data and strict environmental controls.
Middle Tier	Quality Control or Acceptance	Ground reference data may be collected with a recently certified data collection vehicle, manual measurements, or even historical measurements.	Less control over environmental conditions. Ground reference data may not be as "true" as ground reference established for Top Tier sites.	Tolerances should consider that there are fewer controls over environment, and ground reference data may be of a lower quality than Top Tier sites.
Bottom Tier	Quality Control	N/A – The first set of data taken for comparison becomes the reference data set.	Least control over environmental conditions. No ground reference data is measured.	Tolerances should consider few to no controls over the environment and no ground reference data.

Notes for Table 14:

1. Ground reference data options are further described in chapter 4.
2. Existing nationally recognized standards or standards currently being developed may include options for acceptance criteria for certification processes.
3. Top Tier sites may have different acceptance criteria depending on quality management activity. For example, Top Tier sites may be used for certification and have strict tolerances for acceptance. The same sites may be used throughout testing with less environmental controls and use a different set of acceptance criteria.
4. Top Tier and Middle Tier sites may be blind sites as previously described.
5. Control sites may also be used to check the location sensors, including GPS, IMU, and DMI.

Table 15. Example of evaluation (or acceptance) criteria used by the UK board to evaluate different types of control sites at different testing frequencies.

Measured Parameter	Tolerance for Certification (Compare to Top Tier)1	Tolerance for Monthly Checks (Compare to Middle Tier)[2]	Tolerance for Weekly Checks (Compare to Middle Tier)[3]	Tolerance for Daily Checks (Compare to Bottom Tier)[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 (area of cracking)	See Note 6	See Note 6	See Note 6	Seen Note 7	N/A

Notes for Table 15:

1. For certification 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 run and (established ground reference) will be calculated. The distribution of these differences will be assessed. If 65% fall within 0.1, the test shall be classified as successful.
7. The tolerance in the detection of cracking is the minimum percentage of 10 m lengths shown by the reference (initial) survey to contain high or low levels of cracking that are also shown to contain high or low levels of cracking in the repeat (final) survey.

Statistical Procedures for Acceptance of Pavement QMP Testing Data

Data collected from QMP testing—such as validation or verification testing—usually consist of a small sample set. These samples are typically collected from 10 or less repeated data collection runs per site, on a limited number of sites collected for each testing condition. Consequently, the quality-related parameters—e.g., bias—estimated from these testing datasets may not be precise. In other words, the bias of testing equipment, or rater, estimated from typical QMP testing data may vary significantly from test to test given the limited number of observations available for analysis. As a result, a direct comparison between the estimated parameter and the acceptance criterion may be misleading. To consider the uncertainty of the quality-related parameters caused by sample variation when comparing it to the acceptance criteria, it is useful to implement statistical techniques, such as *confidence intervals* (CI) and *hypothesis testing* (see Devore 2015 for information on these methods).

The CI of a parameter is estimated from the sample of repeated measurements for a given *confidence level*—e.g., a 95% confidence level. A possible interpretation of, for instance, a 95% CI of the bias is as follows: if the testing were repeated a large number of times, the true bias of the measurements system would fall within the estimated CI 95% of the times. The boundaries of the parameter CI—as opposed to the parameter estimate—are then compared to the criterion for acceptance, allowing for making more reliable decisions.

The first step in estimating the CI is to determine the parameter distribution and to adopt a confidence level. For example, if the sample is large enough (greater than 30 observations), the distribution of the estimated bias tends to be normal due to the central limit theorem. Non-parametric techniques for CI are used when the distribution of the parameter is unknown, and assumptions of parametric techniques are believed to not be met. Next, the boundaries of the CI are determined such that the resulting interval includes an area equal to the selected confidence level. For example, the boundaries of a 95% CI of the bias contains 95% of the possible values centered on the bias estimate (due to symmetry of normal distribution). Consequently, the higher the confidence level, the wider the CI.

As an example, Figure 15 shows the CI of the measurement method bias with a confidence level, α, from a testing sample dataset with more than 30 measurements. Given the number of measurements and that the variance of the bias parameters is unknown, the bias is assumed to follow a t-distribution. Therefore, if the number of observations from a rut depth validation testing was *n*=40, the confidence level was α=95% (with a corresponding t-critical value of $t_{\alpha/2}$=2.021), the sample mean was x_{bar} ($\bar{x}$)=0.30 inches, the sample standard deviation was s_x=0.04 inches, and the reference value was x_{ref} = 0.33 inches, then the 95% CI of the bias would be (negative 0.043, negative 0.017) inches, or negative 0.03±0.013 inches. The measurement method for rutting data would pass the validation test if the acceptance criteria were wider than the CI, such as ±0.05 inches.

$$CI_{\alpha,bias} = \left(\bar{x} - x_{ref} - t_{\alpha/2}\frac{s_x}{\sqrt{n}}, \bar{x} - x_{ref} + t_{\alpha/2}\frac{s_x}{\sqrt{n}}\right)$$

Figure 15. Equation. CI of measurement system bias for a normally distributed sample mean with *n*, number of observations greater than 30.

Where:

$CI_{\alpha, bias}$= confidence interval of bias for confidence level α

t_α= t-critical value for confidence level α

n = number of observations in a testing data set

Another statistical technique to account for the uncertainty of the estimated quality-related parameter is hypothesis testing, by which a hypothesis about the quality-related parameter is tested using the sample data. The first step consists of stating the *null hypothesis* (H_0), which is the hypothesis to be tested, and the *alternative hypothesis* (H_A), which is contrary to H_0. There are two possible outcomes from hypothesis testing, either that there is evidence to reject H_0 in favor of H_A, or that there is not enough evidence to reject H_0. An example of a possible null hypothesis would be H_0: standard deviation (estimate of measurements method precision) is higher than the acceptable value—i.e., H_0: s_x > Tolerance, while H_A: standard deviation is lower or equal to, the acceptable value—i.e., H_0: $s_x \leq$ Tolerance. If the test statistic computed from the sample data is within the rejection region described for the selected significance level α, then H_0 is rejected. From the previous example, if the test statistic computed using the sample standard deviation is within the rejection region, then the s_x > Tolerance hypothesis can be rejected in favor of the acceptable measurement methods' precision one. (Refer to Devore 2015 for detailed information on how to perform a hypothesis test.).

Example: Analysis of Validation Testing Rutting Data for Acceptance

This section contains an example analysis of validation testing rutting data for acceptance of the measurement method's precision. This analysis is conducted through hypothesis testing of the measurement method's standard deviation. The sample rutting data is assumed to have been collected from field validation testing that involved five repeated runs at three pavements sections with similar testing conditions and level of rutting. The acceptance criterion for the rutting measurement is whether the standard deviation, σ, is ≤0.05 inches.

Figure 16 shows the histogram of the sample rut depth measurements collected from the field validation testing. The sample data is assumed to follow a normal distribution. The sample mean, x_{bar} ($\bar{x}$), is 0.38 inches and the sample standard deviation, s_x, is 0.062 inches. The purpose of this analysis is to evaluate if the measurement's method precision meets the acceptance criterion accounting for the sample variation. The following null hypothesis and alternative hypothesis based on the variance are described as H_0: $\sigma^2 \leq 0.0025$ and H_A: $\sigma^2 > 0.0025$. Therefore, this is a one-tailed test.

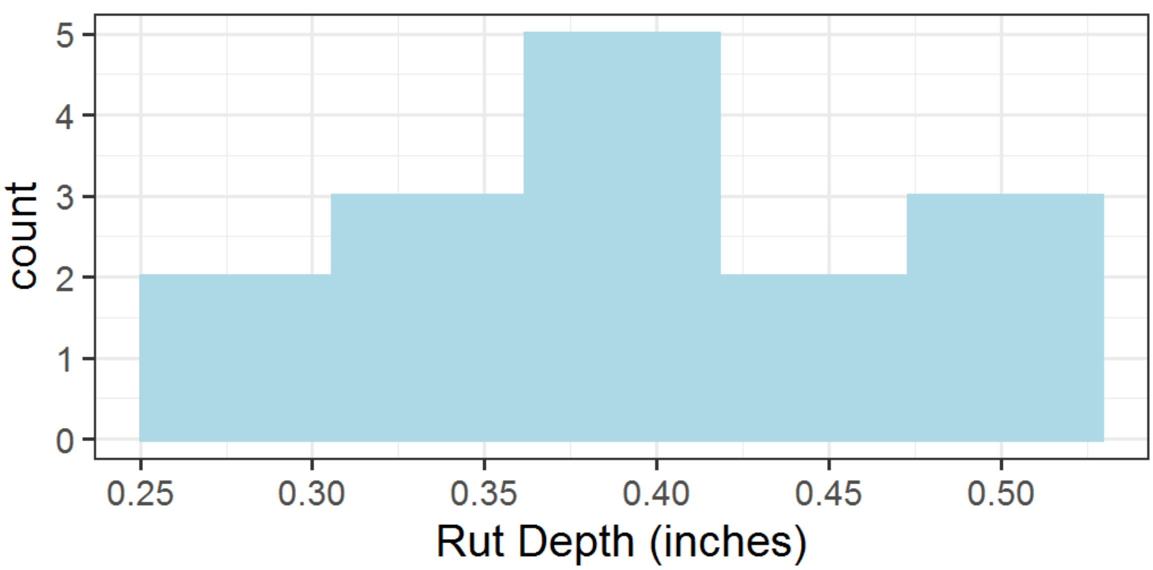


Figure 16. Chart. Histogram of sample rutting data from field validation testing

Since the sample rutting data is assumed to follow a normal distribution in this example, the statistics follows a chi-square distribution, χ^2 with 14 (i.e., n minus 1) degrees of freedom. Using

Figure 17 the test statistic is computed as 21. The confidence level, α, of the test is set to 95%. Therefore, the critical value, $\chi^2_{critical}$, is 23.68. Since the χ^2 value is less than the critical value; there is not enough evidence to reject H_0. In other words, the sample rutting data does not provide enough evidence to conclude that the measurement method's precision exceeds the acceptable limit.

$$\frac{(n-1)s_x^2}{\sigma^2} = \chi^2$$

Figure 17. Equation. Test Statistic Used for Testing Measurement Method's Precision

Where:

n = sample size

s_x^2= sample variance

σ = population (measurement method) variance

Practical limitations from state-of-the-practice measuring technologies and available reference measuring methods are a common limiting factor for agencies in setting acceptance criteria. These acceptance criteria are quality requirements based on agencies' needs. Some commercially available systems may not meet these acceptance criteria. As measuring technologies evolve and achieve higher quality standards, the main driver for determination of acceptance criteria should shift towards the intended usages of the data. Acceptance criteria for different quality management activities based on nationally recognized protocols or relative on-going research are provided throughout this document in relevant chapters.

CHAPTER 4. BEFORE DATA COLLECTION: EQUIPMENT CALIBRATION AND CERTIFICATION

INTRODUCTION

This chapter includes procedures for equipment calibration and certification programs that DOTs may implement into their QMPs. 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 should be tailored to meet DOT specific data definitions and needs. This chapter is divided into two sections, Equipment Calibration, and Equipment Certification.

EQUIPMENT CALIBRATION

This section addresses equipment calibrations. There are two main types of calibrations, sensor calibrations, and algorithm calibrations. These calibrations should be performed and reviewed and accepted by DOT personnel before certification.

Control Sites

Different types of control sites were described in chapter 3. Many equipment vendors or equipment manufacturers develop control sites that can be used for calibration of equipment sensors and subsystems. Sensor calibrations are often performed at these sites, with vendor or manufacturer special equipment that can be used to make sensor adjustments to match a known standard. Sensor calibrations should be performed according to the manufacturer's recommendations by a qualified party. Algorithm specifications include modifying the vendor or manufacturer algorithms to meet DOT specific data definitions. Certification should take place at a control site that meets Top Tier criteria, as described in Section 3.

Sensor and System Calibration

Each data collection vehicle is comprised of different systems that work together 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 draft report of on-going TPF-5(299)/(399) TPP research describes mapping sensors as any sensor which acquires measurements of a surface 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 in 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 Inertial Measuring Unit (IMU) sensors.

Each mapping and location sensor calibration should be 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 is after any maintenance of data collection equipment is performed, or if data quality is suspect, as further described in chapter 7.

Table 16 shows a matrix of typical 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 their 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 data collection and report the issue to the field crew coordinator. DOTs should include something similar in their QMP to identify and understand the systems used in their data collection program.

Table 17 shows the possible calibrations for different systems. These calibrations are summarized based on the QMPs of several DOTs. A similar table should be included in every DOT QMP. As discussed in chapter 2, different DOTs use different methods of data collection for different data metrics. Each DOT should develop tables or include information similar to Table 16 and Table 17 that reflect their unique data collection methods and equipment as a tool to verify that all calibrations and maintenance specific to their data collection program have been performed. Additionally, the frequency of calibration should be included in QMPs. Records of each calibration should be received and approved by the DOT, and proof of calibration records should be kept.

Table 16. Example of a data collection equipment subsystem calibration matrix adapted from PA Turnpike 2018 QMP 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 System (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 that provides 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 17. Summary 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, 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 accuracy of the system.
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. Maintenance procedures vary by vendor. DOTs should consult with their data collection vendor or manufacturer to ensure all manufacturer-recommended annual maintenance is being performed. Pavemetrics' LCMS is a commonly used 3D system on data collection equipment as described in chapter 2. On an annual basis, Pavemetrics recommends returning users' LCMS sensors to Pavemetrics for factory preventive maintenance. The system controller and cables can be omitted. Preventive maintenance ensures that the LCMS sensors operate reliably and at full sensitivity, which helps to achieve accurate crack detection and minimal downtime. The preventive maintenance items include:

- 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 of internal cables.
- Replacement of moisture absorbers.
- Testing and replacement (if necessary) of enclosure seals to ensure water tightness, and
- A firmware update (if needed).

Algorithm Calibrations

Distress data may be automated by 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. As mentioned in chapter 2, many DOTs are moving towards automated and semi-automated distress data collection. It is essential to ensure that the automated or semi-automated distress algorithms meet the specific DOT data definitions to ensure accurate data is being collected.

Calibration of algorithms should be a collaborative effort between DOT, vendor, or manufacturer personnel. Field evaluations comparing different data collection equipment vehicles in Texas shows that distress data and subsequent pavement conditions vary by manufacturer. This research reasonably predicts that the proprietary algorithms can be calibrated to reduce variability and achieve more accurate results (Serigos 2015). DOTs should 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 has a final draft report. The final draft report includes information to assist DOTs in verifying that the proposed data collection equipment is capable of collecting 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.

Roles and Responsibilities for Equipment Calibration

Although calibrations are primarily the responsibility of the vendor or equipment manufacturer, DOTs should be familiar with the manufacturer's recommended calibrations, and review and accept calibration certificates. DOTs should keep records of calibrations. DOTs implementing automated or semi-automated distress data collection methods should have processes in place 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, as previously described. Many DOTs do not include complete certification processes for rutting, faulting, and distress data. Successful certification practices have been requested by many DOTs (Orthmeyer 2018). Certification procedures have been a focus of the on-going TPF-5(299)/(399) research. The information presented here is based on nationally recognized standards and required HPMS protocols under the CFR, and on the results of these on-going studies. Some DOT and FHWA documents use the term “verification” instead of “certification” for procedures that are not nationally recognized. For simplicity, all processes in this document are called “certification”, whether referencing nationally recognized standards or draft procedures developed under ongoing TPF-5(299)/(399) research.

Control sites should be used for equipment certification. Several different types of control sites were described in chapter 3. The control site used for certification processes should meet Top Tier criteria and be DOT-approved. Top Tier control sites meet the strictest criteria for site conditions and ground reference. DOTs should develop Top Tier control sites relevant to each critical data metric (described as one that is used to classify pavement condition or trigger treatment strategy) collected and used in decision-making processes. Certification procedures should ensure that systems are functioning correctly and check that data (IRI, rutting, faulting, cracking, or other distress data) meets the accuracy and precision requirements that have been 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, and 3D systems. The term 3D system is described here as a system that is 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, are capable of automated or semi-automated crack detection. 3D systems can also be used to collect longitudinal profiles and metrics associated with longitudinal profiles (IRI, faulting).

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 data collection procedures developed under TPF-5(299)/(399). Note that DOTs are collecting other metrics with these 3D systems, and they should use judgment as to which certification method is applicable for each of their data metrics that are not explicitly included here. Certification of these systems, including processes that check the supporting location sensor systems, including GPS, DMI, and IMU, are included.

Faulting certification procedures are described separately. According to DOT QMPs, faulting of JCP pavement is collected using either HSIP systems or 3D systems. On-going research under TPF-5(299)/(399) plans to update the relative AASHTO R36 Standard Practice for Evaluating Faulting of Concrete Pavements. Proposed updates include standardizing and clarifying the definition of faulting and providing certification procedures. The draft proposed certification procedures apply to both HSIP systems and 3D systems.

As technology advances, more DOTs may begin implementing 3D systems for the collection of longitudinal profiles and computing IRI. At this time, it is suggested that the procedures for HSIP systems are used for equipment certification. These methods are described in the “Inertial Profiler Certification” section.

