Development of a Quality Management Plan for Pavement Condition Data in Connecticut

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October 3, 2018
Report Number: CT-2309-F-18-7
SPR-2309

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Disclaimer

Acknowledgements

This report was prepared by the University of Connecticut in cooperation with the Connecticut Department of Transportation and the United States Department of Transportation, Federal Highway Administration. The opinions, findings and conclusions expressed in the publication are those of the authors and not necessarily those of the Connecticut Department of Transportation or the Federal Highway Administration. This publication is based upon publicly supported research and is copyrighted. It may be reproduced in part or in full, but it is requested that there be customary crediting of the source.

Standard Conversions

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 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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 (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

Technical Report Documentation Page

1. Report No. CT-2309-F-18-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of a Quality Management Plan for Pavement Condition Data in Connecticut		5. Report Date June 15, 2018
		6. Performing Organization Code
7. Author(s) Don A. Larsen, James Mahoney, and Iliya Yut		8. Performing Organization Report No. CAPLAB 01-2018
9. Performing Organization Name and Address University of Connecticut Connecticut Transportation Institute 270 Middle Turnpike, U-5202 Storrs, Connecticut 06269-5202		10 Work Unit No. (TRIS) N/A
		11. Contract or Grant No. N/A
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 2800 Berlin Turnpike Newington, CT 06131-7546		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code SPR-2309
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation and Federal Highway Administration		

16. Abstract

The research team from the Connecticut Transportation Institute at the University of Connecticut performed this project for the Connecticut Department of Transportation (CTDOT). The major results of this study were a Data Quality Management Plan and a comprehensive procedures manual providing a road map and steps to establish a process for quality control and acceptance of pavement condition data collected with CTDOT's automated 3-D laser systems. The Data Quality Management Plan (DQMP) was submitted for Federal Highway Administration approval in accordance with federal requirements. Ultimately, following the receipt of FHWA comments, CTDOT revised and resubmitted the DQMP, which was approved by FHWA in August 2018.

17. Key Words Data Quality Management, Pavement Condition Data, ARAN, Precision, Reproducibility, Quality Acceptance	18.Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161. The report is available on-line from National Transportation Library at http://ntl.bts.gov.		
19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 72	21. Price
Form DOT F 1700.7 (8-72)	Reproduction of completed page authorized		

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

This report summarizes background information, the research methodology, and major findings for the SPR-2309 project titled “Development of a Quality Management Plan for Pavement Condition Data in Connecticut.” The research team from the Connecticut Transportation Institute (CTI) at the University of Connecticut (UConn) performed this project for the Connecticut Department of Transportation (CTDOT). The major results of this study were a Data Quality Management Plan (DQMP) and a comprehensive procedures manual providing a road map and steps to establish a process for quality control and acceptance of pavement condition data collected with CTDOT’s automated 3-D laser systems. Ultimately, the Data Quality Management Plan (DQMP) was submitted for Federal Highway Administration (FHWA) approval in accordance with federal requirements (*USG2017*).

Problem Statement

The FHWA published final requirements for National Performance Management Measures for the National Highway Performance Program (NHPP) to monitor system performance on the National Highway System (NHS) (23 CFR §490) in early 2017. Part of this requirement is the development, approval by FHWA and utilization of a Data Quality Management Program, on or before May 20, 2018, that addresses the quality of all NHS data reported for the NHPP (*USG2017*).

In Connecticut, the SPR-2297 research study titled “Implementation of a 3-D Sensing Technology for Automated Pavement Data Collection in Connecticut” performed in 2016 found that significantly different results existed between two expectedly identical Automatic Road Analyzer (ARAN) systems used by CTDOT. The differences found included reported results for profile characteristics, roughness, and cracking lengths/severities. The analysis of pavement condition data simultaneously collected by the two ARAN vehicles on a subset of over 2 percent of Connecticut road network called into question the quality of network data collected during 2015 and 2016. This outcome reinforced the need for development of a rigorous quality management process, concurrently with the development of the DQMP as required by the new federal requirements (*USG2017*).

Objectives

The objectives of this study (SPR-2309), as identified in the proposal dated August 14, 2017 are:

1. Prepare a Quality Control Plan to address variability in pavement data in terms of smoothness (IRI), rutting, surface cracking, and road profile characteristics.

2. Develop Quality Acceptance thresholds and error resolution procedures for pavement condition indicators, for smoothness (IRI), rutting, surface cracking, concrete joint faulting, and road profile characteristics.

3. Develop a Quality Management Plan that covers the required quality assurance activities before, during, and after data collection and processing, and that can also be submitted for FHWA approval, by CTDOT, for the NHPP Data Quality Management Program described in 23CFR §490.319 (C) (*USG2017*).

Methodology

This Section describes the project work plan and the methodology used in the analysis for development of the DQMP for pavement condition data at the CTDOT. Accordingly, the CTI research team planned and accomplished the following tasks:

Task 1. Conduct Literature Review

This Task involved a search for and critical review of existing literature on best practices for the development of a DQMP by federal and state transportation agencies (See Chapter 2 for details).

Task 2. Evaluate existing data collection and rating protocol procedures.

The following activities were performed under Task 2 (See Chapter 3 for details):

- Interview CTDOT Photolog personnel on data collection and processing practices with an emphasis on: operator and analyst experience with new pavement survey hardware and software, operations specifics (e.g., speed, wandering, and orientation), and equipment calibration.

- Interview CTDOT Pavement Management personnel on pavement rating protocols currently used to establish the order of importance of specified indices (e.g., roughness (smoothness), rutting, joint faulting, cracking extent, and profile characteristics) in network and project level reports.

- Evaluate existing CTDOT documented guidelines and/or QC/QA procedures used by the Photolog unit for pavement data collection. An emphasis was made on establishment of reference values (for use as ground truth), the use of verification sites, existing precision and accuracy requirements, and corrective action procedures.

Task 3. Establish data acceptance thresholds and statistical evaluation guidelines.

Task 3 included the following steps:

- Use findings from the SPR-2297 project to establish controllable sources of variability in the collected pavement data and to identify distinctions between random and systematic errors in data collection and processing (See Chapter 4 for details).