Elements of Successful Certification Programs

Based on the outcome of the literature review in chapter 2, the following statements have been written for establishing successful certification programs. DOTs should consider the following statements when developing their certification programs for data collection equipment, and include the information in their QMPs:

- Control Site Requirements
  - The control sites in the certification program reasonably represent pavement types in the network. This includes different pavement types (asphalt, JCP, CRCP), and surface texture (rough, smooth, high macrotexture asphalt, tined). It may not be economical or reasonable to develop control sites for every possible combination of pavement types, but they should be representative of typical network pavements.
  - The control sites include a range and variety of ride quality and distresses that are typically encountered in the network.
  - The control sites include all data metrics that are collected and used during DOT decision-making processes.
  - The control sites are of sufficient length to gather enough data for certification processes.
- Ground Reference Measurements
  - The control sites have adequate ground reference established so that the accuracy of data being collected can be checked.
  - The ground reference data are established during similar environmental conditions to certification of the production-type data collection equipment.
- Measurements of high-speed devices or production data collection equipment
  - Certification procedures verify calibrations of sensors and other associated systems (GPS, DMI, IMU, etc.).
  - The data collection certification procedures allow for sufficient repeated runs so that the data precision can be checked.
  - The data collection certification procedures are performed at the same speeds that data is collected in the field.
  - Acceptance criteria, including accuracy and precision, specifically for certification, have been established based on statistical analysis processes so that the data collection equipment can be rated as pass or fail.
- Certification records should be kept for all network data collection vehicles and their operators.

Certification processes that meet these statements are given in the following sections. The processes are based on existing protocols, successful practices reported by DOTs in their QMPs, or the latest procedures based on the on-going TPF-5(299)/(399) research. Due to limited successful practices reported by DOTs, many suggested processes are based on recently developed draft standards or procedures based on limited practices in DOT QMPs. As these are validated in the field, and as new technologies emerge, it is expected that these procedures may evolve and improve and are subject to change. A summary of this content is at the end of this chapter in Table 35.

Inertial Profiler Certification

HSIPs are commonly used to measure longitudinal pavement surface profiles. These profiles can be used to calculate longitudinal profile metrics, including IRI and JCP faulting. AASHTO R56 is the Standard Practice for Certification of Inertial Profiling Systems. AASHTO R56 was explicitly developed for IRI metrics. AASHTO R56 certification procedures ensure more repeatable and consistent surface elevation measurements, although the method does not account for the differences between the nature of IRI and faulting measurements.

AASHTO R36 is the Standard Practice for Evaluating Faulting of Concrete Pavements. AASHTO R36 currently includes limited procedures for verification sections. On-going research intends to include more detailed procedures for certification processes in future versions. These draft certification procedures apply to both HSIP systems and 3D systems. The proposed procedures for JCP faulting certification (applicable to HSIP and 3D systems) are included in a subsequent section. This section discusses the certification procedures for internal profilers used to collect IRI.

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 QMPs. As technology continues to advance, 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). At this time, DOTs using 3D systems to collect IRI should continue to certify the equipment according to the current version of AASHTO R56.

The following sections describe how the HSIP certification processes address the above-referenced statements.

Control Sites

The control sites in the certification program reasonably represent pavement types in the network.

According to AASHTO R56, all surface types on which the HSIP is expected to collect data be included in certification processes.

The control sites include a range and variety of ride quality that is typically encountered in the network.

According to AASHTO R56, control sites for IRI should meet the criteria listed in the Standard, including having a smooth section (30 to 75 inches/mile), semi-smooth section (95 to 135 inches/mile), and rough section (up to 200 inches/mile). The surface macrotexture should be representative of each of the types of pavements in the network. Most DOTs reported having multiple control sites for IRI certification to meet these requirements under AASHTO R56.

The control sites include all data metrics that are collected and used during DOT decision-making processes.

AASHTO R56 was developed specifically for IRI metrics. While AASHTO R56 certification allows for more repeatable and consistent surface elevation measurements using HSIPs, it is not sufficient to account for the differences between the nature of IRI and faulting measurements. If DOTs are to use HSIPs to collect faulting data, a range of faulting values should be included in the control sites as further described in the "JCP Faulting Certification" section.

The control sites are of sufficient length to gather enough data for certification processes.

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 change, distresses, patches/repairs, and significant horizontal curvature, or super-elevation should be avoided.

Ground Reference Measurements

The control sites have adequate ground reference established so that the accuracy of data being collected can be checked.

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. Devices that measure and integrate differential elevations, such as Walking Profilers, may be used to establish the reference profiles using multiple staggering runs to meet the interval requirement. However, the measurements from these devices must be checked with the rod and level at distances along the test profile trace that are multiples of the reporting interval for these devices. The rod and level measurement locations shall be no more than 100 feet apart. Reference profile measurements shall be made on the designated profile trace of each test section as well as on the lead-in to the section.

To evaluate a reference profiler's accuracy, the data collected by a reference profiler should be compared to a benchmark tester (BMT). Currently, there is only one BMT in existence. It was developed by the University of Michigan Transportation Research Institute (UMTRI) under an FHWA project. Improvements are being made to existing protocols in on-going research to make this requirement more accessible to DOTs.

The measured lead-in distance should be at least equal to the longest wavelength of interest (300 feet for the profiles used to collect IRI). The total lead-in should be at least two times the longest wavelength of interest, with four times being very desirable. Most DOTs reported collecting ground reference data with Walking Profilers such as SurPro. Three repeats of reference profiles are required. The repeatability score shall be above 98% of cross-correlation reported by the Profiler Certification Module (PCM) of the FHWA ProVAL software. To qualify reference profiles, FHWA has developed a Benchmark tester. However, there is a lack of a Benchmark tester standard in AASHTO. Currently, a new Benchmark tester standard is being developed under the ASTM E17 committee.

The ground reference data are established during similar environmental conditions to certification of the data collection equipment.

AASHTO R56 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 should consider this when developing certification programs. However, it is challenging to implement these requirements in the field. There are existing tools that can assist, including the research report FHWA-HRT-12-068 “Curl and Warp Analysis of the LTPP SPS-2 Site in Arizona”. This report presented the use of pseudo strain gradient (PSG) to analyze the movement of concrete pavement and how to address it when using pavement profiles from HSIP.

Highspeed Devices Measurements and Evaluation

Certification procedures check other associated systems (GPS, DMI, IMU, etc.).

Most DOTs reported also performing calibration/verification of DMI and performing calibration verifications using bounce and block tests per AASHTO R57. The average of the absolute differences of DMI for both the high-speed and low-speed runs must be less than 0.15 percent to pass the test under R56. Failure of DMI calibration is one of the causes of failed IRI certification.

The data collection certification procedures allow for enough repeat runs with different operators so that the data precision can be checked.

Ten repeat runs are recommended for HSIP, according to AASHTO R56. This specification also certifies the operator with the equipment, so different operators are required to pass their certification tests. Equipment repeatability is checked using cross-correlation of each of the ten profiles to each of the remaining nine. The minimum repeatability shall be above 92% of cross-correlation reported by the PCM of the FHWA ProVAL software.

The data collection certification procedures are performed at the same speeds that data is collected in the field.

According to AASHTO R56, five runs are made at the maximum desired certification speed, and five runs are made at the minimum certification speed. These maximum and minimum speeds should reasonably reflect the intended range of speeds during network data collection.

Acceptance criteria including accuracy and precision requirements specifically for certification have been established based on statistical analysis processes so that the data collection equipment can be rated as pass or fail.

Equipment accuracy is checked using the HSIP data against the reference profile data. The minimum accuracy shall be above 90% of cross-correlation reported by the PCM of the FHWA ProVAL software.

Certification records are kept for all network data collection vehicles.

According to AASHTO R56, a decal or other approved marking should be placed on the equipment as evidence of certification. The decal should show the expiration of the certification. Proof of certification should be kept in a DOT database.

3D System for Transverse Pavement Profiling Certification

Few DOTs reported having established 3D system certification programs. The on-going TPF-5(299)/(399) research includes a project for calibration, certification, and verification of Transverse Pavement Profiling (TPP) Measurements. A result of this project is five draft AASHTO standards for certification of TPP data collection equipment. These standards were developed specifically for 3D systems measuring TPPs of road surfaces used to extract pavement surface parameters of rut depth, cross-slope, and edge/curb drop off. However, these AASHTO standards may be adequate for certifying the equipment specific to other metrics, including evaluating longitudinal profile metrics such as faulting. The on-going TPF-5(299)/(399) JCP Faulting Collection and Analysis project is proposing to evaluate the draft TPP AASHTO standards for suitability of certification of faulting data collection equipment. This is further described in section "JCP Faulting Certification."

Cracking and similar distress data can be determined from the 3D data using fully automated vendor proprietary algorithms, manually by viewing images and video from a computer screen or using a semi-automated combination of both automated detection and manual post-processing. Certification methods for certifying the 3D system for automated and semi-automated cracking are described in the following section "3D System for Automated or Semi-automated Cracking".

The draft AASHTO standards from the FHWA TPP project should be used to certify 3D systems. The five draft standards (with abbreviated title) include:

- Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment (GRE).
- Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems (Body Motion).
- Assessment of Static Performance in Transverse Pavement Profiling Systems (Static).
- Assessment of Navigation Drift Mitigation in Transverse Pavement Profiling Systems (Navigation Drift).
- Assessment of Highway Performance in Transverse Pavement Profiling Systems (Highway).

The following addresses how these draft standards can be adopted for successful certification programs.

Control Sites

The control sites in the certification program reasonably represent pavement types in the network.

The draft AASHTO standard "Assessment of Highway Performance in TPP Systems" can be used to check the data collection equipment performance and capabilities at typical speeds and checks for accuracy against ground reference data. The standard recommends that a range of pavement types be used in certification processes.

The control sites include a range and variety of distresses that are typically encountered in the network.

The draft Highway standard recommends the following ranges of values for certification:

- For rut depth, control sites should exhibit a range of low-level rutting to high-level rutting. For low-level rutting, the minimum rut depth is 2.0 mm. High-level rutting is classified as greater than 20 mm.
- For cross slope, the control site should contain a cross slope of greater than 5%.
- Bounding beams should be placed on the transverse edges of the test site for assessment of edge/curb detection.

DOTs collecting other TPP metrics should consider adding a range of values for those metrics in their certification plan.

The control sites include all data metrics that are collected and used during DOT decision making processes.

As previously stated, the TPP draft Highway AASHTO standard only includes rut depth, cross slope, and edge/curb detection. However, it is reasonable to assume that. Other TPP metrics can be collected using similar methods. DOTs should include other TPP metrics being used in decision-making processes in their control sites.

The control sites are of sufficient length to gather enough data for certification processes.

The draft Highway standard states that all 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 draft standard.

Ground Reference Measurements

The control sites have adequate ground reference established so that the accuracy of data being collected can be checked.

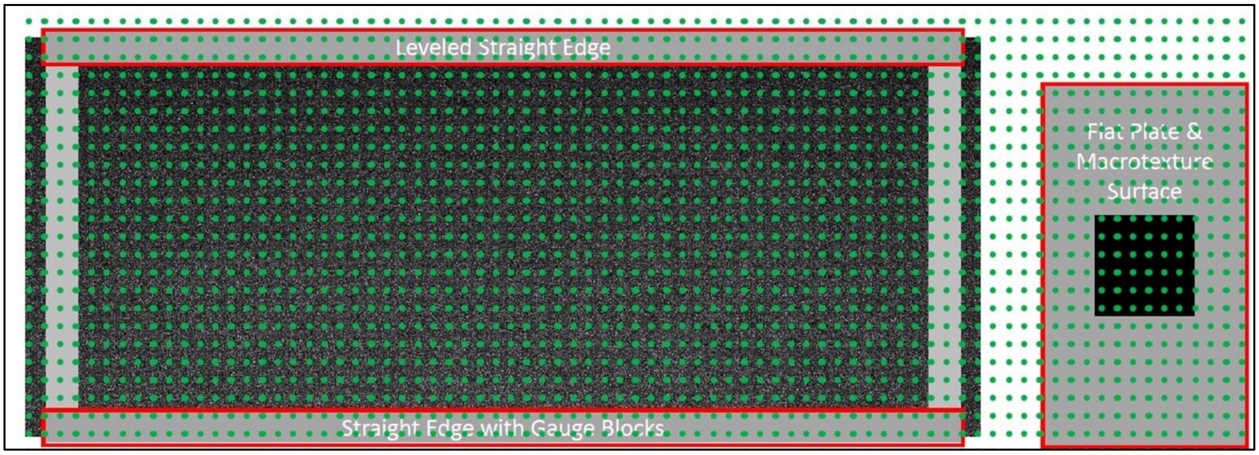
The draft Highway AASHTO standard states that ground reference data should be determined adjacent to the transverse capability test section. Note that the draft Highway AASHTO standard is the only proposed draft standard that requires collecting ground reference data. One of the five draft AASHTO standards is Assessment of Ground Reference Data for Transverse Pavement

Profiling System Assessment (GRE). This standard describes the procedures to verify that measurement equipment is collecting acceptable quality ground reference data to be used in TPP certification procedures. The equipment that was used during the TPP equipment rodeo was the scanning technology based Creaform Metrascan. This equipment is illustrated in Figure 18.

Source: Creaform (2020)

Figure 18. Photograph. Handheld scanning device used during the TPP equipment rodeo to establish ground reference data.

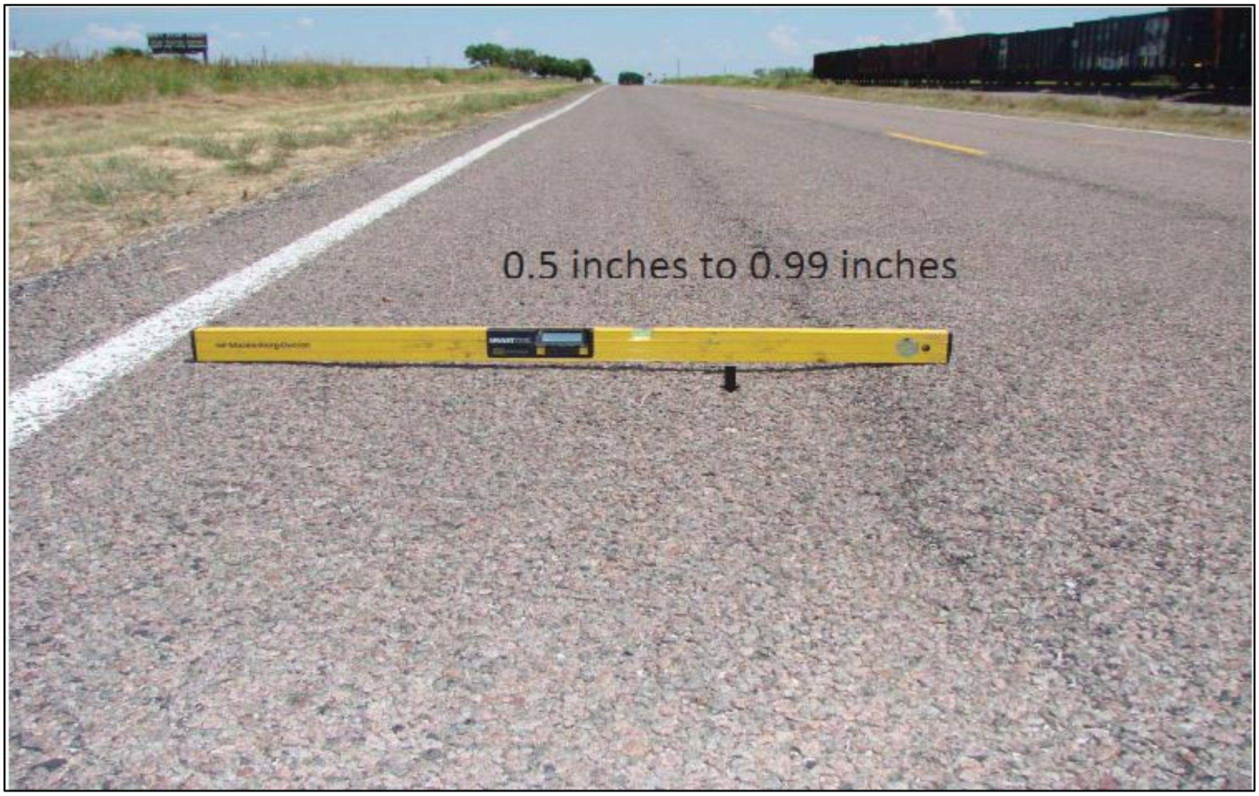
An example of gridded data from the proposed GRE is shown in Figure 19. The data analysis used to compare the ground reference data to the high-speed data collection may use programming to perform. This may be difficult for DOTs to implement before the development of a software similar to the FHWA ProVAL software for the IRI certification.



Source: FHWA TPP draft report (2020)

Figure 19. Illustration. Creaform MetraScan Dataset, illustrating gridded point data on a section of pavement separated by leveled straight edges. This setup is further described in the Draft Highway AASHTO standard.

Other methods reported by DOTs to establish ground reference data for rutting included using manually measuring rut depths. Few DOTs gave specific details as to how this was accomplished. South Dakota DOT (2018) reports taking manual transverse measurements in each wheel path at 20-foot intervals to establish rut depth ground reference. No details are given as to how the manual measurements are taken. Pennsylvania DOT (2018) mentioned using levels and dial gauges to measure rut depths. Connecticut DOT (2018) mentions using a walking profiler to establish a ground reference for a TPP, rutting, roughness (IRI), faulting, and DMI though no details are given as to how this is accomplished. Texas DOT (2018) does include methods of manually collecting rut data using a 6-foot straight edge or string and measuring each wheel path separately. An example of their provided rater's manual is included in Figure 20. Other DOTs likely use a similar approach. The Interstate Highway Pavement Sampling Data Quality Management Plan (Simpson et al. 2018) used MnROAD's Automated Laser Profiling System (ALPS) to measure rut depths for ground reference. This device has an algorithm that computes rut depth values corresponding to the wheel path.



Source: TxDOT (2018)

Figure 20. Photograph. A photograph showing a level spanning one wheel path to measure the maximum rut depth manually.

Manual measurements are arguably inadequate as a ground reference for the complex and intricate data collected by 3D sensors. Additionally, merely checking final metrics without also verifying sensor calibrations and other associated systems does not validate the entire system. Figure 19 shows the gridded data from the scanning equipment proposed by the draft GRE standard. This raw point cloud data for the proposed GRE has a higher density than typical 3D sensor data collection equipment, which makes it appropriate for use as GRE used for certification processes. Additionally, the draft GRE method includes an additional process that certifies the GRE simultaneously to collecting the ground reference data. This is performed by scanning certification objects with known dimensions and features. Because these two processes are performed simultaneously, it can be assumed that the ground reference is "true" as long as the scanning equipment provides accurate data for the certification objects. This process is illustrated in Source: FHWA TPP draft report (2020)

Figure 21. This photograph shows the testing process used to collect the data illustrated in Figure 19. The flat plate and macrotexture surface can be seen in the lower right corner in each figure.

Source: FHWA TPP draft report (2020)

Figure 21. Photograph. Scanning equipment is used to collect ground reference data. Certification objects with known dimensions and features are shown.

The ground reference data are established during similar environmental conditions to certification of the data collection equipment.

The draft standards for TPP do not specifically mention making ground reference measurements during the same environmental conditions as the data collection vehicle. It is suggested that environmental considerations are accounted for when establishing a ground reference for certification purposes.

Draft TPP AASHTO Standard - Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment (GRE)-reference item e.

The criteria statement for ground reference data is summarized in Table 18.

Table 18. Ground reference data statement. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Transverse Measurement Spacing	N/A	N/A	N/A	N/A	2.0
Longitudinal Measurement Spacing	N/A	N/A	N/A	N/A	2.0

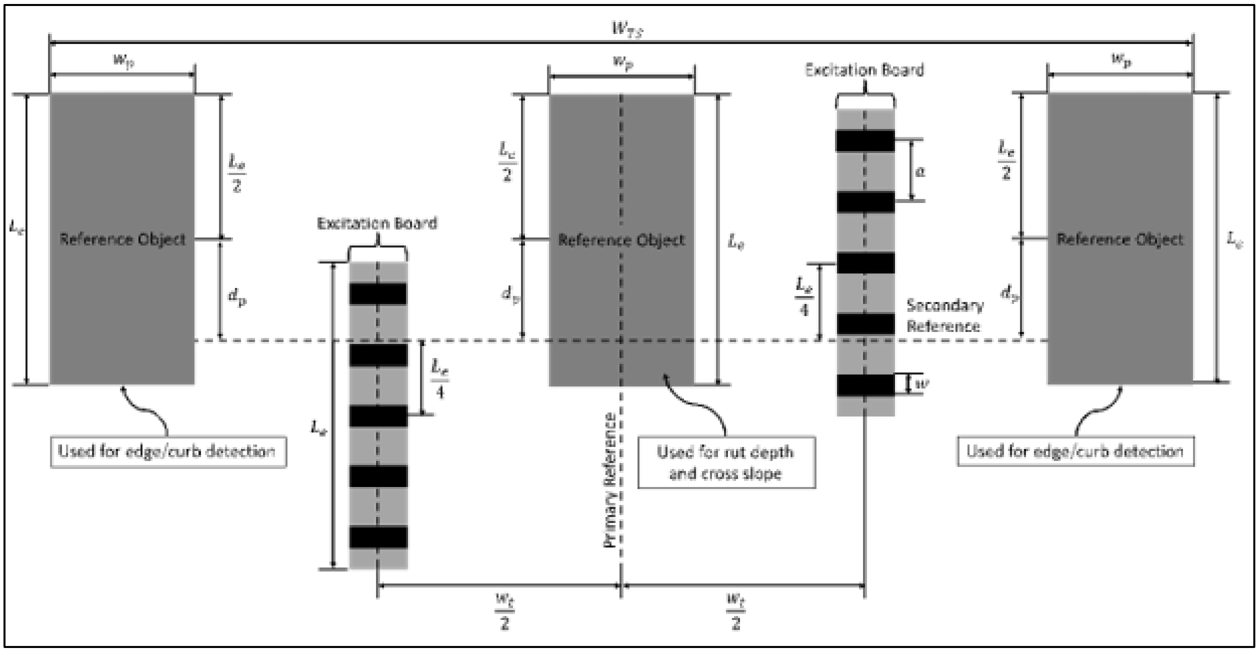
Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Transverse Measurement Error	-0.3	-0.15	N/A	0.15	0.3
Longitudinal Measurement Error	-0.3	-0.15	N/A	0.15	0.3
Vertical Measurement Error	-0.3	-0.15	N/A	0.15	0.3
Transverse Flatness Error	-1.0	-0.5	N/A	0.5	1.0
Transverse Width	N/A	N/A	N/A	N/A	4000
Macrotexture Surface Error	-1.7	-0.7	N/A	0.7	1.7
Planar Flatness Error	-1.0	-0.5	N/A	0.5	1.0
Vertical Measurement Spacing	N/A	N/A	N/A	N/A	0.03

Highspeed Devices Measurements and Evaluation

Certification procedures verify calibrations of sensors and other associated systems (GPS, DMI, IMU, etc.).

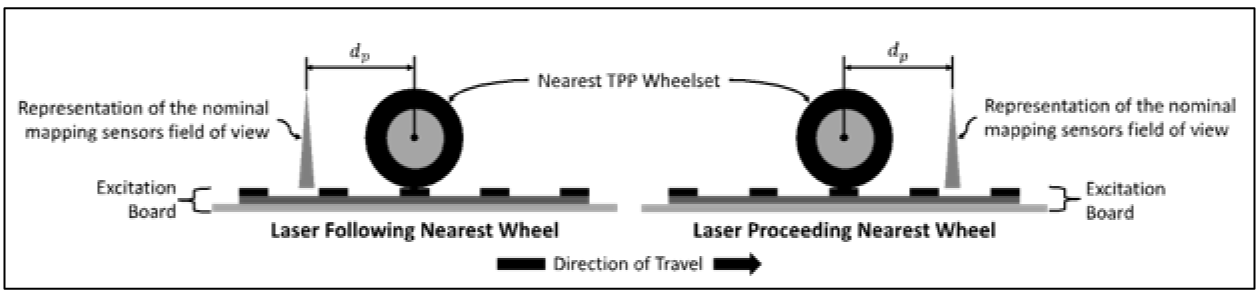
The three TPP draft AASHTO standards verify the other systems associated with the 3D system and are briefly described below.

- Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems: The purpose of this standard is to assess the accuracy and precision of the equipment when the system is excited at the primary ride and wheel hop excitation frequencies. A combination of reference devices and excitation boards should be placed, as shown in Figure 22 and Figure 23. The excitation boards should be aligned according to specific equipment systems. This test is performed at traffic speed and may be placed within the "Highway" control section.
- Assessment of Static Performance in Transverse Pavement Profiling Systems: The purpose of this standard is to assess the accuracy and precision of the sensor system used in static conditions. This test is performed when the vehicle is parked and could be performed concurrently to the block and bounce tests performed on HSIPs during the certification process.
- Assessment of Navigation Drift Mitigation in Transverse Pavement Profiling Systems: TPP systems that provide global positions of road surfaces are often susceptible to drift in the estimate of global position over time. The purpose of this standard is to assess the amount of drift present in localization systems used in the data collection equipment. This test includes driving the vehicle in a small figure eight configuration (illustrated in Figure 24) over a manufactured artifact with a known location to measure the drift.



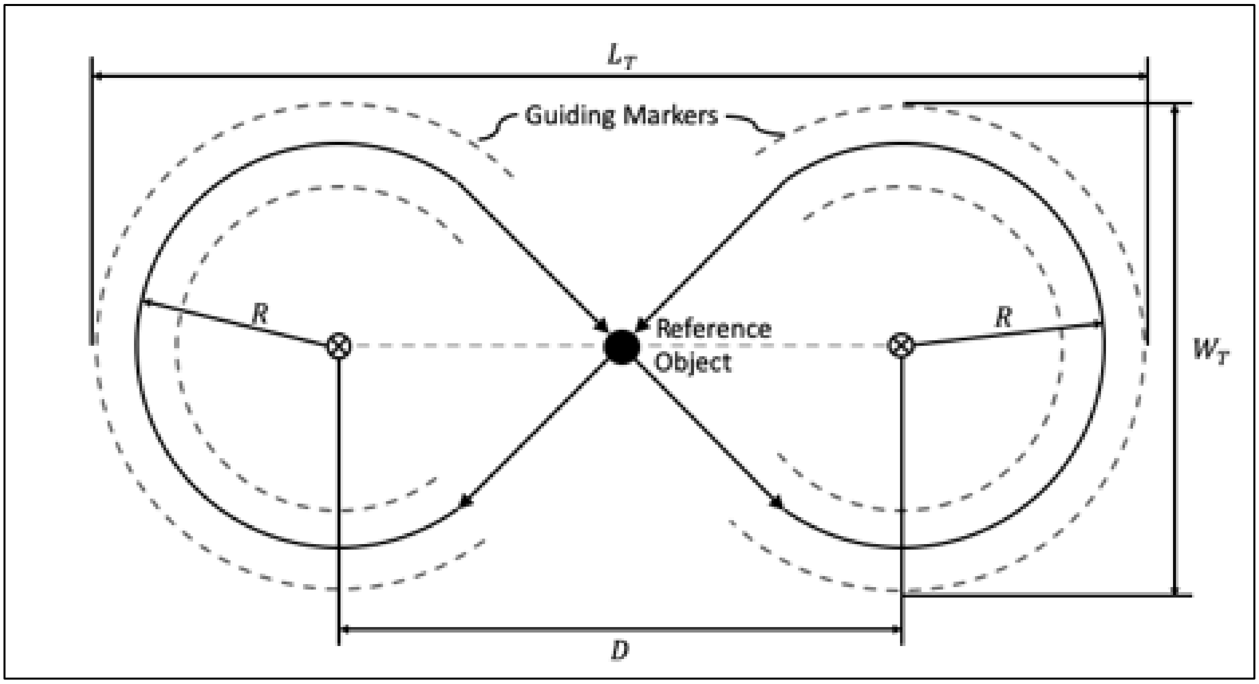
Source: FHWA TPP draft report – draft AASHTO Provisional Standard (2020)

Figure 22. Illustration. The vehicle-in-motion layout of reference objects and excitation boards to induce primary ride and roll for a passenger vehicle.



Source: FHWA TPP draft report – draft AASHTO Provisional Standard (2020)

Figure 23. Illustration. Example of the dimensions for plate offset based on the nominal mapping sensor from the nearest wheelset of the equipment.



Source: FHWA TPP draft report – draft AASHTO Provisional Standard (2020)

Figure 24. Illustration. Example of a layout illustrating a reference object placed at the intersection of the two overlapping circles.

Draft AASHTO TPP Standard - Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems (Body Motion)

The statement for cross-slope, rut depth, and edge/curb drop off are shown in Table 19, Table 20, and Table 21, respectively.

Table 19. Body motion cancelation statement for cross-slope. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Vehicle Body Motion Error	-8	-5	0	5	8
Vertical Measurement Spacing	N/A	N/A	N/A	N/A	1.0

Table 20. Body motion cancelation statement for rut depth. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Vehicle Body Motion Error	-4	-2.5	0	2.5	4

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Vertical Measurement Spacing	N/A	N/A	N/A	N/A	0.1

Table 21. Body motion cancelation statement for edge/curb drop off. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Vehicle Body Motion Error	-4	-2.5	0	2.5	4
Vertical Measurement Spacing	N/A	N/A	N/A	N/A	0.1

Draft AASHTO TPP Standard - Assessment of Static Performance in Transverse Pavement Profiling Systems (Static)

The statement for cross-slope, rut depth, and edge/curb drop off are shown in Table 22, Table 23, and Table 24, respectively.

Table 22. Static performance statement for cross-slope. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Transverse Measurement Spacing	N/A	N/A	N/A	N/A	25
Transverse Measurement Error	-15.0	-12.5	N/A	12.5	15.0
Total Transverse Width	3800	N/A	N/A	N/A	N/A
Straightness Error	-8.0	-3.0	N/A	3.0	8.0
Vertical Measurement Spacing	N/A	N/A	N/A	N/A	1.0
Vertical Measurement Error	-2.0	-1.0	N/A	1.0	2.0

Table 23. Static performance statement for rut depth. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Transverse Measurement Spacing	N/A	N/A	N/A	N/A	10
Transverse Measurement Error	-7.5	-5.0	N/A	5.0	7.5
Total Transverse Width	4000	N/A	N/A	N/A	N/A
Straightness Error	-2.5	-1.0	N/A	1.0	2.5
Vertical Measurement Spacing	N/A	N/A	N/A	N/A	0.1
Vertical Measurement Error	-1.5	-1.0	N/A	1.0	1.5

Table 24. Static performance statement for edge/curb drop off. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Transverse Measurement Spacing	N/A	N/A	N/A	N/A	10
Transverse Measurement Error	-7.5	-5.0	N/A	5.0	7.5
Total Transverse Width	4250	N/A	N/A	N/A	N/A
Straightness Error	-2.5	-1.0	N/A	1.0	2.5
Vertical Measurement Spacing	N/A	N/A	N/A	N/A	0.1
Vertical Measurement Error	-1.5	-1.0	N/A	1.0	1.5

Draft AASHTO TPP Standard - Assessment of Navigation Drift Mitigation in Transverse Pavement Profiling Systems (Navigation Drift)

The requirement statement for cross-slope, rut depth, and edge/curb drop off are shown in Table 25, Table 26, and Table 27, respectively.

Table 25. Navigation drift statement for cross-slope. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Easting (x) Position Error	-1000	-500	N/A	500	1000

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Northing (y) Position Error	-1000	-500	N/A	500	1000
Elevation (z) Position Repeatability	-150	-100	N/A	100	150

Table 26. Navigation drift statement for rut depth. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Easting (x) Position Error	-1000	-500	N/A	500	1000
Northing (y) Position Error	-1000	-500	N/A	500	1000
Elevation (z) Position Repeatability	-150	-100	N/A	100	150

Table 27. Navigation drift statement for edge/curb drop off. Accuracy and precision described as bias and confidence intervals (mm).

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Easting (x) Position Error	-1000	-500	N/A	500	1000
Northing (y) Position Error	-1000	-500	N/A	500	1000
Elevation (z) Position Repeatability	-150	-100	N/A	100	150

The data collection certification procedures allow for enough repeat runs with different operators so that the data precision can be checked.

The draft Highway AASHTO standard recommends three runs at each driving speed. Driving speeds range from approximately 10 mph to 65 mph, increasing at increments of 10 mph. Operator certification is not mentioned in the draft standard. DOTs should consider whether the certification for 3D sensors is specific to each operator and include operator certification similar to the requirements in AASHTO R36.

The data collection certification procedures are performed at the same speeds that data is collected in the field.

The draft Highway AASHTO standard recommends driving speeds ranging from approximately 10 mph to 65 mph increasing at increments of 10 mph for TPP certification. The JCP faulting research is proposing certification under field conditions for precision and joint detection only to eliminate the environmental effects of curling and warping in accuracy evaluation. No specific speeds are given at this time, but it is reasonable to use the speeds anticipated during data collection.

Acceptance criteria, including accuracy and precision statements specifically for certification have been established based on statistical analysis processes so that the data collection equipment can be rated as pass or fail.

The draft AASHTO standards from the TPP project include accuracy and precision options for rut depth, edge/curb drop off, and cross slope certification. The options for certification acceptance criteria for the draft AASHTO standards are summarized here.

Draft AASHTO TPP Standard - Assessment of Highway Performance in Transverse Pavement Profiling Systems (Highway).

The statement for cross-slope, rut depth, and edge/curb drop off are shown in Table 28, Table 29, and Table 30, respectively.

Table 28. Highway performance statement for cross-slope. Accuracy and precision described as bias and confidence intervals (mm)

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Transverse Measurement Spacing	N/A	N/A	N/A	N/A	25
Effective Transverse Width	3800	N/A	N/A	N/A	N/A
Longitudinal Measurement Spacing – Network	N/A	N/A	N/A	N/A	3000
Longitudinal Measurement Spacing – Project	N/A	N/A	N/A	N/A	500
Point Cloud Vertical Error (as standard deviation from a reference distribution)	-2.5	-1.0	N/A	1.0	2.5
Gridded Data Vertical Error (as standard deviation from a reference distribution)	-1.7	-0.7	N/A	0.7	1.7
Cross Slope Error (as percent)	-0.4	-0.15	N/A	0.15	0.40

Table 29. Highway performance statement for rut depth. Accuracy and precision described as bias and confidence intervals (mm)

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Transverse Measurement Spacing	N/A	N/A	N/A	N/A	10
Effective Transverse Width	4000	N/A	N/A	N/A	N/A
Longitudinal Measurement Spacing – Network	N/A	N/A	N/A	N/A	3000
Longitudinal Measurement Spacing – Project	N/A	N/A	N/A	N/A	500

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Point Cloud Vertical Error (as standard deviation from a reference distribution)	-2.5	-1.0	N/A	1.0	2.5
Gridded Data Vertical Error (as standard deviation from a reference distribution)	-1.7	-0.7	N/A	0.7	1.7
Rut Depth Error	-2.5	-1.0	N/A	1.0	2.5

Table 30. Highway performance statement for edge/curb drop off. Accuracy and precision described as bias and confidence intervals (mm)

Output Test Statistic	Lower Bounds (percentile) 90% (5%)	Lower Bounds (percentile) 50% (25%)	Bias	Upper Bounds (percentile) 50% (75%)	Upper Bounds (percentile) 90% (95%)
Transverse Measurement Spacing	N/A	N/A	N/A	N/A	10
Effective Transverse Width	4250	N/A	N/A	N/A	N/A
Longitudinal Measurement Spacing – Network	N/A	N/A	N/A	N/A	3000
Longitudinal Measurement Spacing – Project	N/A	N/A	N/A	N/A	500
Point Cloud Vertical Error (as standard deviation from a reference distribution)	-2.5	-1.0	N/A	1.0	2.5
Gridded Data Vertical Error (as standard deviation from a reference distribution)	-1.7	-0.7	N/A	0.7	1.7
Edge/curb Transverse Location Error	-50	-25	N/A	25	50
Edge/curb Vertical Magnitude Error	-2.5	-1.0	N/A	1.0	2.5

Certification records kept for all network data collection vehicles.