- Investigate and propose appropriate statistical methods for data quality control and quality acceptance (See Chapter 4 for details).

Task 4. Develop DQMP for pavement condition data.

To accomplish this Task, The CTI research team utilized and adopted as appropriate federal guidelines (*Pierce2013, USG2017*), other state agencies' experience (for example, Indiana and Virginia), and the CTDOT existing processes. As a result, the DQMP covered the following topics (See Chapter 7 for details):

- Description of pavement data collection equipment and business processes at the CTDOT
- Outline of personnel training and qualification requirements, and equipment calibration and certification
- Procedures for quality control of pavement data collection (before, during, and after field surveys)
- Guidelines for quality acceptance of collected and processed pavement condition data
- Assignment of roles and responsibilities to CTDOT personnel involved in quality control and acceptance processes for pavement condition data

The findings from Task 2 led to a conclusion that special emphasis had to be put on detailed field operations procedures to manage quality of pavement data. The three formal phases of data flow are (1) pre-production, (2) production, and (3) post-production (also identified above as before, during and after field surveys). Therefore, two addendums to the DQMP document were created (See Chapter 7 for details):

1. Photolog Field Data Collection Standard Operating Procedures (created by the Photolog Unit based on previous knowledge and experience plus CTI recommendations)
2. Manual for Quality Control of Pavement Condition Data Collection (created by CTI)

<u>Task 5. Prepare and submit DQMP for pavement condition data.</u>

This Task was allocated for finalizing the DQMP document and its addendums based on the reviews by the CTDOT and FHWA. It was anticipated that additional time would be required to answer questions and address unexpected issues before and after the submission of the DQMP to FHWA.

Organization of Final Report

Chapter 2 of this report presents a summary of a literature review and specific information on quality management of pavement condition data for a few selected states. Chapter 3 discusses the existing data collection procedures and rating protocols in Connecticut. Chapter 4 summarizes guidelines for statistical evaluation of pavement data quality and provides details on development of precision and accuracy limits for data acceptance. The process for selecting and establishing validation sites and verification sections is described in Chapter 5. Chapter 6 provides a summary of the contents of the DQMP and two supporting addendum documents. Lastly, Chapter 7 contains study conclusions and recommendations on further activities that would lead toward improvement of the quality of pavement condition data in Connecticut.

Chapter 2. Literature Review and Summary

Introduction

An effective Pavement Management System (PMS) must provide data and information that is recognized and certified to be complete, accurate, precise and reliable (*Ong et al., 2010*). The critical importance of reliable information is obvious in that it is paramount for making budgetary decisions for pavement maintenance and rehabilitation. In addition, as noted elsewhere in this report, the FHWA requires the development and utilization of a Data Quality Management Plan that must be approved on or before May 20, 2018, for monitoring system performance on the National Highway System (NHS).

A search and review of literature and information on other state's activities regarding quality management for pavement data collection was performed. The results of the literature review are provided below.

Precision and Accuracy of Data

A traditional approach to data quality delineates deviations from a true value that are due to both random and systematic errors. *Random errors result in dispersion, or low precision, around a reference value, while systematic errors shift the observed mean of a series of measurements away from the actual value, resulting in bias or low accuracy* as illustrated in Figure 2.1 (after *Pierce et al., 2013*)

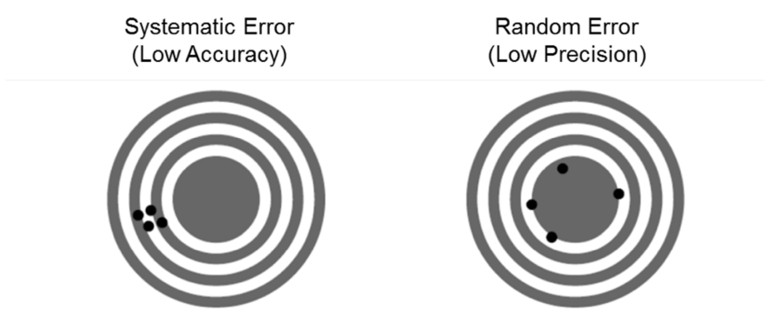

Figure 2.1. Illustration of data quality measures (after *Pierce et al., 2013*)

In a PMS, a systematic misrepresentation of a distress definition or its severity manifests a systematic error, which results in certain distress types that are misidentified (and under or over reported). An example of random error is occasional unrecorded distress or recorded distress where none exists. True random errors affect primarily the pavement section where they are recorded and have a minimal impact on overall network level ratings. (*Shekharan et al., 2007*).

According to Flintsch and McGhee (2009), in NCHRP Synthesis 401, with the large number of measurements required during network-level pavement condition data collection, random errors tend to offset each other and systematic errors become the most important influence on data quality. The synthesis also notes that compared to the application of Quality Control (QC) principles and methods to manufacturing, PMS is particularly challenging because the ground truth or reference value often is difficult to determine. As stated another way by Morian et al, (2002), the principles of statistical quality assurance for collection of pavement condition data differ in that for manufacturing the desirable product is known, whereas for pavement data collection, the right product is not known.

The literature reviewed for this study generally distinguishes between two primary concepts of quality management, which are (1) quality control and (2) quality acceptance. Some agencies, such as Indiana DOT, utilize term quality assurance for their data quality management (*Ong et al., 2010*). A third quality management principle is independent assurance. The following discussion is summarized from NCHRP Synthesis Report 401 (*Flintsch and McGhee, 2009*).

Quality Control (QC) – QC includes the activities needed to adjust production processes toward achieving the desired level of quality of pavement condition data. Those comprise checks on surveying equipment (including following equipment manufacturers' recommended calibration and QC procedures), using properly trained personnel to be responsible for data collection, and the data collection process itself.