DOTs should develop certification decals and records similar to those used for HSIPs so that certification can be approved, recorded, and tracked.

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.

Few DOTs described the training and certification procedures for manual raters establishing a cracking ground reference. This process is further described in chapter 5.

TPF-5(299)/(399) efforts also include a project for 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). The objective of this project is to develop procedures that include technical assessment protocols for automated and semi-automated pavement cracking (and other distresses) data collection/analysis systems and/or services for use in agency vendor selection contracting documents. This project includes verification based on control sites with ground reference data that is collected by manual raters. The draft Successful Practices for Cracking report utilizes the HPMS cracking definitions to illustrate the methods and also includes procedures for other crack-like distresses so that DOTs can adapt the methods for state-specific data definitions. DOTs may find these proposed verification processes suitable for their cracking equipment certification processes. The draft Successful Practices for Cracking report also includes image criteria checks to ensure that the images are adequate for cracking and distress identification. These processes are further described according to the certification statements given at the beginning of this section.

It is critical to communicate DOT specific cracking and distress definitions to the data collection vendor or manufacturer before certification processes. According to the draft Successful Practices for Cracking report, historically, the main difference between the vendor's and DOT's interpretation of the distress definitions and collected data has little to do with the equipment or the identification of cracking, but rather on the difference of data definitions. Calibration of algorithms (for automated or semi-automated procedures) should be completed before equipment certification.

Control Sites

The control sites in the certification program reasonably represent pavement types in the network.

The draft Successful Practices for Cracking report proposes a minimum of three control sites per each pavement type in the network. Most DOTs have different cracking definitions for each pavement type (asphalt, JCP, CRCP). If a DOT has all three pavement types in the network, a total of nine control sections should be established.

The control sites include a range and variety of distresses that are typically encountered in the network.

The procedures suggest that the sections have a variety of cracking and distresses representing a range of types and severities according to DOT definitions. The draft Successful Practices for Cracking report includes options for weighting control sites and distresses, which is further described below.

The control sites include all data metrics that are collected and used during DOT decision making processes.

The draft Successful Practices for Cracking report recommends that each DOT should identify the range of distress types and severity levels to be included in their control sites. They report that it is appropriate to focus on those distresses or indices, which are crucial to decision making. An examination of the decision trees or processes used by a state should reveal that there are a specific number of distresses used to make decisions. Further discussion on this topic is found in chapter 2 of this document. Within a DOTs list of critical treatments, it is common to find a system of weights between distresses, which determines the most important distresses in terms of triggering a treatment (or other decision). For example, the most common distress which triggers treatment in asphalt pavements is fatigue cracking. In most situations, the presence of fatigue cracking triggers a rehabilitation consisting of repair and overlay. In JCP, distresses such as corner breaks or severe spalling drive different decisions. Punchouts are commonly considered the critical distress for CRCP.

Distress types that are being collected that do not impact decision-making processes may not be economical or efficient to include in control sites. A historical review of the PMS should allow the agency to determine the most significant pavement types, surface types, and distress types present in their system. It is not practical that all pavement surfaces and all distress combinations be included.

The significance of distress types should be weighted consistently with the importance of the specific distress in the agency decision-making process. Those distress types which drive the majority of treatment decisions should be weighted more heavily than those with less impact on overall PMS treatment. For example, for most agencies, fatigue cracking of asphalt pavements triggers the more extensive treatments, including overlay or reconstruction. Therefore, this distress would be weighted more heavily (perhaps two times more) than others.

The control sites are of sufficient length to gather enough data for certification processes.

The draft Successful Practices for Cracking report includes the following criteria for control site lengths.

- Asphalt and CRCP surfaces: 0.3 miles (1,584 feet).
- JCP surfaces: 0.5 miles (2,650 feet) or 100 slabs – whichever is greater.

Recommendations are provided for subdividing control sites to create subsections for verification (or certification). Minimum subsection lengths of 0.03 miles are recommended for asphalt concrete and continuously reinforced pavements. For jointed concrete pavements, the recommended subsection length is 0.05 miles or 10 slabs, whichever is greater. The draft Successful Practices for Cracking report provides a discussion on subsection lengths and statistical evaluation in the document appendix.

Ground References

The control sites have adequate ground reference established so that the accuracy of data being collected can be checked.

As previously discussed, ground reference for cracking and other surface distresses are performed manually with human raters. Training and certification of manual raters are further described in chapter 5. All manual raters establishing a ground reference for control sites should be certified as a manual rater according to DOT specific data and HPMS data.

The draft Successful Practices for Cracking report gives the following procedures for how to conduct manual ratings of ground reference for cracking and other distresses.

- Use a string line and paint to layout wheel paths and relevant distances in the control sites before manual ground reference rating. The area should be closed to traffic. DOTs may consider using a layout template similar to the one shown in Figure 25 to increase the efficiency of the layout process. The sections and subsections should be marked: Start, End, and Intermediate Points.
- If a DOT chooses to conduct replicate ratings (either by using multiple independent raters or by having a single rater rate the section multiple times) for determination of the ground reference value, equivalence testing of each independent rating should be assessed, following the same procedure used to compare vendor ratings to the ground reference (as further described below). Either a single rating or a consensus rating should be used as the ground reference. Replicates should not be averaged in determining the final reference rating, but rather only one of the "equivalent" replicate ratings should be used, or a consensus on the ground reference be determined.
- All cracking equal to or greater than 1 mm in width should be reported for ground reference measurements.

Source: FHWA Morian et al. (2020) draft report

Figure 25. Photograph. A template that may be used to increase the efficiency of wheel path layout taken from the draft report developed under Developing TPF-5(299)/(399) Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection/Analysis Systems and/or Services.

The ground reference data are established during similar environmental conditions to certification of the data collection equipment.

Several environmental conditions have been identified, which can affect the outcome of distress identification. These are identified in the draft Successful Practices for Cracking report, including factors that physically impact the apparent distress observed in a pavement. The most prominent of these is pavement temperature, which can change the size and affect the visibility of cracks on the pavement surface. Moisture conditions and cloud cover can also result in changes in observed distress levels, particularly in the visibility of fine cracks. To avoid the environmental influence of results, the draft Successful Practices for Cracking report gives the following considerations:

- Conduct ground reference and data collection verification (or certification) procedures under similar conditions to prevent the observable distress from actually being different between the two procedures.

- Conduct annual distress surveys during the same seasonal conditions from year to year to avoid introducing climatic induced differences into the observable pavement condition.

Highspeed Devices Measurements and Evaluation

Certification procedures verify calibrations of sensors and other associated systems (GPS, DMI, IMU, etc.).

The procedures in the Successful Practices for Cracking report do not include verification of sensors or other associated equipment. The 3D sensors are verified in TPP draft standards. Optional accuracy and precision statements are available for rut depth, edge/curb detection, and cross slope. These statements have been adapted to apply to faulting metrics in the draft JCP Faulting report. It is reasonable for State DOTs to consider these procedures and statements and adapt them to meet their cracking definitions.

A critical component of certification of 3D systems that are used to detect cracking and other distresses is ensuring the adequacy of video and image quality. Note that even DOTs who use fully automated procedures for cracking data collection report 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 should be included in certification processes. The draft Successful Practices for Cracking report includes procedures for image equipment verification requirements and image quality checks. DOTs should consider using these procedures in their certification program. The procedures are described below.

Imaging System Clarity

Either line scan or frame type digital cameras can be used to collect pavement images. The use of frame type cameras can result in some distortion of the image 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, 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. Finer cracks can be identified by higher resolution cameras. 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: Pixel fills factor indicates the light gathering area of the photodetector being used. The proportion of the pixel area insensitive to light is indirectly indicated.

The minimum suggested fill factor is 90%. This practice indicates that 10% of the pixel is insensitive to light. The photodetectors commonly used are most often a silicon chip or a metal oxide semiconductor. 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 higher fill factor than earlier technologies. It also reduces the smearing of images of fast-moving objects. The application of the 3D range data with laser image lighting has resulted in a significant reduction in image clarity issues from variable lighting conditions and improved 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 used 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. However, compression algorithms may be proprietary to equipment vendors and manufacturers. An example of the current minimal rules and validation procedures for standard data format based are listed in Table 31.

Table 31. 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 is "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 to the given one	If a checksum is given, calculate the checksum based on the file content and check if it equals to the given checksum.
Header Correctness	The values in the header fields are valid	For each value, if the field takes only 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 be fit into a width * length matrix of that given data type.

Image Capture Width

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

System Capabilities

- Illumination source: The downward perspective image should be collected with a uniform and consistent form of illumination applied to the pavement surface. The illumination should be regulated to provide sufficient contrast and crack-shadows for the clear discernment of cracking and patching. Images are bearing ambient and/or 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 as to 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 being able to meet the requirements for image clarity and interpretation of the information stored in the retrieved image. The size of the storage is significantly affected by requirements to collect 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 can be interpreted by different systems at different points in time. Self-contained is described as data for interpretation is included within the data "container." For example, metadata should not only provide the identifying information such as location and date but also 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 draft 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 should perform as a quality management activity, including certification. DOTs should evaluate their data definitions and criteria for any additional requirements that are specific to their data management program. The AASHTO R86 criteria for image quality include the following statements:

- The images should provide 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 in.), 60 percent of all cracks present from 3 mm (0.12 in.) and under 5 mm (0.2 in.) wide, and 85 percent of all cracks 5 mm (0.2 in.) wide or wider regardless of orientation or type. The determination of this capability should be made 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 that a section of pavement without distress, discontinuities, or pavement markings contain 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 in.), whichever is larger, of the actual width with at least 85 percent confidence.

Other considerations are given in the draft 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 clearly viewed.
- A crack width of 1 mm should be identifiable (for a stationary or low-speed system), with a 2 mm width identifiable when the image is collected while the collection vehicle travels at 60 mph.
- The image size should be sufficient to accommodate some vehicle wander while data is being collected. It is not practical to avoid vehicle wander, particularly when traveling on an active highway.

The data collection certification procedures allow for enough repeat runs with different operators so that the data precision can be checked.

Some DOTs have already reported using the paired t-test method for data comparison in their QMPs. The draft Successful Practices for Cracking report found that an improved method was to consider the paired t-test for equivalence. For two ratings to be equivalent, it does not mean that they are identical. It means that the ratings produce satisfactorily the same outcome. The draft Successful Practices for Cracking report states that the equivalence method provides a better approach for the analysis for the following reasons:

- The goal is to identify vendors or equipment that give the same results as the ground reference or results close enough not to affect the outcomes.
- Equivalence tests are hypothesis tests formulated for when equivalence, rather than significant difference, is the goal.
- Using a paired t-test for the equivalence testing, with the ratings carefully paired on the same rating subsections, offsets the variability in the pavement along the length of the control sites.

Each reference site is evaluated for statistical equivalence independently using the paired t-test. This process means that an adequate value for sample size, N, should be available within each reference site. The sample size is considered as the number of subsections. Higher values of N result in the greater power of the statistical equivalence test. A minimum N of 10 subsections is recommended (test sections of 0.3 miles -for asphalt and CRCP- subdivided into sections of 0.03 miles). An example of a power curve using the paired t-test for equivalence is shown in Figure 26.

The data collection certification procedures are performed at the same speeds that data is collected in the field.

According to a report by Dr. Tsai, the Georgia Tech 3D (crack detection) system can identify a 1 mm crack, and a 2 mm crack when images are collected above 60 mph. (Tsai 2017). Current DOT requirements range from 3 mm to 1 mm systems, with no clarifications on how that is measured or evaluated. The draft Successful Practices for Cracking report suggests the vendor provide (1) the speed at which a 1 mm crack is detected, (2) the speed at which a 2 mm crack is detected, and (3) the speed at which a 3 mm crack is detected. In principal, 1 mm sampling intervals can be used to detect a 2 mm crack.

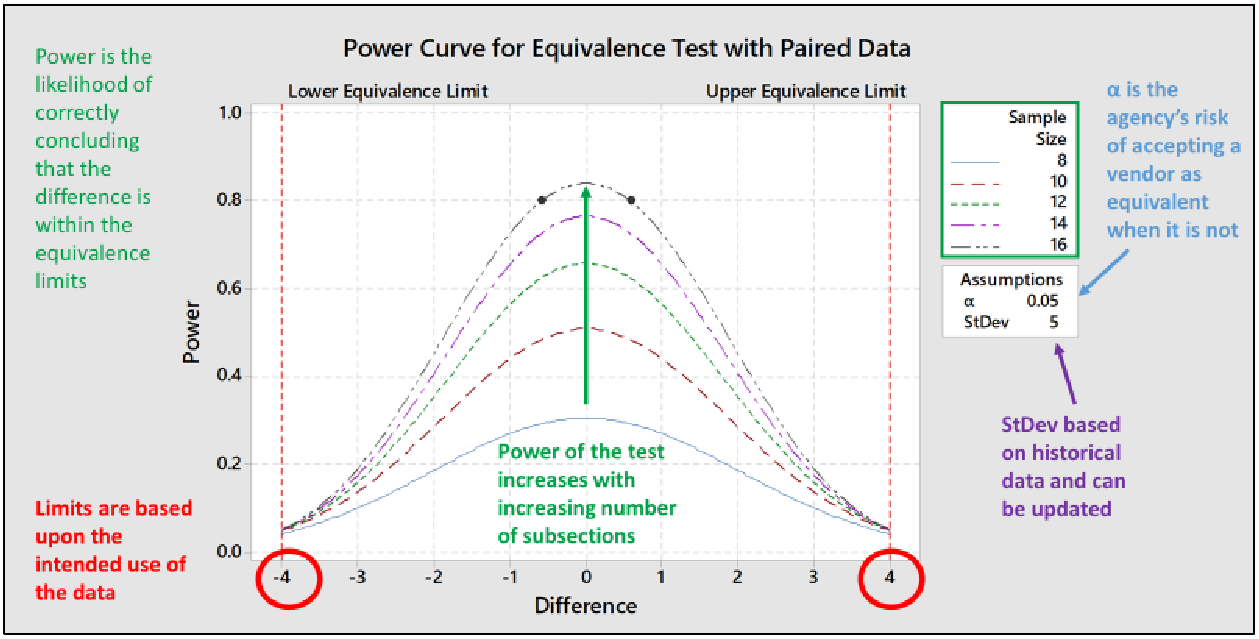
The draft Successful Practices for Cracking report does not explicitly give criteria for the speed of data collection. However, it is implied based on the system capabilities statement, and data should be collected at or near prevailing highway speed, typically 45 to 65 mph. Speed affects the resulting data resolution. Therefore, certification collection speeds should reasonably simulate actual data collection speeds to ensure resolution requirements can be achieved.

Acceptance criteria, including accuracy and precision requirements, specifically for certification, have been established based on statistical analysis processes. Therefore, the data collection equipment can be rated as pass or fail.

As previously described, the proposed tool for evaluating the certification data against ground reference data is the paired t-test for equivalence. Note that this analysis may need the use of a statistical software package, preferably national standard tools with transparency and stability.

As mentioned throughout this document, each DOT has different decision-making processes, data use, data definitions, and indices used in pavement management. Equivalence limits may be different for different DOTs. The variability of the differences between the vendor ratings and reference ratings may also be different. Therefore, values for all statistical inputs may differ. DOTs should establish their requirements for certification based on their unique needs.

At a minimum, the draft Successful Practices for Cracking report suggests generating power curves for the specific decision variables and associated equivalence limits.



Source: FHWA Morian et al. (2020) draft report

Figure 26. Illustration. Example of an annotated power curve for two-sided paired t-test for equivalence taken from the draft report developed under Developing TPF-5(299)/(399) Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection/Analysis Systems and/or Services

More information on using the paired t-test for equivalence is found in the draft Successful Practices for Cracking report. Additional information for establishing acceptance criteria are summarized in chapter 7.

Certification records are kept for all network data collection vehicles.

DOTs should develop certification decals and records similar to those used for HSIPs so that certification can be approved, recorded, and tracked.

JCP Faulting Certification (Inertial Profilers and 3D Systems)

The on-going TPF-5(299)/(399) research includes a project for JCP Faulting Collection and Analysis. Draft reports from this on-going project state that most DOTs are using 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. This procedure includes certification processes for faulting data collection equipment.

For HPMS reporting, faulting data is reported as a weighted average of all joints within each measured section to the nearest 0.1 inches. HPMS references AASHTO Standard R36 Standard Practice for Evaluating Faulting of Concrete Pavements. AASHTO R36 was explicitly written for manual devices and HSIP. The on-going research for JCP faulting intends to update

AASHTO R36 to consider 3D systems and HSIP. AASHTO R36 provides limited information for verification sections. Draft certification processes have been developed under the on-going research but have not been tested for suitability. Based on limited alternatives for faulting equipment certification, these certification processes are included here despite not being field evaluated. These processes may be updated and calibrated after pilot testing to ensure they are suitable for widespread use. These processes apply to both HSIP and 3D systems.

The following statements include considerations for faulting certification based on the on-going TPF-2(299)/(399) research:

Control Sites

The control sites in the certification program reasonably represent pavement types in the network.