QC Plan - The purpose of a QC plan is to (1) quantify the variability in the process and maintain it within acceptable limits, (2) identify manageable sources of variability, and (3) take the necessary production adjustments to minimize the "controllable" variability. From a survey of states and provinces performed for NCHRP Synthesis 401, the responders noted that in their QC plans, the main tools and methods used for quality control are:

- Calibration and verification of equipment/methods prior to data collection
- Testing of known control segments prior to data collection
- Testing of known control and/or verification segments during data collection
- Software routines that check the reasonableness, completeness, and consistency of the data, and compare the production data with existing time-series data

Quality Acceptance (QA) – QA includes activities to verify that PMS data meet specified requirements. The two important aspects of quality acceptance are (1) establishing of acceptance criteria and (2) specifying the sample size for verification. In 2009, approximately half of the state and provincial highway agencies reported having a formal quality acceptance plan for their agency.

Quality Management Plan (QMP) – The QMP is a program-specific document that describes the general practices of the program. It may be viewed as the "umbrella" document under which individual quality activities are conducted. As an example, a QMP for distress data collection may include the following activities (*Shekharan et al., 2007*).

- Distress definitions
- Rater training (and equipment calibration) methods

- Systematic data-collection process management
- Systematic data handling and processing
- An effective quality control system
- An effective quality acceptance check system
- Timely identification and implementation of corrective actions
- Timely report development
- Delivery of results to the owner agency or client

The management of data quality can also be enhanced by implementing an *Independent Assurance (IA)* process. IA may include, for example, resampling up to 10% of data using a third party, and comparing the results with the production results, with an example ultimate goal to identify any random and systematic errors. From the NCHRP 401 survey it is noted that as of 2009 only 4% of the agencies surveyed use independent verification for quality control and 12% for quality acceptance. However, as noted by *Shekharan et al*. (2007), the elimination of systematic errors is critical for the success of a network level data collection program.

Sources of Variability in Pavement Data Collection

Variability is inherent in pavement condition data collection. To be able to compare results and establish target control and acceptance levels for quality management, it is important that agencies understand the magnitude and sources of variability in the data being collected. Table 2.1 contains a list of data collection variability sources for cracking, rutting, joint faulting and smoothness (IRI) (as obtained from the NCHRP 401 survey of State Highway Agencies) (*Flintsch and McGhee, 2009*).

Table 2.1. Sources of Variability in Pavement Data Collection (after *Flintsch and McGhee, 2009*)

Pavement Attribute	Sources of Variability
Cracking	• Type of equipment/data collection method Image quality for automated and semi-automated surveys. Type of image generating technology (analog, images, laser-based). Resolution of the imaging equipment Field of view Quality of the color contrast of the pavement image Lighting method.
	• Rater's vision—in case of windshield surveys.
	• Raters/equipment operator training Experience Understanding of rating protocols
	• Processing software (algorithm)
	• Environmental conditions during measurement (weather, canopy coverage, etc.)
Rutting	• Type of equipment Sensor type (point laser, ultrasonic, continuous scanning laser) Rut bar width Number of sensors

	• Equipment operation Wheelpath wander Edge drop-off and/or narrow lanes Operator experience, training, and driving skills
	• Rut depth calculation method (wire, straight edge, multiple points)
	• Environmental conditions Temperature, wind, humidity, and surface moisture Surface contamination Lighting conditions (for optical sensors) Surface texture (open-graded, chip seals and other highly textured surfaces)
Joint Faulting	• Identification Properly categorizing crack faulting and joint faulting
	• Data Interpretation Classification – High severity faulting more easily detected than low severity
Smoothness (IRI)	• Type of profiler Height sensor type and properties (ultrasonic, laser; sampling rate, resolution, footprint, range)
	• Accelerometer type and location
	• Distance measurement system (linear, GPS)
	• Profiler operation Operator experience, training, and driving skills Wheelpath wander Longitudinal positioning/triggering Speed of profiler Lane measured Tire inflation pressure (affects longitudinal distance measurements) Calibration
	• Profile data interpretation and processing Filters (high, low, unwanted, option or not) Profiler computation algorithm IRI calculation algorithm and procedure Integration interval (segment length)
	• Wheelpath measured
	• Presence of bridges, railroad crossings, and unadjusted manhole lids.
	• Environmental conditions
	• Surface shape (texture, distresses, PCC versus HMA, cross-slope and grade)

Detailed Literature Review

Metrics of particular concern that have been identified in the literature for quality management of pavement performance data include smoothness (IRI), rut depths, and crack lengths. A survey of state highway agencies indicated an increasing number of agencies that perform some QC/QA activities to improve reliability of pavement data collection (*Flintsch and McGhee, 2009; Pierce et al, 2013*). However, even by 2013, the FHWA reported only a few agencies were found to have a comprehensive QMP in place for pavement condition surveys (*Pierce et al., 2013*).

<u>FHWA-Practical Guide for Quality Management (*Pierce et al., 2013*)</u>

Pierce et al. (2013) has produced for FHWA a Practical Guide for quality management of pavement condition data collection. The Practical Guide provides information for the development and implementation of a QM program and examples or case studies using pavement condition data from a variety of state DOTs. This guide provides a rich source of information for CTDOT to use during implementation of QC/QA for pavement management data collection. The Practical Guide also contains a data quality management plan template and a discussion of the major procedures in a QM plan, as well as the responsible party for each.

FHWA notes in the Practical Guide that without a documented plan, such as a formal QMP, agencies are less likely to apply QM activities consistently from year to year, nor assess the effectiveness of the techniques used. First and foremost in the list of requirements for a successful QM program for pavement data collection is a *definition of methods, standards and protocols*. FHWA notes that pavement condition rating protocols/guides should clearly define the distress types, severity levels, rating methods (e.g., count, length, or area), reporting interval, and the method used to compute condition values. This well-defined foundation should help ensure the usefulness and consistency of the information collected and disseminated.

The next important item is specifying *data quality standards*, such as *resolution* – e.g., rut depth measured to the nearest inch (mm) or International Roughness Index (IRI) measured to the nearest inch/mile (m/km), *accuracy* - specified in absolute values, percent, standard deviation, or other statistical measure, and *repeatability* - a comparison of repeated measurements of the same section under the same or similar conditions. In addition, quality acceptance criteria must define the allowed variability of the data for accuracy and repeatability, and the percentage of data that must comply with the data quality standards.