Faulting is only applicable to JCP pavements. The draft reports for JCP faulting suggest using a variety of pavement surfaces (such as tining and grooving) and joint configuration.

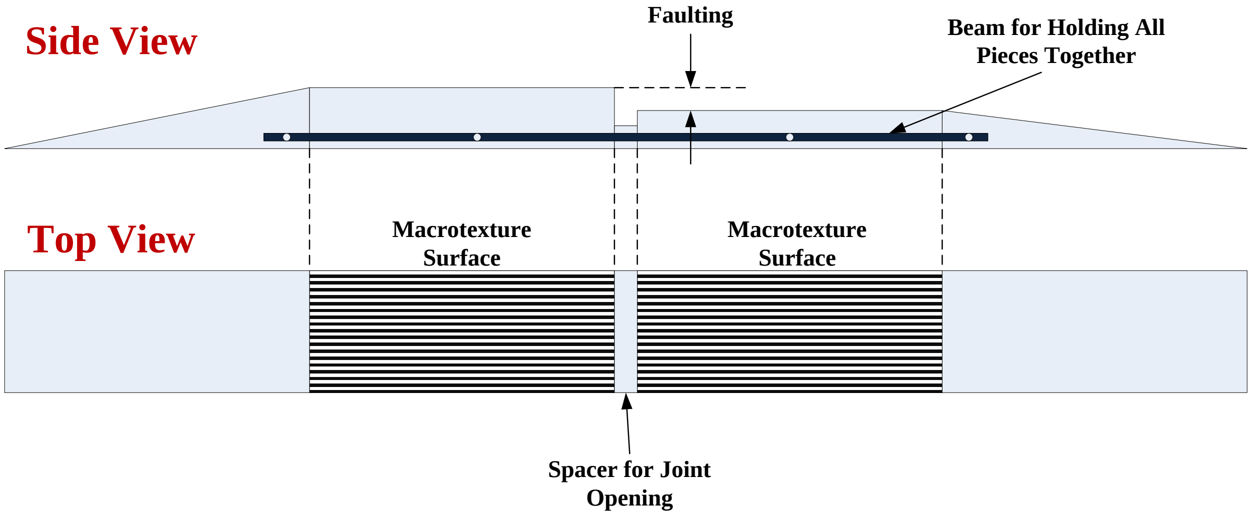
The control sites include a range and variety of distresses that are typically encountered in the network.

The proposed certification procedures in the draft JCP faulting reports includes two processes. These processes are:

- Faulting Certification under Controlled Environment for Accuracy (controlled environment)
- Faulting Certification under Field Environment for Precision and Joint Detection (field environment).

The first proposed certification process (controlled environment) is to check the capabilities of the system sensors to identify different fault depths accurately. The environmental effects of curling and warping can significantly change fault depth. This effect makes certification processes challenging, as the data collected for ground reference and the data collected with the collection vehicle may be significantly different if they are collected under different conditions on different days. To overcome these effects, the draft report proposes the use of a manmade artifact that can simulate faulting at different depths. The artifact is built from materials that do not experience the same curling and warping effects as JCP and are not subject to the influence of the environment. An example of the proposed artifact is shown in Figure 27. The artifact should be capable of providing a range of fault values from zero to 0.5 inches in increments of 0.1 inch. This procedure provides a range of faulting distresses for accuracy checks.

The second proposed certification process (field environment) is to check the capabilities of the equipment to produce fault values under realistic conditions encountered during network data collection. This method includes precision checks and joint detection. The proposed control site criteria for the field environment certification process includes a range of faulting magnitude that can be expected to be encountered during production data collection.



Source: FHWA JCP Fault Draft report (2019)

Figure 27. Illustration. Example of the proposed joint fault reference device.

The control sites include all data metrics that are collected and used during DOT decision-making processes.

This certification process is specific to faulting. This item is not applicable.

The control sites are of sufficient length to gather enough data for certification processes.

The field environment certification process suggests a control site length of at least 30 joints. For typical 15 foot spacing, this is roughly a section length of 0.1 miles, which is consistent with IRI control site length. Note that this is not consistent with the proposed length of JCP pavement for automated or semi-automated crack detection.

Ground Reference Measurement

The control sites have adequate ground reference established so that the accuracy of data being collected can be checked.

The controlled environment certification process referenced in the draft JCP faulting report proposes the same ground reference equipment criteria and procedures referenced in the draft TPP AASHTO standard. Ground reference measurements are made on the manmade artifact. Ground reference is not collected for the field environment certification processes as this is only intended to check precision and joint detection.

There were few ground reference devices reported by DOTs for establishing ground reference data for faulting. The devices reported include manual measurements using a straightedge or use of the Georgia fault meter. These methods have limitations, including only measuring a single point within the wheel path (which is arguably a limitation of the HSIP). However, some agencies with limited decision-making processes based on faulting, or limited JCP in their network may find that manual fault measurements are adequate for establishing ground reference data. This should be further evaluated by State DOTs based on their decision making processes.

The ground reference data are established during similar environmental conditions to certification of the data collection equipment.

Accuracy of fault depth measurements is not considered in the field environment testing. This is primarily due to the factors in the field that may affect the faulting measurements. As discussed previously, faulting is affected by temperature-related curling and moisture-related warping, which may vary within a few hours (Chang et al. 2008). Since the field environment tests are designed to have little influence from the environment, environmental conditions are not as critical. However, repeat runs for the field environment testing should be made in the shortest time frame as possible to reduce the effects of curling and warping.

Highspeed Devices Measurements and Evaluation

Certification procedures verify calibrations of sensors and other associated systems (GPS, DMI, IMU, etc.).

Most DOTs are collecting or are planning to collect faulting data with 3D systems. The draft AASHTO standards that were developed under the TPF-5(299)/(399) TPP study were not developed specifically for fault measurement purposes. However, the general requirements specified for the equipment apply to faulting measurements for 3D systems. These methods should be evaluated to see if they apply to HSIP systems. The draft report for JCP faulting gives options for accuracy and precision statements applicable to faulting metrics based on the draft AASHTO standards. The applicable draft AASHTO standards and the modified options for accuracy and precision statements relative to faulting are shown in the following sections.

Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems (Body Motion).

The extent of a typical vehicle body motion is greater than the typical range of faulting by orders of magnitude. Therefore, the faulting equipment should not present any bias resulting from the vehicle motion. The certification procedure in the Body Motion Standard is adopted for faulting, with the adapted requirement statement shown in Table 32.

Table 32. Body motion requirement statements for faulting. Accuracy and Precision described as Bias and Confidence Intervals, inch.

Output Test Statistic	Lower Bounds (percentiles) 90% (5%)	Lower Bounds (percentiles) 50% (25%)	Bias	Upper Bounds (percentiles) 50% (75%)	Upper Bounds (percentiles) 90% (95%)
Vehicle Body Motion Error	-0.05	-0.02	0	0.02	0.05

Assessment of Static Performance in Transverse Pavement Profiling Systems (Static)

Sensor characteristics are important for identifying faulting and should be certified. The certification procedure in the above standard is also adopted for faulting, with the adapted requirement statement shown in Table 33.

Table 33. Static sensor system requirement statements for faulting. Accuracy and Precision described as Bias and Confidence Intervals, inch.

Output Test Statistic	Lower Bounds (percentiles) 90% (5%)	Lower Bounds (percentiles) 50% (25%)	Bias	Upper Bounds (percentiles) 50% (75%)	Upper Bounds (percentiles) 90% (95%)
Transverse Measurement Resolution	N/A	N/A	N/A	N/A	0.75
Transverse Measurement Accuracy and Precision	-0.6	-0.5	N/A	0.5	0.6
Straightness Error	0.10	-0.06	N/A	0.06	0.10
Vertical Measurement Resolution	N/A	N/A	N/A	N/A	0.004
Vertical Measurement Accuracy and Precision	-0.06	-0.04	N/A	0.04	0.06

Assessment of Navigation Drift Mitigation in Transverse Pavement Profiling Systems (Navigation Drift).

For faulting, the location sensors are the primary source of information for the joint location. Since the typical JCP joint spacing (e.g., 15 ft.) is much larger than the spacing between TPP measurements, any device meeting the TPP statements are appropriate for faulting. Note that any drift error is expected to impact all longitudinal measurements equally, and not relative to each other. Because faulting measurement is computed relative to the joint location, the impact of drift error on joint faulting computation is expected to be negligible, and the only impact is expected to be in terms of identifying the joint location.

The data collection certification procedures allow for enough repeat runs with different operators so that the data precision can be checked.

The draft procedure suggests a minimum of three repeat runs for joint detection and repeatability testing.

The data collection certification procedures are performed at the same speeds that data is collected in the field.

The proposed controlled environment procedure includes a suggested speed of 5 mph. This speed is based on safety concerns when driving over the manmade artifact. A static version of the test, or optimized speeds, may be considered during pilot testing.

The proposed field environment procedure does not specifically mention the testing speed. It is suggested that the runs are made at the speeds that are encountered during production testing, similar to the TPP draft highway standard.

Acceptance criteria, including accuracy and precision requirements specifically for certification have been established based on statistical analysis processes so that the data collection equipment can be rated as pass or fail.

The controlled environment test proposed requirement statements for faulting (bias against the ground reference measurements of the manmade artifact) is shown in Table 34.

Table 34. Controlled test requirement statements for faulting. Accuracy and Precision described as Bias and Confidence Intervals, inch.

Output Test Statistic	Lower Bounds (percentiles) 90% (5%)	Lower Bounds (percentiles) 50% (25%)	Bias	Upper Bounds (percentiles) 50% (75%)	Upper Bounds (percentiles) 90% (95%)
Faulting Error	-0.02	-0.01	0	0.01	0.02

The field environment draft certification procedure considers that the repeatability level for faulting measurements can be assessed based on practical uses of faulting data. As an example, consider a DOT that has defined the low severity faulting as those having a magnitude less than 0.2 in. An engineer calculates faulting for a given joint that is equal to 0.18 in. and categorizes the joint as low severity faulting. However, if the repeatability of the fault measurement method used was given as ± 0.08 in., it means that a second fault measurement run on the same joint has a 95 percent probability of resulting in a faulting magnitude that ranges from 0.10 in. to 0.26 in. In other words, there is a relatively good chance that the joint may have a medium severity faulting rather than low severity. On the other hand, if the repeatability of the fault measurement was given as ± 0.02 in, then a second fault measurement run has a high probability (95 percent) of yielding a fault value between 0.16 in. and 0.20 in. (i.e., low severity). As such, the DOT may feel more comfortable with the initial fault value of 0.18 in. and may decide not to make an additional fault measurement for the joint being considered.

Considering the example above and the resolution used for fault measurement, the researchers deem it reasonable to require repeatability of 0.02 in. or 0.03 inches.

To assess the repeatability for faulting certification, a minimum of three repeat runs should be made. The variance of the fault magnitude should be calculated for each joint and pooled together to yield an overall representation of the fault variance, as shown in Figure 28.

$$S_{Pool}{}^{2} = \frac{\sum_{i=1}^{n}(m-1)S_i^2}{\sum_{i=1}^{n}(m-1)}$$

Figure 28. Equation. Calculating the pooled standard deviation.

In the above equation, S_{pool} is the pooled standard deviation, S_i is the standard deviation from the individual joints, and m is the total number of repeat runs (minimum of 3). The S_{pool} represents the expected variability of a single fault measurement run and is also known as the one-sigma-limit, according to ASTM C 670. The S_{pool}, however, does not represent the repeatability of the fault measurements. If another fault measurement run is made by the same operator and same equipment, the second run also has a variability (or uncertainty) of S_{pool}. The difference between the first and the second fault measurement run results in a standard deviation (S_{Diff}) as calculated by the equation shown in Figure 29.

$$S_{Diff}{}^2 = S_{Pool}{}^2 + S_{Pool}{}^2 = 2 \cdot S_{Pool}{}^2$$

Figure 29. Equation. Calculating the standard deviation of two repeat runs.

Assuming a normal distribution for the differences in two fault measurements, the above indicates there is a 95 percent probability that the absolute difference between the two fault measurements is less than 1.96 times the standard deviation of the difference, as shown in Figure 30.

$$|\mathbf{X_1} - \mathbf{X_2}| < \mathbf{1.96} \cdot \mathbf{S_{Diff}} = \mathbf{1.96}\sqrt{\mathbf{2}} \cdot \mathbf{S_{Pool}}$$

Figure 30. Equation. Calculating the difference two-sigma limit.

The right side of the equation above is also referred to as the "difference two-sigma limit" in ASTM C 670 and represents the repeatability level achieved by the fault measurement. If the difference two-sigma limit is calculated to be less than the desired repeatability level (i.e., 0.02 in. or 0.03 in.), then the fault measurement is accepted for repeatability certification. Otherwise, it should be rejected, and the cause of poor repeatability should be examined.

Certification records are kept for all network data collection vehicles.

DOTs should develop certification decals and records similar to those used for HSIPs so that certification can be approved, recorded, and tracked.

Roles and Responsibilities for Equipment Certification

Based on QMP reviews and the DOT comments from the FHWA peer exchanges regarding data QMPs, setting up certification control sites and ground reference data is something that many DOTs are struggling to do. DOTs should 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 own resources or with 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 is responsible for ensuring 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 should have records of all calibration and certification activities and results. The records should be easily accessible so that DOTs can access them should any data quality issues arise.

The following points identify elements that should be included in calibration and certification reports and records:

- Reviewed and approved vendor or manufacturer calibration records that identify that the elements pass calibration criteria.
- Reviewed and approved certification records that identify that system pass certification criteria.
  The expiration dates of calibration and certification specific to all data collection vehicles and operators.

Table 35. Summary of criteria for certification of HSIP, 3D sensor systems for TPP, 3D systems for automated and semi-automated cracking, and faulting (HSIP or 3D systems).

Criteria Statement	HSIP	3D System (For TPP)	3D System (For automated or semi-automated cracking)	JCP Faulting (HSIP or 3D systems)
References	AASHTO R56, AASHTO R57 Note: these are required protocols for all HPMS IRI data, most DOTs reference these protocols per 23 CFR 490.111.	Draft AASHTO standards and developed under TPF-5(299)/(399). Note: these are draft standards and subject to change.	Draft Successful Practices for Cracking developed under TPF-5(299)/(399). Note: these are in draft form and are subject to change.	Draft JCP faulting procedures developed under TPF-5(299)/(399). Note: these are in draft form and are subject to change.
The control sites in the certification program reasonably represent pavement types in the network.	Control sites should include all surface types encountered in the network.	The draft standards suggest that a range of pavement types be used in certification processes.	The draft report proposes a minimum of three control sites per each pavement type in the network.	Faulting is only performed on JCP. A range of surface types (grooved, tined) and joint spacing is suggested.

Criteria Statement	HSIP	3D System (For TPP)	3D System (For automated or semi-automated cracking)	JCP Faulting (HSIP or 3D systems)
The control sites include a range and variety of ride quality and distresses that are typically encountered in the network.	• Smooth section (30-75 inches/mile). • Semi-smooth section (95-135 inches/mile). • Rough section (up to 200 inches/mile). • The surface macrotexture should be representative of each of the types of pavements in the network.	• For rut depth, control sites should exhibit a range of low-level rutting to high-level rutting. For low-level rutting, the minimum rut depth is 2.0 mm. High-level rutting is classified as greater than 20 mm. • For cross slope, the control site should contain a cross slope of greater than 5%. • Bounding beams should be placed on the transverse edges of the test site for assessment of edge/curb detection. • It is suggested that additional metrics being collected using the 3D system, should include a range of that metric.	• The draft report suggests that the sections have a variety of cracking and distresses representing a range of types and severities according to DOT definitions. • The draft report suggests that each DOT should identify the range of distress types and severity levels for inclusion in their control sites based on how data is used in decision-making processes.	• The JCP faulting on-going research suggests the use of a manufactured adjustable artifact as a ground reference, as shown in Figure 27 to check the accuracy of the data collection equipment. The equipment should be able to simulate fault depths from zero to 0.5 inches in increments of 0.1 inches. • The on-going research suggests a range of faulting that would be encountered during data collection for the field-testing portion of the certification process.
The control sites include all data metrics that are collected and used during DOT decision making processes.	AASHTO R56 generally only describes IRI metrics. If DOTs are using HSIPs to collect faulting data, a range of faulting values should be included in the control sites.	TPP draft Highway AASHTO standard only includes rut depth, cross slope, and edge/curb detection. However, it is reasonable to assume that additional metrics could be checked using similar procedures.	• The draft report suggests that each DOT should identify the range of distress types and severity levels for inclusion in their control sites. • Focus on those distresses or indices that are key to decision making.	This item is specific to faulting.

Criteria Statement	HSIP	3D System (For TPP)	3D System (For automated or semi-automated cracking)	JCP Faulting (HSIP or 3D systems)
The control sites are of sufficient length to gather enough data for certification processes.	• Each test section should be at least 528 feet in length. • 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.	• All 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 suggested.	• Asphalt and CRCP surfaces: 0.3 miles (1,584 feet). • JCP surfaces: 0.5 miles (2,650 feet) or 100 slabs – whichever is greater. • Sections should be subdivided into lengths of 0.03 miles for asphalt and CRCP and 0.05 miles for JCP.	Control sites should include at least 30 joints. Note that this is approximately the same length as HSIP certification for IRI (for 15-foot joint spacing), but different compared to the JCP length for automated or semi-automated crack detection.
The control sites have adequate ground reference established so that the accuracy of data being collected can be checked.	• Devices that measure and integrate differential elevations, such as the Dipstick® and Walking Profiler, may be used to establish the reference profiles. • Measurements from these devices must be checked with the rod and level at distances along the test profile trace.	• Draft AASHTO Standard Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment (GRE) is being proposed for TPP metrics (rutting, edge/curb detection, cross slope). • May be appropriate for other metrics collected using 3D sensor systems. • Some DOTs report the use of manual measurements for rut depth. These methods may be inadequate for the complex data collected using 3D systems.	• Ground reference is collected using manual raters. The draft report includes detailed procedures on how to subdivide areas for manual rating. These areas should be closed to traffic, and sufficient layout should be provided to delineate the wheel path. Manual raters should be sufficiently trained, as further described in chapter 5.	• Draft AASHTO Standard Assessment of Ground Reference Data for Transverse Pavement Profiling System Assessment (GRE) is being proposed for faulting. The GRE should be used to evaluate the manmade artifact (including ramps). • Some DOTs report using Georgia Fault Meters for ground reference data. This should be further evaluated. These methods may be inadequate for the complex data collected using 3D systems.

Criteria Statement	HSIP	3D System (For TPP)	3D System (For automated or semi-automated cracking)	JCP Faulting (HSIP or 3D systems)
The ground reference data are established during similar environmental conditions to certification of the data collection equipment.	• AASHTO R56 does not explicitly mention collected ground reference data during the same environmental conditions. However, this is critical, particularly for JCPs, as curling and warping can greatly affect ride quality. Research report FHWA-HRT-12-068 "Curl and Warp Analysis of the LTPP SPS-2 Site in Arizona" presented the use of pseudo strain gradient (PSG) to analyze the movement of concrete pavement and how to address it when using pavement profiles from HSIP.	• It is suggested that the environment is considered when establishing a ground reference for certification purposes.	• Several environmental conditions can affect the outcome of distress identification. • Make ground reference and data collection verification (or certification) procedures under similar conditions. • Conduct annual distress surveys during the same seasonal conditions from year to year to avoid climatic induced differences into the observable pavement condition.	• The manmade artifact is used to avoid the environmental effects of curling and warping. • Field certification procedures should make repeat runs in the shortest amount of time possible to avoid environmental effects.
The data collection certification procedures allow for enough repeat runs with different operators so that the data precision can be checked.	• Ten repeat runs are required per AASHTO R56. • AASHTO R56 certifies the operator with the equipment, so different operators are required to pass their certification tests.	• The draft Highway AASHTO standard suggests 3 runs at each driving speed. • Operator certification is not mentioned in the draft standard. DOTs should evaluate data collection sensitivity to operators and include this if necessary.	A minimum N of 10 subsections is suggested (this is performed by subdividing each control site).	The proposed procedure suggests 3 repeat runs.

Criteria Statement	HSIP	3D System (For TPP)	3D System (For automated or semi-automated cracking)	JCP Faulting (HSIP or 3D systems)
The data collection certification procedures are performed at the same speeds that data is collected in the field.	• According to AASHTO R56, five runs are made at the maximum desired certification speed, and five runs are made at the minimum certification speed. • These maximum and minimum speeds should reasonably reflect the range of speeds that network data collection intends to use.	Driving speeds ranging from approximately 10 mph to 65 mph, increasing at increments of 10 mph for TPP certification.	• No explicit criteria for the speed of data collection. However, it is implied based on the system capabilities statement of data that should be collected at or near prevailing highway speed, typically 25 to 65 mph. • It is suggested that certification collection speeds reasonably simulate actual data collection speeds.	• The controlled environment testing using the manmade artifact can't be made at traffic speeds due to safety concerns. It is suggested that this test is performed at 5 mph, though this has not been field verified. • The field environment test does not explicitly state that the testing is performed at highway speeds, though it is implied that the speeds should reflect speeds encountered during data collection.
Acceptance criteria, including accuracy and precision requirements specifically for certification have been established so that the data collection equipment can be rated as pass or fail.	• Equipment precision is checked using cross-correlation of each of the ten profiles to each of the remaining nine. • Equipment accuracy is checked using cross-correlation of each of the ten profiles to the reference profile. • Analysis can be completed in ProVAL software.	• Each draft standard has optional requirement statements that are summarized in the previous section. • Data analysis may require developing a program to analyze the data.	Paired t-test for equivalence. Note that this analysis may require the use of a statistical software package.	• The proposed method has an optional requirements statement for the controlled environment test. • Data analysis may require developing a program to analyze the data. • Precision is checked using the field environment collected data using the proposed statistical analysis method described previously.

Criteria Statement	HSIP	3D System (For TPP)	3D System (For automated or semi-automated cracking)	JCP Faulting (HSIP or 3D systems)
Certification procedures verify calibrations of sensors and other associated systems (GPS, DMI, IMU, etc.).	• Most DOTs reported also performing verification of DMI and performing calibration verifications of sensors using bounce and block tests per AASHTO R57.	• The three remaining TPP draft AASHTO standards verify the other systems associated with the 3D system. • Assessment of Body Motion Cancelation in Transverse Pavement Profiling Systems • Assessment of Navigation Drift Mitigation in Transverse Pavement Profiling Systems • Assessment of Static Performance in Transverse Pavement Profiling Systems.	• AASHTO R86-18 (formerly AASHTO PP68) Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection as a reference for image quality requirements, which references the following criteria. • 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 clearly viewed. • A crack width of 1 mm should be identifiable (for a stationary or low-speed system), with a 2 mm width identifiable when the image is collected while the collection vehicle travels at 60 mph. • The image size should be sufficient to accommodate some vehicle wander while data is being collected. It is not practical to avoid vehicle wander, particularly when traveling on an active highway.	• The draft procedures suggest using the TPP draft standards. This is assumed to be appropriate for data collected with 3D systems. This should be field verified. • The procedures may be appropriate for HSIP equipment but should be field verified.

Criteria Statement	HSIP	3D System (For TPP)	3D System (For automated or semi-automated cracking)	JCP Faulting (HSIP or 3D systems)
Certification records kept for all network data collection vehicles.	A decal should be placed on the equipment as evidence of certification with the expiration date. It is suggested that proof of certification also be kept in a DOT database.	DOTs should develop certification decals and records similar to those used for HSIPs so that certification can be approved, recorded, and tracked.	Certification records are kept for all network data collection vehicles.	A decal should be placed on the equipment as evidence of certification. The decal should show the expiration of the certification. It is suggested that proof of certification also be kept in a DOT database.

CHAPTER 5. BEFORE DATA COLLECTION: TRAINING

INTRODUCTION

This chapter includes successful practices for training personnel involved in automated, semi-automated and/or manual data collection.

DATA COLLECTION TRAINING

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

Data collection equipment includes complex systems, and proper training is critical to ensuring quality data is collected. Many DOTs did not include general training requirements in their QMPs. The following case studies highlight some of the successful training practices for data collection teams found during the QMP 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 QMP. 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 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 begin and end of day procedures. Data collection term definition and best practice is 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, and rutting, grade, GPS, texture, pavement imaging, Surveyor, and camera subsystems.

- *Troubleshooting (ARAN Manager/Operator)* The ARAN data collection system consists of many subsystems working together. 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 is 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 is used to integrate 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. Other levels of field technicians and operators are evaluated by the equipment vendor, and the training matrices are kept by PennDOT. Reviewing and keeping detailed training records is an example of a successful practice to ensure 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 of the 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 and can demonstrate proper driving technique as related to ARAN data collection and can drive consistently in the wheel path.
- Can complete ARAN daily mechanical inspection checklist in SalesForce/understands why Checklist has to 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 plan to route the sections for collection by utilizing Mission Management without supervision.
- Can refer to the section being collected on 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, selecting the type of collection, how to delete sections (explaining why sections were deleted).
- Can utilize Data Management, backup data, export data, and generate End of Day Report.
- Can access Daily Report, complete daily CSV reports, and how to 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 is aware of the location of all ARAN equipment.
- Can perform the Daily Report on SalesForce.
- Can perform data shipment, hard drive inventory, and can navigate through SalesForce/Saasmaint effectively without supervision.

DATA ACCEPTANCE TRAINING

This section includes training for the data acceptance team. Data acceptance should 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 should include training on any 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 better understand the data collection processes and potential sources of data error. A few successful practices found during QMP 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 that the data collection vendor provide 2 full-day training sessions at Alaska DOT&PF general office on the installation and use of the data collected for desktop and web-based applications. The first session is upon delivery of the first data set (initial five percent) and the second session when the full data set is delivered for the first year.

- Additionally, AK DOT&PF requires that the data collection vendor provide up to 80 hours of onsite technical support training at Alaska DOT&PF's discretion. Establishing these training requirements for data analysis is good 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 both vendor data collection software and asset management software. The training is conducted annually, and detailed topics are included in the QMP. The training topics listed for vendor software 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 including detailed training topics can ensure that the data acceptance team has the training and knowledge to perform their quality management tasks, and the data can be processed and exported to asset management software used 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 QMPs. Many DOTs reported that performing 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 did report using manual ratings for establishing ground reference data, performing manual acceptance checks of automated distress detection, or when using PSR in areas with speed limits below 40 mph as allowed in the HPMS Field Manual. These activities should be considered manual ratings, and personnel performing any ground reference rating or QC, or acceptance checks should be certified specific to DOT data protocols. As previously 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. Manual raters, including those performing ground reference or QC and acceptance activities, should be subject to training and certification.

If the State DOT intends to 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, then the State has the option of certifying that manual data collectors follow the PSR manual condition rating method described in the HPMS Field Manual. If a State DOT elects to use an alternative pavement condition method (e.g., PCI, PSI, etc.) to PSR, the manual data collectors must be certified for that methodology and 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 QMP 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 QMP reviews of manual rater certification.

Successful Case Studies

Texas Department of Transportation (TxDOT)

TxDOT (2018) reports in their QMP 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 QMP 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 how to rate state-specific distress definitions for each pavement type (Asphalt, JCP, CRCP).

South Dakota Department of Transportation (SDDOT)

The SDDOT QMP (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 how to use the crack editing software.
- A written examination is given to raters to verify that they have the 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. 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 QMP 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 36.

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 36. Summary of the purposes, goals, and timing of SCI distress rater training activities during each of the three phases adapted from SDDOT's QMP.

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 personal become 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, a series of training sessions with Pavement Management staff introduce the trainees to safety procedures (to include a defensive driving course), what the day to day operations are 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 actual 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 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 student's 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 that 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 phases of training have been completed to the satisfaction of the Instructor(s), the raters are considered to be 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 perform data collection should still review and accept training procedures and records. DOTs should ensure that they have sufficient detail of vendor programs to ensure adequate training is taking place. DOTs who self-collect data should ensure that proper training is provided to DOT personnel. This training may be performed in-house or by the equipment vendor or manufacturer.

REPORTING AND RECORD-KEEPING FOR TRAINING

DOTs should keep training records for all personnel associated with data collection or data analysis activities. Training records should include an expiration or a requirement for recertification. TxDOT (2018) does not mention how long certification is valid, but they do record the year certification was awarded. SDDOT (2018) mentions that manual certification is subject to evaluation but does not specify how frequently. Proper training is critical for data quality management, and proper record keeping ensures that these training activities are occurring as intended.

CHAPTER 6. DURING DATA COLLECTION: QUALITY MANAGEMENT ACTIVITIES

INTRODUCTION

This chapter includes successful practices of quality management activities performed during data collection, also referred to here as QC activities. Based on DOT QMP reviews, QC activities were a common strength among DOTs.

CONTROL SITES

A common QC activity referenced in QMPs is verification at control sites. DOTs typically did not differentiate between control sites used for certification activities, and control sites used for QC (or acceptance) activities. Certification control sites should be considered "Top Tier," as described in chapter 3 and have the strictest requirements requiring control site criteria and ground reference and described in chapters 3 and 5. These sites may not be economical or practical for QC activities. It is suggested that DOTs use other types of control sites for QC activities, including "Middle Tier" or "Bottom Tier." DOTs should 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 QC activity should be appropriate to the activity being performed. Successful practices identified in the DOT QMPs 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 should be included in the QMP. More examples of appropriate frequencies for quality management activities during data collection are summarized under the Case Studies section of this chapter.

ACCEPTANCE CRITERIA

The DOT or vendor may establish acceptance criteria for QC activities. DOTs should review and approve vendor acceptance criteria for QC activities (if using vendor services). Different criteria should be established for different activities described in the following sections. Acceptance criteria for quality checks should consider testing controls, as described in chapter 3 and chapter 7.

ELEMENTS OF SUCCESSFUL QUALITY CONTROL PROGRAMS

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

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

- Cross rater checks (as applicable). Checking the difference in results between different raters is important for ensuring year to year consistency of collected data.
- QC 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 acceptance criteria.
- Procedures include a responsible role in completing QC activities.

DOTs should 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 used on data collection equipment, as further described in chapter 2. Pavemetrics recommends the following data QC tools specific to LCMS laser systems and software. 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 LCMS:

1. Lens Cleaning
    - Field crews should clean LCMS lenses regularly to ensure that they are free from dust and contaminants. Depending on road conditions, this could need daily cleaning.
2. Wet Road Surfaces
    - Data should not be collected when the pavement surface is darkened due to moisture, or where there is standing water or potholes filled with water. Surfaces should be allowed to dry following rainfall.
3. Monitoring LCMS Images During Collection
    - Field crew should monitor LCMS intensity and range images during field data collection to ensure that they are well-exposed and sharp in appearance.
    - Field crew should review a percentage of collected LCMS images daily at the end of each day to ensure that data collected is of acceptable quality for subsequent data processing.
4. Periodic Sensor Validation
    - The field crew should periodically validate the calibration of each sensor using Pavemetrics' LCMS 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 31. A close up of the LCMS Validation Object shown in the intensity image is also illustrated in Figure 32. An example of the LCMS Validation Tool software

being used to check data quality using the LCMS Validation Object is shown in Figure 33.

- 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 is not able to adjust the calibration. It assesses whether the sensors are still well aligned.

5. Spot Checks
    - If field crew are uncertain as to 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.
6. 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 any 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 make a note of any apparent repairs that have been made to the pavement or significant deterioration since the last survey.
    - Field crews should process the LCMS 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 to see cracking, rutting, and roughness values that are relatively the same or moderately worse. If the values show improvement or significant deterioration, and the field crew did not note any maintenance or deterioration that explains the changes, the data should be flagged, and equipment malfunction should be investigated further.
    - Data from control sites should be collected at the end of the data collection season before storing the equipment. This process provides a measure to compare to in the spring of the next year or next data collection cycle.

Source: Pavemetrics (2020)

Figure 31. Photograph. Example of LCMS Scanning of the Validation Object.

Source: Pavemetrics (2020)

Figure 32. Photograph. Example of LCMS Validation Object shown in the intensity image.

Source: Pavemetrics (2020)

Figure 33. Illustration. Example of LCMS Validation Tool software being used to check data quality using the LCMS Validation Object.

The LCMS recommendations for the use of control sites generally align with suggested procedures for “Bottom Tier” control sites. DOTs should establish acceptance criteria for these control sites to standardize the process.

CORRECTIVE ACTION AND TROUBLESHOOTING

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

Error resolutions logs should be established when QC checks do not meet acceptance criteria. Many DOTs report having error logs, though they are typically only specific using them for data acceptance checks. Error logs, including error resolutions, should be kept for all data quality activities. CTDOT (2018) states in their QMP 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 of errors for QC and quality acceptance in logs. QC logs include both delivery data and resolution data, as shown in Table 37. These logs are separate from quality acceptance logs, though the content in each log is similar. DOTs should receive all QC error logs from data collection teams to ensure that any errors are resolved appropriately.

Table 37. Example of QC logs adapted from Oregon DOT 2018 QMP.

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

- No Data

SUCCESSFUL CASE STUDIES

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

Maryland DOT

Maryland DOT (2018) self collects network-level PSC data. Their QMP includes detailed tables for quality management activities specific to data collection equipment checks, pavement condition metrics checks, 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 38, Table 39, and Table 40. Other DOTs implement similar tables but may leave out one or more of these elements.

Note that because Maryland DOT self collects data, QC activities and quality acceptance activities are not separated. It is common for QC and quality acceptance activities to overlap in

DOT QMPs. The information presented in the following tables includes typical QC and quality acceptance activities, classified by Maryland DOT as “quality management” activities. The responsible party for these activities varies. Acceptance activities should not be performed by the data collection team, as further described in chapter 7.

Note that the responsible parties in Table 38, Table 39, and Table 40 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 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 /QA of the collected data.
- Pavement Management Assistant Division Chief (PM ADC).

Table 38. Summary table of procedures for the quality management of data collection equipment adapted from Maryland DOT 2018 QMP.

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 completely populated • Measurements within a reasonable range of value and consistent with 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 39. Summary table of procedures for the quality management of PSC metrics adapted from Maryland DOT 2018 QMP.

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 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 explanation (e.g., recent construction activities or data collection lane changes) are to 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 > 1% in comparison 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 40. Summary table of procedures for the quality management collected imaging, inventory, and other data adapted from Maryland DOT 2018 QMP.

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 listed in Table 41. 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 QMP whether Oregon DOT required the contractor to include corrective action and error resolution. QC plans should include this information. Note that "validation runs" occur at established control sites.

Table 41. QC requirements adapted from Oregon DOT 2018 QMP.

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

Deliverable	Quality Expectations	Activity	Frequency
Distress	• Std. dev. ≤ 10 percent (3 runs and/or historical average).	Validate	Pre-deployment and monthly
Data Reduction	• Review sample images for clarity, color, and luminance • Review bounce test output. • Review power spectral density anomalies. • Process and review sample 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 correct pavement type. • Confirm images meet quality requirements. • Confirm events marked as required. • No missing values without valid exclusion and reason codes. • IRI: 20 ≤ IRI ≤ 800 inches/mile. • Rutting: 0.00 ≤ Rut ≤ 2.00 inches. • Faulting: 0.00 ≤ Fault ≤ 1.00 inches. • Distress within range.	Check	Before data submittal

ROLES AND RESPONSIBILITIES

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

REPORTING AND RECORD-KEEPING

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

In addition to the more general items discussed above, the following should be included in QC 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 of 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 taken.
- Copies of all correspondence.