Third item is the *identification of responsibility*. Pierce et al. (2013) note that the QMP should identify the staffing, roles, and responsibilities for QC and QA, including reporting, documentation, and tracking/resolution of problems.

QC for pavement condition data collection should include equipment calibration and method acceptance; personnel training; control and verification site testing; distress rating checks; and data reduction and processing checks.

According to (Pierce et al, 2013), *QA* should include "*Global checks, sampling, and time-series comparisons to check the quality of the delivered data. Typical global checks include inspecting for data that are out of expected ranges, missing segments or data elements, and statistical analysis to check for data inconsistencies. Other acceptance testing might include re-analyzing or resurveying a sample of the sections and GIS checks. The QM plan should establish the timeframe or recurring frequency for performing data acceptance checks*." (*Pierce et al., 2013*, p. xi)

Other areas recommended by FHWA for inclusion in quality management are defining types of *corrective action* to be taken if data are found not to meet the quality requirements and *reporting and documentation* requirements of the QC/QA process.

Finally, the Guide contains a data quality management plan template, which can be used by any state that is developing a QMP. NOTE: This template was used for this CTDOT project and forms the basis for the QMP submitted to FHWA CT-Division on May 18, 2018.

<u>Other State and Provincial Activities</u>

In the Practical Guide for Data Quality Management, it is noted that Virginia DOT identified a number of benefits for having and using a QMP for pavement data collection. These important benefits are replicated below (Pierce et al., 2013):

- Better compliance with external data requirements.
- Better credibility within the organization.
- Better integration with other internal agency data.
- Cost-savings from more appropriate treatment recommendations.
- Improved accuracy and consistency of data.
- Improved decision support for managers.
- Increased accuracy in reporting deficient pavements.
- Increased accuracy in reporting existing condition indices.
- Increased accuracy of budget need determinations.

During FHWA sponsored quality management regional workshops held in seven states during 2015 including Connecticut, it was noted that data quality is extremely important as condition data are often used for many things, such as (Zimmerman, 2017):

- Reporting current conditions
- Predicting future conditions
- Identifying feasible treatments
- Preparing multi-year work programs
- Evaluating the impacts of different investments
- Determining funding needs

Shekaran et al. (2007) note that without a quality plan, agencies may be under or over estimating maintenance and rehabilitation needs by 25% or more.

It was found from a survey for the above-noted FHWA workshops that automated pavement data is being collected in at least 37 states as of 2015 (Zimmerman, 2017). A few agencies reported developing data quality standards for accuracy and precision of smoothness measurement (IRI) equipment for use in their respective state and/or province. Examples are indicated in Table 2.2 below.

Table 2.2. Selected Agency Criteria for IRI (from Zimmerman, 2017)

Agency	Accuracy	Precision
British Columbia	± 10 percent of Class I profiler	± 6.3 in/mi standard deviation of 5 runs
Alabama	± 5 percent of control section	± 1 in/mi average of 5 passes
Virginia	± 5 percent of agency value	< 5 percent of 10 runs
Oklahoma	± 5 percent of dipstick or Class I profiler	± 5 percent run to run for three repeat runs

A few state agencies have also established control (validation) sites for calibration of field distress data collection equipment. Some examples are indicated in Table 2.3 below.

Table 2.3 Selected Agency Validation Site Examples (from *Zimmerman, 2017*)

Agency	Number of Sites	Details
Oklahoma	2 asphalt 2 Jointed Concrete Pavement (JCP)	• Used as part of scoring proposal• • 0.5 mi long
Pennsylvania	4 asphalt 2 JCP	• Run each test vehicle prior to production testing •~0.5 mi long
Virginia	8 asphalt 2 JCP 2 Continuously Reinforced Concrete (CRC) Pavements	• Calibrate distress rating • Establish precision and bias • Variable length

A few agencies have established agency verification sites and/or procedures for checking equipment, and for use in either agency QA or for Independent Assurance (IA). Some examples are indicated in Table 2.4 below.

Table 2.4 Agency Verification Site/Procedures Details (from Zimmerman, 2017)

Agency	Details
British Columbia	• 1 site every 3 days • For long contracts (> 30 days) verify repeatability
Louisiana	• Review 5% of collected sections
Maryland	• IRI & rut depth each month (> 3 times during survey) • Compare cracking index with previous year's results

Nebraska	• 10% of segments spot checked in field
Oklahoma	• Weekly evaluation of validation or verification sites (6 to10 per survey year)
Pennsylvania	• 2 roughness and rut depth sites • Re-tested on a monthly basis

According to a September 2015 summary of state DOT survey responses (performed for the FHWA workshops discussed above), U.S. states with similar situations to CTDOT, meaning that they operate Fugro™ automated field equipment for in-house data collection, include Arkansas, Maryland, Maine, Missouri and South Dakota. A contact attempt (email) was made with these state DOTs in September 2017 to determine if they had developed quality management programs for their pavement data collection. A very limited response was received, but these states should still be considered as resources for CTDOT should the need arise.

Indiana Department of Transportation

The Indiana Department of Transportation (INDOT) is a noteworthy agency that was proactive in independently developing a QC/QA program for pavement management data. Purdue University performed a study for Indiana in 2009 *(Ong et al., 2010)* and they reported that "*quality assurance of pavement condition data can be viewed in terms of (i) completeness of the delivered data for pavement management; (ii) accuracy, precision and reliability of pavement roughness data; and (iii) accuracy, precision and reliability of individual distress ratings and an aggregate pavement condition rating."* The INDOT study denotes the differing responsibilities between the data collector (either a vendor or owner) and the data user.

The INDOT study identifies and delineates three data phases of interest for QC as: 1) pre-project (pre-data collection), 2) during data collection, and 3) post-processing. These three phases generally occur in Indiana on a recurring annual cycle that is similar to Connecticut, where pre-project occurs during April/May, data collection takes place June-August, and post-processing is September/October *(Ong et al., 2010)*.

Ong et al. (2010) identifies Pre-project QC to include equipment calibration for lasers, accelerometers, bounce tests, and distance calibration tests on control sections. During the data collection phase, standard quality control checks are performed daily and quality control/assurance tests performed at the following stages in the data collection cycle:

- Before the actual data collection cycle
- After the completion of Interstate pavements
- After the completion of Non-Interstate NHS and Non-NHS pavements for each INDOT District
- At the end of the data collection cycle

The INDOT field data quality control plan calls for (*Ong et al., 2010*):

- re-collection of control site data periodically
- bounce and equipment tests weekly
- real-time operator graphs
- completeness checks every two hours
- daily report software
- an operators daily checklist
- a view of images in real-time

Post-processing QC in INDOT includes a back-end test for completeness and accuracy and logic checks on data for pavement type, lane, event, etc.

The INDOT QA process focuses upon:

1) completeness of delivered data,
2) accuracy and reliability of roughness data, individual distress ratings and an aggregate pavement condition rating (PCR),
3) certification of data collection vehicles during pre-project phase,
4) quality assurance tests on selected pavement sections (within the INDOT highway network), and
5) quality assurance checks for completeness and error before importing data to the PM database.

Similarly to what is being performed for CTDOT during this study, Purdue performed a review of INDOT practices for automated pavement condition data collection, including documentation of existing QC practices, establishment of accuracy and variability, development of a set of statistical QA procedures and a recommended QC/QA plan. An innovative two-stage approach to evaluate the delivered data for integrity and completeness was developed at Purdue. The first stage involves the evaluation of Codd's[1] integrity constraints to test for entity, column, and referential integrities. The second stage evaluates the delivered database for errors, completeness, and consistency. Specifically, for data management, the INDOT study includes *data cleansing*, which includes detecting and correcting corrupt or inaccurate records, and identifying incomplete, incorrect, inaccurate, irrelevant parts of data that can be replaced, modified or deleted, as well as, *data integrity*, which includes data validation. A number of statistics were developed for data management including: an integrity rating, free of error rating, completeness rating and consistency rating, all of which involve a ratio of defects to total data units, where a desired ideal ratio score is 1.0. For example, a completeness rating is calculated as numeral 1 minus the ratio of the number of incomplete items to total data items (*Ong et al., 2010*).

$$Completeness\ rating = 1 - \frac{Number\ of\ incomplete\ items}{Total\ \#of\ items}$$

For surface distress, the Purdue study concluded that, "…*when pavement management applications at the project level are of interest, statistical models must be developed to convert* *the surface distress ratings obtained from automated techniques to that from benchmark visual surveys. Project-level surface distress ratings provide a better depiction of actual pavement conditions*". (*Ong et al., 2010, p.135*).

The only caveat with the above 2009 INDOT study is that unlike Connecticut, Indiana data collection is primarily performed under contract with a vendor. Therefore, the QC processes described above are under the control of the vendor, with QA by INDOT.

*Footnote*___________________

1. Codd's rules refers to a set of 13 database management system rules (0-12) developed by E.F. Codd in 1969-1970. Codd's rules are also referred to as Codd's law, Codd's 12 rules or Codd's 12 commandments. Codd's 12 rules define an ideal relational database, which is used as a guideline for designing relational database systems. (*https://www.techopedia.com/definition/1170/codds-rules*)

Other Organizations with Pavement Data Collection QC/QA Activities

Although the literature review focused primarily on data collection quality management in North America, an interesting "specification for road condition data collection services" was found online (*IPWEA, 2017*). It appears to have been developed for New Zealand contractors performing roadway data collection. It contains useful information on the requirements of data collection contractors on topics such as:

- data collection specifications, e.g., specifying actions to be taken in the case of data gaps
- survey procedures, e.g., correct location referencing
- calibration and validation of equipment, e.g., ensuring that all measuring devices are functioning properly on a regular basis (via daily checks and calibration)
- quality control and assurance, e.g., explanation of how identification of random, operator and systematic errors will be handled
- a contractor-developed quality management plan

NCHRP Synthesis 401, Quality Management of Pavement Condition Data Collection (Flintsch and McGhee, 2009)

In summary, from the subject Synthesis report, (and as evidenced by states described previously), typical Quality Management tools and methods used for quality control and acceptance are:

- Calibration/verification of equipment and methods before the data collection
- Testing of known control segments before data collection
- Testing of known control or verification segments during data collection, and
- Software routines for checking the reasonableness and completeness of the data.

Other promising quality management techniques that are not yet commonly used include:

- Analysis of time-series data both at the project and network-level,

- Independent (quality control or acceptance) verification and validation of the pavement condition data by an independent quality auditor , and
- Use of blind site monitoring during the production quality acceptance process

A comprehensive *quality control plan* typically includes the following elements:

- Clear delineation of the responsibilities,
- Documented (and available) manuals and procedures,
- Training requirements for the survey personnel
- Equipment calibration and inspections procedures,
- Equipment and/or manual process verification procedures (e.g., testing of known control section) before starting production testing,
- Production quality verification procedures (e.g., testing of known or blind control sections during production testing), and
- Checks for data reasonableness and completeness.

Typical *quality acceptance* activities include:

- Establishing acceptance criteria (data accuracy and precision and reliability);
- Verification of the equipment/analysis criteria before data collection;
- Testing of known or blind (preferred) control or verification sites before and during data collection;
- Software data check for reasonableness, completeness, and consistency; and
- Time-series comparisons.

Literature Review Summary and Conclusions

Although there is not an abundance of published literature on quality management plans specific to pavement data collection, what has been published is comprehensive and well suited for use by agencies developing QMPs. The first comprehensive state-of-practice analysis related to quality management of pavement condition data collection is provided in the NCHRP Synthesis 401 (*Flintsch and McGhee, 2009*). The study for Indiana DOT (*Ong et al., 2010*) from 2009 noted that from their review of other states, very few states were actively pursuing QC/QA for pavement management at that time. The more recent study for FHWA (*Pierce et al., 2013*) indicates that states are becoming more aware and concerned about quality, but that much greater emphasis should be placed on quality management for pavement management. Thus, a conclusion would be that the mandate for NHS QMPs in 2018 appears to be needed, timely and appropriate. Based upon the literature reviewed for this project, and the FHWA mandate for a QMP, it appears that the items identified in the project proposal should be in-line with CTDOT's needs and FHWA requirements.