CHAPTER 7. AFTER DATA COLLECTION: DATA EVALUATION

INTRODUCTION

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

ELEMENTS OF SUCCESSFUL DATA ACCEPTANCE PROCEDURES

DOTs should have data acceptance procedures established for accepting data. Based on the current QMP reviews on the FHWA approved QMPs 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, including 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. 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. Data acceptance should 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 data batch minimizes the time between batches and reduces the potential for data reprocessing or re-collection. Based on QMP 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 should 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 should be communicated immediately with the data collection team to improve troubleshooting and avoid any 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 QMP reviews, 100 percent checks are typically performed for IRI, rutting, and faulting metrics. DOTs that use labor-intensive acceptance review checks may find it uneconomical to review 100 percent of collected data. The most labor-intensive checks reported in DOT QMPs 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 that are greater than the roadway length values. Alternatively, QA checks on distress data that are manually assessed have a sample size of 5 percent. DOTs should 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 should 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 should include their justification of sample size in their QMPs. In general, the sample size for manually or labor-intensive data review checks typically ranges from 2 to 20 percent (FHWA 2018).

Analysis Methods for Data Acceptance Review

Review checks and acceptance criteria for collected pavement data should be developed for each data metric. Data review checks conducted by DOTs should 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. Procedures for qualitative data acceptance review is provided in Section “Image Checks for Acceptance” of this chapter.

Based on QMP 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. As an example, Table 42 shows a subset of the data acceptance checks, with their respective acceptance PWL and error resolution procedure, adapted from the Oklahoma DOT’s (2018) QMP. Note that the table describes different levels of cracking that are specific to Oklahoma DOT’s data definitions which may not be applicable to all DOTs.

Table 42. Oklahoma DOT's data acceptance checks (2018).

Deliverable and Quality Expectation	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 the comparison of the collected data against the values reported for the previous year (or years) at the corresponding pavement section (or set of sections). This 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 more than 1% with respect to the HPMS deliverable submitted for the previous year (extracted from their QMP). Similarly, Maryland DOT flags HPMS condition metrics data if the State-wide mean values (for IRI, cracking percent, rutting, and faulting) vary by more than 2% with respect to the value from the previous year. SDDOT uses a temporal check for acceptance that is further detailed in section “Successful Case Studies for Data Evaluation.”

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 Section “3D System for Automated or Semi-automated cracking”. This analysis can be performed in standard statistical analysis software packages. Information about paired or independent t-test 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 should include information regarding their methods in their QMPs.

Analysis Criteria for Acceptance Review Checks

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

- 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 be indicative of the two sensors having technical issues.
- the requirement from pavement management system software, or other software—such as input data format.

As stated in chapter 4, the acceptance criteria of measurement methods testing data should be determined—when a standard specification is not available–considering the intended use of the data. PSC data is used in many pavement management applications—such as forecasts and budget estimations. Data not passing the acceptance criteria should be 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) should include the corrective action, including reprocessing or recollecting the rejected data.

Figure 34 shows three types of review checks reported in DOT QMPs on collected pavement data along with examples for each type of check.

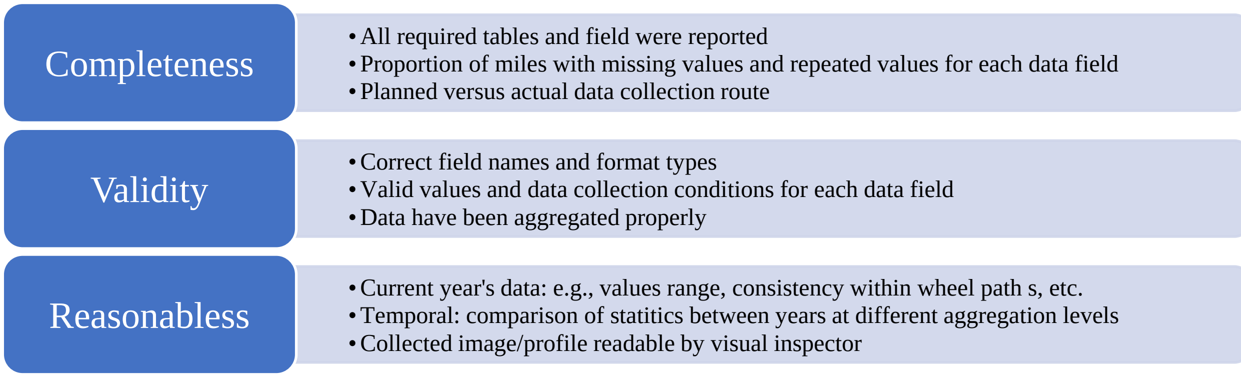


Figure 34. Chart. Typical types of review checks conducted by State agencies on collected pavement data.

The following include 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 relative to the mileage planned for the batch. For example, if the batch under review contains the data collected for an entire county, 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 should 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 may be described for each field as follows:

- formatting requirements (e.g., acceptable data collection year 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 data QMPs:

- 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 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 data QMP documents:

- Reasonable roughness values: 95 percent within the limit of an IRI range 30 to 400 inches/mile.
- Consistency across condition metrics: if IRI is low, then the cracking values should also be low, and if IRI is high, then the cracking values should also be 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 singe 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% in comparison to the previous year.
- Temporal changes in inventory data: flag data if total lane mileage by surface type has changed more than 1% in comparison to the previous year.
- Location data: flag starting and ending route collection points in inventory list with latitude and longitude coordinates differing by more than 22.18 feet of the closest GPS coordinate collected by the data collection vans.

Total mainline lane-miles of missing, invalid, or unresolved section s for data submitted under 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 types of review checks conducted on pavement data for acceptance of 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 35 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 portion reported data with events was relatively large for some state-route combinations, such as for 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, and the results were communicated immediately to the data collection team. These flags, as well as other flags in the batch, were subsequently 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 43 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.

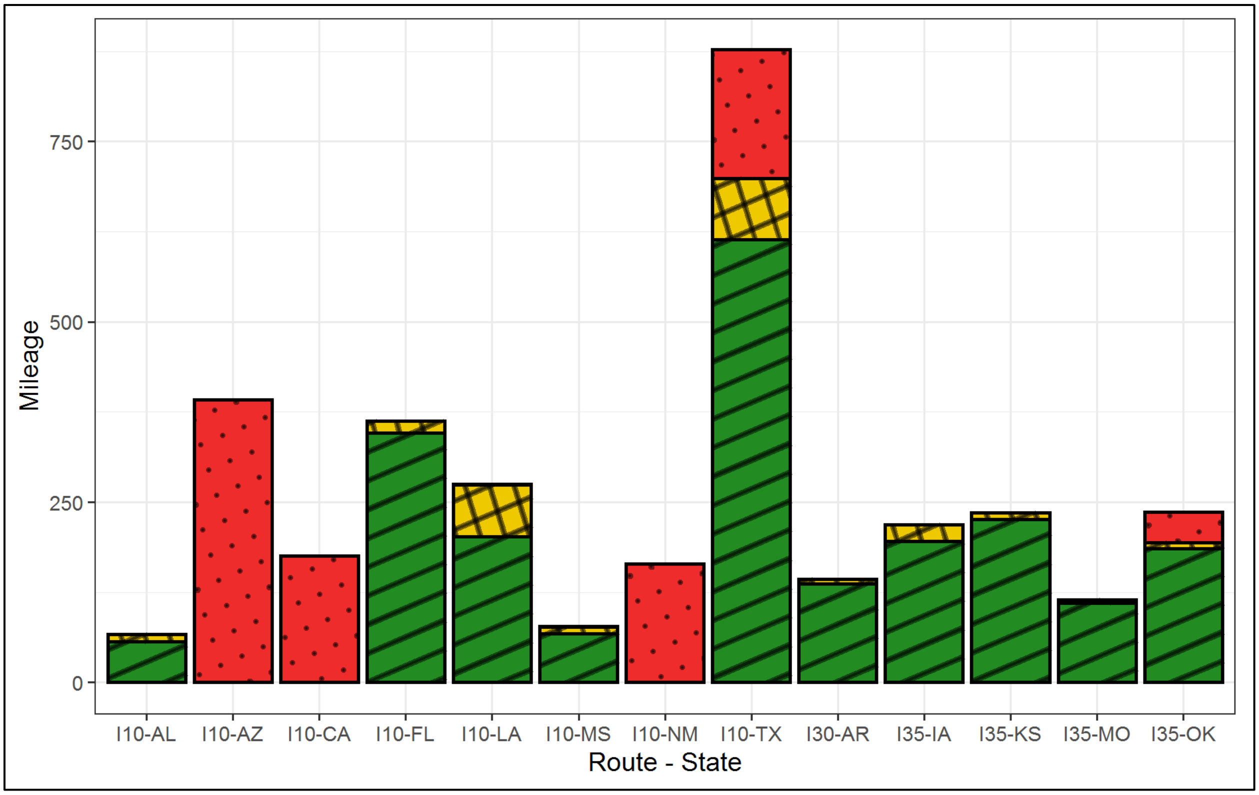


Figure 35. Chart. Collected mileage in data batch color-coded by missing, reported with events, and reported without events.

Table 43. 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 surface other than JCP
Rutting_surface_QC consistency	0.0%	rutting on surface other than ACP

Image Checks for Acceptance

Acceptance processes should include image checks. Image checks were previously described in chapter 4 under certification procedures. These quality checks should occur after data is collected. DOTs may use the same criteria that they establish for certification purposes, but should also check for missing images, image completeness, and proper stitching together of images. The following data acceptance tests image checks are reported from 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. 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 very grainy and seem to be out of focus, or it results 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 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 is traveling in a forward direction.

Successful Case Studies for Data Evaluation

Oregon DOT

Oregon DOT (2018) uses a data collection vendor and includes the following procedure in their QMP 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. Each week, the Contractor must submit the previous week's sensor data and images, and 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, and the timely review and feedback to the contractor ensures 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. As part of the process, Oregon DOT conducts independent range checks on collected data. 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 current year 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 is required to submit a pre-final delivery with all data for acceptance. If widespread issues remain in the final delivery, a subsequent final delivery may be requested to ensure the data is corrected as agreed upon between Oregon DOT and the contractor. Table 44 summarizes the data and image acceptance criteria.

Table 44. Acceptance Criteria (adapted from Oregon DOT 2018 QMP).

Deliverable (& Frequency)	Acceptance	Checks Performed	Action If Criteria Not Met
Route, lane, direction, LRS (Weekly)	100 percent	Review 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 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 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 create 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 review 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 value 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 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 review process is repeated for any recollected segments. The Pavement Condition Engineer is responsible for performing the acceptance reviews and identifying 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 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 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 review process is repeated for any recollected segments. The Pavement Condition Engineer is responsible for performing the acceptance reviews and identifying 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 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%, then data collection is stopped until issues are resolved. The segment is reviewed to determine if the difference can be explained (ex. 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 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 using 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 the cracks located 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 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 beis accomplished before the rater using 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 as per the HPMS Field Manual. The calculated cracking percent located by the rater using the combination of automated data and edited images are 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 started 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 should be established before data collection. Each acceptance activity should 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 QMPs:

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

DOT QMPs should identify what type of corrective action best resolves data errors. Error resolutions logs should be established when acceptance checks do not meet established criteria. Data collection personnel should 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 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 of 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 37) but include a review date. An example of the Oregon DOT quality acceptance log is shown in Table 45. 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 on future data.

Table 45. Example of quality acceptance logs adapted from Oregon DOT 2018 QMP.

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 should establish written error resolution processes that are agreed upon by the DOT and vendor before data collection. These processes should include data errors that trigger data reprocessing and re-collection. Acceptance checks should 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 46.

Table 46. 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 and Vernor Hwy W (Northbound)	Yes

Notes for Table 46:

1. BMP = Beginning Measure Point
2. EMP = End Measure Point

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, as described in chapter 4. The following describes Colorado DOT’s pilot data delivery requirements, as referenced from their QMP.

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 both Colorado DOT (and the data collection vendor) to follow their typical end to end process using real data. This ensures that all procedures, software, and configurations, are working as designed. Additionally, DOT personnel can evaluate the final reports and make changes to any step of the process 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 QMP.

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:
  - 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.
- Appropriate corrective action employed by the vendor.

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. Errors can either be discovered by the vendor during the QC process or by Colorado DOT during the QA process. In addition, Colorado DOT staff may identify problems before accepting the final deliverables.

All sections failing the vendor internal quality review are corrected before forwarding the deliverable to Colorado DOT. The vendor provides documentation of these checks, identifying any management sections which required re-rating and identifying the potential source of the original errors. If the errors are identified as systematic, then 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. When errors are discovered in 10% or less of the deliverable checked, the entire deliverable is accepted. 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 QMP:

- The issue or disagreement shall be clearly identified by both 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 clearly addresses the issue, the Data Collection Contractor's PM and the ARDOT PM are both required to 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 are those that may impact schedule, contract, and/or 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. This example mainly addresses manual checks of distresses based on images. However, NMDOT reported that they are in the process of developing procedures for verification of 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 are randomly selected by the NMDOT 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 47.

Table 47. Independent verification criteria adapted from NMDOT 2018 QMP.

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.

Corrective action and error resolution procedures should accompany any verification testing or other acceptable activity.

ROLES AND RESPONSIBILITIES

DOTs should have acceptance criteria and data checking processes that are 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 should verify the data. At a minimum, DOTs should perform database checks, image checks, and review 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 should establish a reasonable sample size of data to review that represents the pavement in their network, as previously described. DOTs may 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. Some DOTs include partial reporting and keeping records of specific tasks, including calibration records, certification records, and data acceptance records. QMPs should 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, and blind sites and reference values 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 that are taken.
- Recommendations for improvements.

CHAPTER 8 AFTER DATA COLLECTION DATA QUALITY REPORTING AND IMPROVING THE PROCESS

DATA QUALITY REPORTING

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 (Peirce et al. 2013). Reporting is a critical part of the quality management process. Reporting gives DOTs the ability to create a timeline of data quality. This timeline is valuable for identifying timeframes of when data quality may have been compromised, keep track of data quality issues, and prevent them from reoccurring in the future.

The reporting process is critical and was previously addressed in relevant sections specific to calibration and certification, training, quality management activities during data collection, and data evaluation after data collection. The content to consider in data quality reporting is summarized in Table 48.

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 Commissions QMP.

All steps in the data review must be documented as per Vendor International's regional Quality Assurance Plan (QAP). The office QAP describes office-wide planned processes and systematic actions, quality practices, and resources that are to be undertaken and which vendor (is responsible) to deliver quality data products. It requires that all client deliverables must be reviewed by the person executing the task, by a qualified colleague, (and) the project manager. All reviews must be documented in the office-wide Baker Quality Management Application (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 review of Pavement Management Projects (PMP).

Table 48. Summary of content for data quality management reporting.

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 that identify that the elements pass calibration criteria. • Reviewed and approved certification records that identify that system pass certification criteria. • The expiration date of calibration and certification specific to all data collection vehicles and operators.	• Reviewed and approved training records for all personnel associated with data collection or data analysis activities. • Expiration date or requirement for recertification.	• 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 of 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 taken. • Copies of all correspondence.	• A description of quality standards and acceptance criteria. • A description of control, verification, and blind sites and reference values 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 taken. • Suggestions for improvements

DATA QUALITY MANAGEMENT TOOLS

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

Automated Software Data Checks

Many agencies perform a series of quality checks on the entire database, as described in chapter 7. This quality check is typically performed using a set of queries stored for use with 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 type, 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 (Peirce et al. 2013).

Geographic Information Systems

GIS, as used in the context of asset management, are tools 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 be used to plot the collected data on a shapefile of the road network to check the accuracy of the segmentation process 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. The ability to examine the data visually 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 in the use of GIS as a QM data tool involves creating keyhole markup language (KML) files from the condition and inventory data and importing them for use with a browser-based GIS such as Google Earth™ mapping service. The ability to use an Internet application to display pavement data onto the road network along with satellite images, is proving to be very helpful in checking the data (Peirce 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 7.

IMPROVE THE PROCESS

Similar to this report, DOT QMPs are intended to be a living document that is 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 well-constructed QMPs are only effective when they are well maintained (Pierce et al. 2013). DOTs should consistently work towards improving data quality management processes. Several DOTs include methods to improve data quality management processes in their QMPs. 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 QMP (specific to manual distress ratings). The following processes take place between data collection seasons:

- SDDOT Region Fall Inspections – The distress data is compiled, 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 data that was collected reflects what is seen in the field.
- State Transportation Improvement Program (STIP) meeting – After candidate projects have been selected by the PMS for inclusion into the STIP, a large meeting takes place. 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 QMP. Lessons learned can be very useful training tools to reduce repeat issues with data quality. The lessons learned in the Caltrans QMP 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 encountered that were not reported.

CHAPTER 9. CONCLUSIONS

This document provides successful practices for DOT data QMPs based on the literature research, evaluation of existing DOT QMPs, and recently developed or on-going research relative to PCS data quality. Some of the information provided in this document, particularly regarding certification processes, have not been widely tested in pilot studies. These procedures are subject to change and evolve as the research and procedures are further tested and calibrated. This report should be updated and revised after the Phase II pilot studies are completed, depending on approval. This document should continue to be updated periodically as technology and procedures evolve.

Many DOTs already have successful elements and quality management activities reported in their QMPs. It is suggested that DOTs review their existing data QMPs 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 data QMPs 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 was not typically documented in DOT data QMPs. Reporting and record keeping is a critical part of quality management and should be included in written plans and procedures, as described in chapter 8. Without proper record keeping, it is difficult to receive the full benefits of a quality management program.

Many DOTs only included HPMS defined metrics required for submittal under 23 CFR 490.319(c). DOTs should also consider expanding their existing QMPs to include all data metrics used in their decision making processes. Documentation of 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 ensure quality during the turnover of employees, the addition of new employees, selection of new data collection vendors, and other changes occurring between collection seasons.

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 means that that two or more competent raters are evaluated on 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 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 an orientation) of the sensor, and thereby the body to which it is attached, in a global reference frame. Data from location sensors are typically used in the rotation and translation of data in a body-fixed frame to a global reference frame (Ferris et al. 2019).

Longitudinal profile: The vertical deviations of the pavement surface taken along a line in the direction of travel referenced as a horizontal datum (Pierce et al. 2019).

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

Measure: an expression based on a metric that is used to establish targets and assess progress towards 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 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 outlies.

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 taken to assure that the data collection processes are being followed, as required, such 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 path s are offset from the center of the lane by 14.75 inches and therefore 29.5 inches apart. (Peirce et al. 2019). Note that DOTs may have their own unique definition of wheel path .

BIBLIOGRAPHY

Alaska Department of Transportation and Public Facilities (2018). Highway Distress Data Collection Quality Management Plan. Alaska Department of Transportation and Public Facilities, Juneau, AK

American Association of State Highway and Transportation Officials (AASHTO), (2010). Standard Equipment Specification for Inertial Profiler. AASHTO M 328-10. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2010) Standard Practice for Collecting the Transverse Pavement Profile. AASHTO PP 70-10. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2010) Standard Practice for Determining Pavement Deformation Parameters and Cross Slope from Collected Transverse Profiles. AASHTO PP 69-10. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2010) Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Images Utilizing Automated Methods, AASHTO PP 67-10. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2010) Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection. AASHTO PP 68-10. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2012) Pavement Management Guide, Second Edition. Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2013) Standard Practice for Determining Rut Depth in Pavements. AASHTO R 48-10. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2013) Standard Practice for Quantifying Cracks in Asphalt Pavement Surface. AASHTO R 55-10. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2013) Standard Practice for Evaluating Faulting of Concrete Pavements. AASHTO R 36-13. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2014) Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces from Collected

Images Utilizing Automated Methods. AASHTO PP 67-14. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2017) Standard Practice for Collecting the Transverse Pavement Profile. AASHTO PP 70-14. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2017) Standard Practice for Evaluating Faulting of Concrete Pavements. AASHTO R 36-17. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2017) Standard Practice for Quantifying Roughness of Pavements. AASHTO R 43-13. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2017) Standard Practice for Determining Pavement Deformation Parameters and Cross Slope from Collected Transverse Profiles. AASHTO PP 69-14. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2017). Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection. AASHTO PP 68-14. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2017) Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Images Utilizing Automated Methods. AASHTO PP 67-16. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Equipment Specification for Inertial Profiler. AASHTO M 328-14. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Operating Inertial Profiling Systems. AASHTO R 57-14. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Certification of Inertial Profiling System. AASHTO R 56-14. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Measuring Pavement Profile Using a Rod and Level. AASHTO R 40-10. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Determining Pavement Deformation Parameters and Cross Slope from Collected Transverse Profiles. AASHTO R 87-18. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Pavement Images Utilizing Automated Methods. AASHTO R 85-18. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection. AASHTO R 86-18. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Collecting the Transverse Pavement Profile. AASHTO R 88-18. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Assessment of Highway Performance in Transverse Profiling Systems, Draft Standard, American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Assessment of Static Performance in Transverse Profiling Systems, Draft Standard, American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Assessment of Navigation Drift Mitigation Performance in Transverse Profiling Systems, Draft Standard, American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Assessment of Body Motion Cancelation in Transverse Profiling Systems, Draft Standard, American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), (2018) Standard Practice for Assessment of Ground Reference Data for Transverse Profiling Systems, Draft Standard, American Association of State Highway and Transportation Officials, Washington, DC.

American Society for Testing and Materials (ASTM), (2014). Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods, ASTM E177–14. ASTM International, West Conshohocken, PA.

Arkansas Department of Transportation (2018). Pavement Performance Data Quality Management Program. Arkansas Department of Transportation, Little Rock, AR.

California Department of Transportation (Caltrans) (2018). Pavement Condition Survey Data Quality Management Plan. California Department of Transportation, Sacramento, CA.

Chang, G.K., Watkins, J., and Orthmeyer, R. (2012). Practical Implementation of Automated Fault Measurement Based on Pavement Profiles, International Symposium on Pavement Performance: Trends, Advances, and Challenges, STP 1555, ASTM International, ISBN13: 978-0-8031-7541-9.

Coenen, T.B.J., Golroo, A. (2017). A review on automated pavement distress detection methods, Cogent Engineering, London, England.

Colorado Department of Transportation (2018). Pavement Data Quality Management Program, Colorado Department of Transportation, Denver, CO.

Connecticut Department of Transportation (2018). Network-Level Pavement Condition Data Collection Quality Management Plan, Connecticut Department of Transportation, Newington, CT.

Coughlin, C. and Novy, D. (2011). Domestic and International Border Effects: State Size Matters, Economics.

Devore, J.L. (2015). Probability and Statistics for Engineering and the Sciences, Cengage Learning.

European Commission. EC Policy Orientations on Road Safety 2011–2020 (2017).

Federal Register, National Performance Management Measure (2017). Assessing Pavement Condition for the National Highway Performance Program and Bridge Condition for the National Highway Performance Program, Volume 82, No. 11. 80 FR 8250.

Ferris, J.B., Altmann C.T. (2020), Calibration, Certification, and Verification of Transverse Pavement Profile Measurements, Draft Report, Federal Highway Administration, Washington, D.C.

Flintsch, G., McGhee, K. (2009). NCHRP Synthesis 40 Quality Management of Pavement Data Collection, National Academies of Sciences, Engineering, and Medicine, DOI: 10.17226/1425, Washington D.C.

Gestion de L‘entretien des Chaussées (GEC), (2003). Relevé d‘état et Appréciation en Valeur D‘indice. (The Swiss Association of Road and Transportation Experts), (VSS) SN-640925B.

Guerre, J., Groeger, J., Van Hecke, S., Simpson, A., Rada, G., and Visintine, B. (2012). Improving FHWA’s Ability to Assess Highway Infrastructure Health - Pilot Study Report, FHWA-HIF-12-049, Federal Highway Administration, Washington, D.C.

Highway Performance Monitoring System Field Manual (HPMS) (2016). OMB Control No. 2125-0028, U.S. Department of Transportation, Washington D.C.

IRMP, (1988). Istruzioni Sulla Pianificazione Della Manutenzione Stradale (Instruction for Road Maintenance Planning), CNR BU N.125/88.

Jia, X., Huang, B., Dong, Q., Zhu, D., Maxwell, J. (2016). Influence of Pavement Condition Data Variability on Network-Level Maintenance Decision, Transportation Research Record 2589, Washington D.C.

Karamihas, S. (2011). Benchmark Test Evaluation Report FHWA Project Improving the Quality of Pavement Profiler Measurement, University of Michigan Transportation Research Institute, Ann Arbor, Michigan.

LCPC, Laboratoire Central des Ponts et Chaussées, (1998). Catalogue des Dégradations de Surface des Chaussées, LCPC, Paris, France.

Maine Department of Transportation (2018). Pavement Condition Data Collection Quality Management Plan. Maine Department of Transportation, Augusta, ME.

Maronna, R.A., Martin, R.D., Yohai, V.J., Salibian-Barrera, M. (2019). Robust statistics: theory and methods (with R). John Wiley & Sons.

Maryland Department of Transportation (2018). Pavement Data Quality Management Program. Maryland Department of Transportation, Hanover, MD.

Mathavan, S., Kamal, K.; Rahman, M. (2015). A review of three-dimensional imaging technologies for pavement distress detection and measurements, IEEE Transactions on Intelligent Transportation Systems, DOI: 10.1109/TITS.2015.2428655.

Michigan Department of Transportation (2018). Data Quality Management Plan for Pavement Surface Condition Metric Data, Michigan Department of Transportation, Lansing, MI.

Minnesota Department of Transportation (2018). Pavement Data Quality Management Plan. Minnesota Department of Transportation, Maplewood, MN.

Minnesota Department of Transportation (MnDOT), (2012). Network-level Bit & BOC Decision Tree (07/01/12), Available online: http://www.dot.state.mn.us/materials/pvmtmgmtdocs/Bituminous_Decision_Tree_07-01-12.pdf, last accessed February 20, 2020.

Minnesota Department of Transportation (MnDOT), (2015). Pavement Condition Rating Overview, Available online: https://www.dot.state.mn.us/materials/pvmtmgmtdocs/Rating_Overview_State_2015V.pdf, last accessed February 20, 2020.

Montana Department of Transportation (2018). Network-Level Pavement Condition Data Collection Quality Management Plan Version 1.0, Montana Department of Transportation, Helena, MT.

Morian, D.A., Frith, D., Stoffels, S., Jahangirnejad, S. (2020). Developing Guidelines for Cracking Assessment for Use in Vendor Selection Process for Pavement Crack Data Collection/Analysis Systems and/or Services, Draft Report, Federal Highway Administration, Washington, D.C.

New Hampshire Department of Transportation (2018). Pavement Data Quality Management Program, New Hampshire Department of Transportation, Concord, NH.

New Jersey Department of Transportation (2018). Pavement Data Collection Data Quality Management Plan, New Jersey Department of Transportation, Trenton, NJ.

New Mexico Department of Transportation (2018). Pavement Distress Data Quality Management Plan. New Mexico Department of Transportation, Santa Fe, NM.

Oklahoma Department of Transportation (2018). Pavement Performance Data Quality Management Program, Oklahoma Department of Transportation, Oklahoma City, OK.

Olsen, M.J., Roe, G.V., Glennie, C. Persi, F., Reedy, M., Hurwitz, D., Williams, K., Tuss, H., Squellati, A., Knodler, M., (2013). Guidelines for the Use of Mobile LIDAR in Transportation Applications, NCHRP Report 748.

Oregon Department of Transportation (2018). Data Quality Management Plan for Pavement Condition National Highway Performance Program. Oregon Department of Transportation, Salem, OR.

Orthmeyer, R. (2018) "Webinar: Data Quality Management Program (DQMP) 23 CFR 490.319(C)", Presented as a webinar through FHWA, Available online: https://www.fhwa.dot.gov/pavement/mana.cfm, last accessed January 23, 2020.

Papagiannakis, A., Gharaibeh, N., Weissmann, J., Wimsatt. A. (2009). Pavement Scores Synthesis, FHWA/TX-09/0-6386-1, Texas Department of Transportation and the Federal Highway Administration, Austin, TX.

Pavemetrics, Laser Crack Measurement System, (website), Available online: http://www.pavemetrics.com/applications/road-inspection/lcms2-en/, last accessed January 23, 2020.

Pennsylvania Department of Transportation (2018). Data Quality Management Program. Pennsylvania Department of Transportation, Harrisburg, PA.

Peshkin, D., Smith, K.L., Wolters, A., Krstulovich, J. (2011). Preservation Approaches for High-Traffic-Volume Roadways, National Academies of Sciences, Engineering, and Medicine, DOI 10.17226/14508, Washington D.C.

Pierce, L.M., McGovern, G., Zimmerman, K.A. (2013). Practical Guide for Quality Management of Pavement Condition Data Collection, Contract No. DTFH61-07-D-00028, U.S Department of Transportation, Washington D.C.

Pierce, L.M., Weitzel, N.D. (2019). NCHRP Synthesis 531 Automated Pavement Condition Survey, National Academies of Sciences, Engineering, and Medicine, DOI: 10.17226/25513, Washington D.C.

Rodriguez, M.Z., Barraza M.F.S., Alvarez, M.J.A., Viles, E., Jaca, C. (2017). Information Quality in Companies Committed to TQM, Engineering Systems, and Networks. DOI 10.1007/978-3-319-45748-2_21, Switzerland.

Saliminejad, S. and Gharaibeh, N. (2013). Impact of Error in Pavement Condition Data on the Output of Network-Level Pavement Management Systems, Transportation Research Record 2366: 110-119, Washington, D.C.

Serigos, P. A., Burton, M., de Fortier Smit, A., Prozzi, J. A., and Murphy, M. R. (2014) Field Evaluation of Automated Distress Measuring Equipment, Report No. FHWA/TX-14/0-6663-2, Center for Transportation Research, Austin, TX.

Serigos, P. A., Chen, K., de Fortier Smit, A., Murphy, M.R., and Prozzi J. A. (2015). Automated Distress Surveys: Analysis of Network-level Data (Phase III), Report No. FHWA/TX-15/0-6663-3, Center for Transportation Research, Austin, TX. (2015).

Serigos, P. A., Prozzi, J. A., Nam B. H., and Murphy M. R. (2012) Field Evaluation of Automated Rutting Measuring Equipment. Report No. FHWA/TX-12/0-6663-1, Center for Transportation Research, Austin, TX.

Serigos, P.A., Visintine, B.A., Simpson, A.L., Rada, G.R., and Groeger J.L. (2018). Quality Management Program for Pavement Condition Data Collected on the National Highway System, Transportation Research Record, Washington D.C.

Siabil, S.Z. (2016). Integration of Heuristics and Statistics to Improve the Quality of Network-level Pavement Condition Data, Report No. SWUTC/16/600451-00052-1, U.S. Department of Transportation, University Transportation Center, State of Texas, College Station, TX.

Simpson A.L., Rada, G.R., Bryce, J., Serigos, P.A., Visintine, B., and Groeger, J.L. (2018). Interstate Highway Pavement Sampling Data Quality Management Plan, FHWA-HIF-18-032, Federal Highway Administration, Washington D.C.

Simpson, A., Serigos, P., Kouchaki, S., Rada, G., Groeger, J. (2020). Interstate Highway Pavement Sampling Final Phase 2 Report, Draft Report, Federal Highway Administration, Washington, D.C.

Simpson, A.L., Rada, G.R., Visintine, B., and Groeger, J.L. (2016). Interstate Pavement Condition Sampling, FHWA-HIF-17-022, Federal Highway Administration, Washington, D.C.

South Carolina Department of Transportation (2018). Pavement Management Data Quality Management Plan, South Carolina Department of Transportation, Columbia, SC.

South Dakota Department of Transportation (2018). Quality Management Plan for Network Level Pavement Condition Data Collection, South Dakota Department of Transportation, Pierre, SD.

Texas Department of Transportation (2018). Quality Management Plan for Pavement Data Collection, Texas Department of Transportation, Austin, TX.

Texas Department of Transportation (2019). Unified Transportation Program, Report 2019, Austin, TX.

Tsai, Y-C. J. (2019). Evolution of Proposed Standard Data Format and Compression Algorithms for 2D/3D Pavement Surface Image, Draft Report, Federal Highway Administration, Washington, D.C.

Tsai, Y-C..J., Chatterjee, A. (2017). Quantitative Crack Detection Algorithm Performance Evaluation System. "Journal of Computing in Civil Engineering, American Society of Civil Engineers (ASCE), Volume 31. Issue 5, Reston, VA.

TTI-PMS, Tech Transportation Institute, PMS Pavement Management Services Ltd, Ireland Department of Transport Tourism & Sport, (2015). Development and Implementation of a Simplified System for Assessing the Condition of Irish Regional and Local Roads. In Proceedings of the 9th International Conference on Managing Pavement Assets, Virginia Tech Transportation Institute (VTTI), Alexandria, VA, USA.

UK Roads Liaison Group (website), Available online: http://www.ukroadsliaisongroup.org/, last accessed February 13, 2020.

Unknown (Regions), "What are the Regions of the United States?" (website) Available online: https://study.com/academy/lesson/what-are-the-regions-of-the-united-states.html, last accessed December 19, 2019.

US DOT (2015) "Evaluation of Long-Term Pavement Performance (LTPP) Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide (MEPDG) Calibration and Other Pavement Analysis" Available online: https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/15019/008.cfm, last accessed December 19, 2019.

US DOT (2017) "National Highway System Length – 2017, Miles by Functional System" (website) Available online: https://www.fhwa.dot.gov/policyinformation/statistics/2017/pdf/hm41.pdf, last accessed December 19, 2019.

Wang, K.C.P, (2018). Next-Gen High-Speed 3D Sensors and Cognition Based Intelligent Solutions for Condition and Safety Surveys: Status and Direction, Road Profiles Users' Group (RPUG) Conference, South Dakota.

Wang, K.C.P., Li, Q.J., Chen, C. (2016). Development of Standard Data Format for 2-dimensional and 3-dimensional Pavement Image Data use to Determine Pavement Surface Condition and Profiles, Task 2- Research Current Practices, Federal Highway Administration, Washington, D.C.

Wang, R.Y. (1998). A Product Perspective on Total Data Quality Management, Communications of the ACM, Volume 41, No. 2.

WayLink Systems Corporation, (website), Available online: https://waylink.com, last accessed September 3, 2020.

Zhang, A., Wang, K.C.P., Fei, Y., Liu, Y., Tao, S., Chen, C., Li, J.C., Li, B. (2018). Deep Learning-Based Fully Automated Pavement Crack Detection on 3D Asphalt Surfaces with an Improved CrackNet, DOI: 10.1061/(ASCE)CP.1943-5487.0000775, American Society of Civil Engineers.

Zimmerman, K.A. (2017). NCHRP Synthesis 501 Pavement Management Systems: Putting Data to Work, DOI: 10.17226/24682, National Academies of Sciences, Engineering, and Medicine, Washington D.C.