Chapter 3. Existing Data Collection Procedures and Rating Protocols in CTDOT

This Chapter discusses the evaluation of current guidelines and procedures (i.e., prior to 2018) employed by the CTDOT to control the quality of pavement data. Under Task 2 of this Project, the CTI/UConn research team conducted an interview of the data collection and processing personnel, and evaluated existing documentation on the subject.

Photolog and PMU Personnel Interview

Personnel from the CTDOT Photolog and Pavement Management (PMU) units were interviewed by the CTI/UConn team in order to evaluate existing pavement data collection and processing practices. The interview focused on the experiences of CTDOT operators and analysts regarding equipment calibration and operations of pavement survey hardware and software. Two other groups of questions targeted in-place quality management (QC/QA) practices, including the determination of "ground truth", the presence of validation and verification sites, existing precision and accuracy requirements, and corrective action procedures. The interview questionnaire was adapted from the PMU personnel questions developed by Flintsch and McGhee (2009) for the NCHRP Synthesis 401 titled "Quality Management of Pavement Condition Data Collection." The full text of questions and answers can be found in Appendix A, whereas the outcome of the interview is discussed below.

Questionnaire Structure

The 37 questions asked during the interview are clustered into the following four groups:

1. General information to understand the extent of the road network surveyed, the type of pavement condition data collected, the methods of data collection, and the frequency of surveys (12 questions).
2. Quality management activities such as the presence of formal documentation for the QC/QA process, equipment calibration and data verification procedures, and precision/accuracy thresholds for data acceptance (7 questions),
3. Personnel training, such as average experience with the collection processes, type of training and formal certifications (4 questions), and,
4. Data quality-related operation specifics for pavement data collection, such as use of daily checklists, following the manufacturer's operation manual, and familiarity of personnel with quality-related checks from the manual (14 questions).

Organization of Pavement Data Collection, Processing, and Use

An organization chart depicting pavement data collection, processing and use by the CTDOT is given in Figure 3.1. The Photolog Section personnel, who are part of the Roadway Information Systems Office in the Bureau of Policy and Planning, collect, upload, and segment all the raw data. This raw data is then processed by the Pavement Management Unit, within the Engineering Services Section in the Bureau of Engineering and Construction, to calculate such performance indicators as cracking, rutting, and IRI at the network level (0.1-mi average values). On an as-needed basis, The Pavement Management Unit also reports combined performance indices, such as PCI, for instance. This information, as well as some performance indicators, are ultimately used by the Strategic Planning and Projects Office to assist in the development of policies and performance measures. In addition, other offices in the Bureau of Engineering and Construction, as well as in the Bureau of Highway Operations, use the data for developing pavement preservation and paving programs, and for individual project designs.

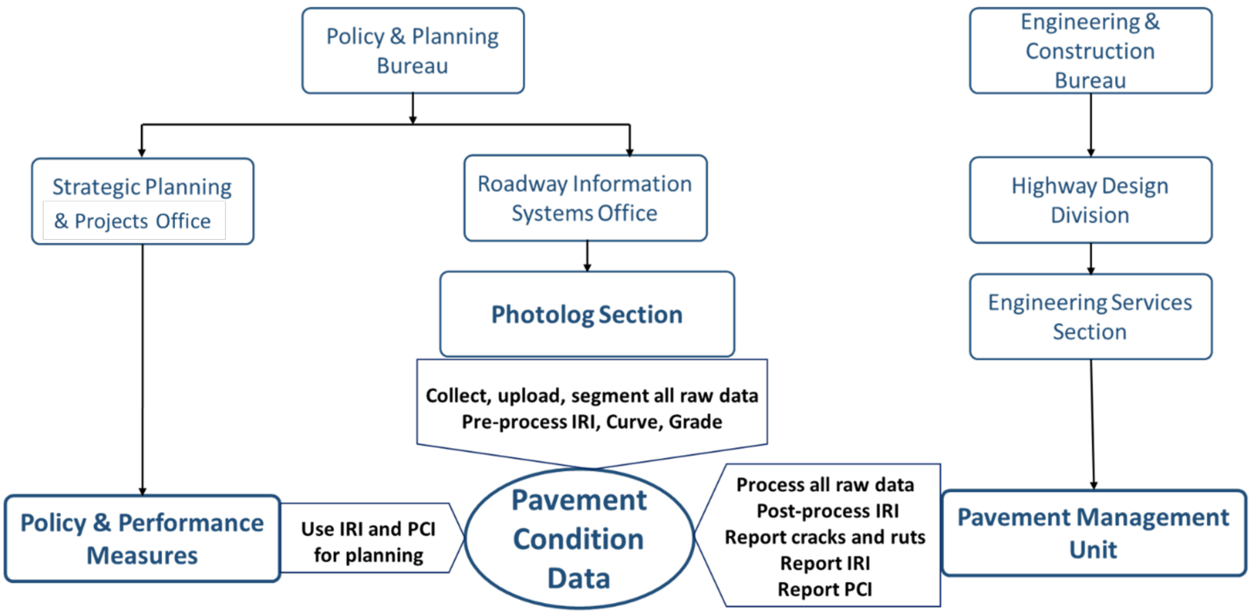

Figure 3.1. Organization chart for pavement data collection, processing, and use.

It is important to note that with respect to pavement condition data there are some overlaps between "collector," "processor," and "user" functions. For instance, the Photolog Section pre-processes IRI, Curve, and Grade data to report those parameters at the project level (5-m average values). In addition, IRI, cracking, and rutting data are used by both PMU and Strategic Planning personnel. The reason for the aforementioned overlaps in functions is that prior to reorganizations within the CTDOT in recent years, Photolog and PMU personnel were part of the same group. Although they were separated after reorganization, they remain in collaboration to preserve continuity of pavement management practices within the CTDOT.

General Information on Pavement Data Collection System

The Photolog Section has been collecting various roadway field data since 1970, but it only began conducting in-house automated pavement surveys around 1996. As of 2018, two ARAN vehicles are used to survey 7,438 directional miles (for the 3,719 centerline-mile-state-maintained roadway network) of Connecticut roads to collect three-dimensional profiles of the pavement surface and data and information for the adjacent right of way. The profile measurements are processed to calculate geometric characteristics such as cross-slope, grade, and curves. They are also used to determine the amount of surface distress and surface smoothness parameters. Multiple surface distress indicators (linear cracking of different orientations and locations; rutting and IRI in both wheelpaths; and cross-slope) are combined to arrive at a Pavement Condition Index (PCI). Faulting levels are also collected automatically for Jointed Concrete Pavements (JCP).

The network-level data are collected annually on all highway and arterial roads under State jurisdiction in rural and in urban environments. In addition, sample conditions on 350 miles of collectors/local roads are collected and reported for the FHWA Highway Performance Monitoring System (HPMS) database. For the collection purposes, all roads are travelled in both directions in the most operational through lane (usually, the outermost right lane), Both GPS coordinates and mileposts are used for location reference.

Quality Management Activities

Prior to this study, the CTDOT did not have a formal Quality Management Program for pavement data collection. However, according to a survey of the state transportation agencies, this is not uncommon for a state agency with less than 5,000-mile of surveyed roads (*Flintsch and McGhee, 2009*). With respect to other quality checks, The Photolog Section performs pre-production calibration of the ARAN equipment in accordance with manufacturer (Fugro, Inc.) specifications. A full calibration is performed annually by Fugro, Inc. as part of a preventative maintenance program. The Distance Measurement Instrument (DMI) calibration is performed by the Photolog Section on a monthly basis.

There are two 'control' segments (Brook St. and Big Loop) where all operational ARAN vehicles are run occasionally to compare the measured outcomes between vans. During production, up to five percent of collected IRI and rutting data from the Big Loop are checked for the reasonableness in variation of reported results over time, as well as compared for differences between the vans. In regards to post-production verification procedures, the Photolog and PMU utilize software (Roadware Vision) alerts and warnings to identify gaps in data and corrupted files.

Currently, no formal statistical routines are in place to verify data inconsistencies or compliance with expected ranges. However, newly collected data are compared with past data to detect deviations from historical trends. In addition, the IRI data at speeds lower than 25 mi/hr are removed from the network-level calculations to avoid reporting unreasonable IRI values. Based on occasional data quality checks, about five percent of the surveyed network ends up resurveyed.

The last question about quality management activities asked to identify factors that have the greatest impact on the quality of pavement condition data. Despite the lack of formal quality management procedures in place, the Photolog and PMU representatives appeared to have high awareness of the importance of the following factors:

- Calibrated and properly functioning equipment (vehicle, hardware, and software)
- Use of consistent units of measure
- Proper processing routines
- Adequate personnel training
- Timely detection of errors

Photolog Personnel Training

Currently, the Photolog Section employs two ARAN teams (driver and operator) for pavement data collection, which are led by a section manager and assisted by a data analyst/processor. The average experience of the personnel using the ARANs for automated data collection is 12 years. Although no formal certification is required, the Photolog personnel receive on-the-job training from the experienced staff. Note that both driver and operator receive the same training and, therefore, their positions are interchangeable.

Quality-Related Operating Procedures

The ARAN operation manual (*Fugro, 2017*) prescribes two sets of procedures to be performed on a daily basis: (1) “start of the day” and (2) “end of the day.”

As follows from the interview, for “start of the day,” the operators walk around the ARAN to ensure no visible damage to DMI and RutBar enclosures exists. They also run “dummy” files and data reviews for discrepancies twice a day. There is no, however, mechanical inspection checklist in place. The operators clean the ROW camera daily and the LCMS laser glass, as needed. The Photolog personnel do not control ARAN Collection System (ACS) settings. The ACS settings are controlled and changed if needed by Fugro, Inc. during annual preventative maintenance procedures.

The Photolog operators perform the “end of the day” procedures to include generating daily reports, reviewing QC Video and PCS files, and backing up, exporting and uploading daily collected data to the FTP space.

During the production run (actual data survey), the Photolog operators monitor video collection to ensure that ROW/Pavement videos are displayed every mile of collection, the frame numbers are incrementing appropriately, and the GPS is fixed at the start of each section. The operators also monitor some sensor data (IRI and grade) in real time through a graphical interface to ensure that the measurements are within expected ranges.

The ARAN drivers are aware of the importance of driving at a constant speed (some are using cruise control where possible).

Contribution of the Manufacturer to the In-House Data Collection Processes

- Fugro, Inc. is the vendor/supplier of the Roadware ARAN (Automatic Road Analyzer) hardware and software.

- Fugro, Inc. is sole developer of Roadware Vision processing and reporting algorithms and routines.

- The CTDOT PMU processing personnel have limited ability to change some report templates but cannot change the processing routines.

Evaluation of Documented QC/QA Guidelines and Procedures

At the time of the kick-off meeting for this project (September 13, 2017), the CTDOT had no formal QC/QA guidelines for pavement data collection and management in place. However, quite a few important developments occurred since then, as discussed below.

Development and documentation of the formal QC/QA procedures for pavement data collection

Prior to October 20, 2017, an ARAN 9000 Manual 2.0 (*Fugro, 2016*) served as the only formal guideline for the automated pavement data collection when using the new ARAN 9000 vehicles. The Manual includes, in addition to the details on every ARAN 9000 component, safety requirements and instructions on calibration of major components (DMI, GPS, LCMS) as well as other configuration items, such as data validation and mission management (collection event) configuration. It is a 214-page document that appears to be most useful for training but less so for daily quality control.

A more relevant document for day-to-day operations was received from Fugro on October 23, 2017. This 48-page document is titled "Field Operations Standard Processes" (*Fugro, 2015*). It lists step-by-step procedures as follows:

- Start-of-the-day routine
- ARAN operational safety guidelines
- Weather and lighting requirements for successful operation
- Daily collection routines
- Daily mechanical checklist
- End-of-the-day routine

Special attention is given in the document on the importance of driving in the wheelpath (within paint stripes). Accordingly, both driver and operator of the ARAN vehicle should be aware that any deviation from the center of the driving lane might result in big changes in the amount of reported distress, while not capturing the real pavement surface condition (*Fugro, 2015*).

Another important document titled "ARAN 9000 Operation Guide 2.2" contains succinct instructions on day-to-day operations and routines, with special emphasis on the collection process and transferring the data from the ARAN Collection System to the processing office (*Fugro, 2017*).

Based on the three above documents, as well as several years of experience, the Photolog Section developed a checklist of standard operations procedures (Received by the CTI/UConn team on November 6, 2017). The following is the list of pre- and post-collection procedures to be conducted on daily basis:

1. Inspect outside of ARAN collection vehicle for any damage (walk around)
2. Inspect & Clean the HD capture window
3. Inspect & Clean grade sensors on the van
4. Inspect & Clean IRI lasers on the van
5. Inspect & Clean LCMS lasers on the van

6. Check & adjust tire pressure as needed
7. Adjust side mirrors prior to vehicle movement
8. Start vehicle and listen for any unusual noises (ex. broken belt…)
9. Check for and Insert hard drives if none are currently in computers
10. Start Inverters and ARAN 9000 sub-systems
11. Map & create network shares for hard drives
12. Run ARAN 9000 system diagnostics and check for errors (allow 15 min. idle time for GPS accuracy)
13. Run dummy file and review data for any discrepancies
14. Select routes/roads to collect and add to list. Ensure that checkpoints for routing are in proper order (a glitch sometimes causes them to be scrambled)
15. Verify data at end of day
16. Create end of day log sheet

Chapter 4. Development of Data Acceptance Thresholds

This Chapter describes the process for developing the ARAN data acceptance parameters, such as precision and accuracy limits. A general description of statistical processes applicable to pavement condition data quality is presented first. Next, variability influence factors are analyzed, and the expected ranges of values for pavement condition characteristics are introduced and defined. Note that in the absence of any previously established validation sites, the data from ARAN repeatability runs obtained under the previous SPR-2297 study were used for the analysis of variability. Therefore, only precision and reproducibility of ARAN measurements is discussed herein. Required accuracy limits relative to reference values (ground truth) at validation sites are not provided, and must still be determined in the future at CTDOT, after validation sites are established. Historical CTDOT PMIS data from 2008-2016 were used for arriving at the expected ranges of pavement condition characteristics for IRI, rut depth, and cracking extent, which can be used for acceptance checking for data outliers. As a result of implementation of the latest ARAN equipment in CTDOT, some refinements to these expected ranges may be necessary in the future.

Proposed Guidelines for Statistical Evaluation of Pavement Data Quality

The process for evaluating the quality of pavement condition surveys includes multiple analyses. One procedure is used to analyze the difference between two or more datasets collected from the same road section by one or more surveying systems or crews. For this analysis, the question to be answered is whether a difference exists between the datasets. Also, if the answer is yes, one must determine whether this difference is random or easily explained across the dataset. Another common scenario is to determine if collected data meets specified limits, such as a precision limit or falls within an expected range of values.

There is a wide variety of statistical methods available, ranging from comparison of means to multivariate regression analysis, which are suitable for quantifying quality of measurement (*Vardeman and Jobe, 2007*). *The Practical Guide for Quality Management of Pavement Condition Data Collection* cites the F-test for variance, paired t-test, the Cohen's kappa statistic, and percent within limits as the most common methods used by highway agencies (*Pierce and Zimmerman, 2015*). Note that these statistical test methods serve different purposes and, therefore, are not interchangeable. Table A.1 in The *Manual for Quality Control of Pavement Condition Data Collection* (*CTDOT, 2018c*) contains descriptions of the four aforementioned tests, including information on their objective, type of data analyzed, suitability, and interpretation of the results. Examples of computations and interpretations of the test results can also be found in Appendix A of the "*Manual for Quality Control of Pavement Condition Data Collection*" (*CTDOT, 2018c*).

Methodology of Data Analysis

<u>Establishment of acceptance thresholds for precision and reproducibility</u>

At the time of publication of this report, no validation sites had been established in the field by CTDOT. Therefore, accuracy of ARAN measurements compared with reference measurements could not be determined.

In order to establish acceptance thresholds for precision and reproducibility of data collected with CTDOT vans, the research team first analyzed distributions of variability. The measures used for characterizing the variability of pavement condition indicators (e.g., IRI, crack lengths, and rut depths), as well as for roadway geometric characteristics (i.e., cross slope and grade), included absolute difference between means, standard deviation from mean (St. Dev.), and coefficient of variation (C.o.V.=St.Dev./mean) within and between ARAN datasets. The data used for this analysis was collected under the previous SPR-2297 research project. It should be noted that the roadway pavement sections used for the SPR-2297 study did not necessarily meet AASHTO standards for characteristics of geometry and distress extent. In addition, the ARAN vehicles could possibly not have been calibrated and operated in complete accordance with AASHTO standards during that timeframe.

For each pavement condition indicator analyzed (such as IRI, rut depth, cracking), a plot of cumulative percentile (or probability of occurrence) was first created (see Figure 4.1 for one example). Next, a value corresponding to the 95th percentile was identified. This 95th percentile value is defined as the maximum acceptable value or limit of variability (precision or reproducibility). In accordance with the aforementioned approach, no more than 5 percent of surveyed sections were expected to exhibit variability higher than the limit. Furthermore, all sections with variability higher than the maximum acceptable level would be recommended for further review (i.e., should be flagged for review). The example in Figure 4.1 shows the 95th percentile value of the C.o.V. for total crack length (TOT_CRACK) between two ARAN systems is 62 percent. Therefore, a reproducibility limit for TOT_CRACK would be set at 62-percent maximum allowed C.o.V. between two ARAN systems.

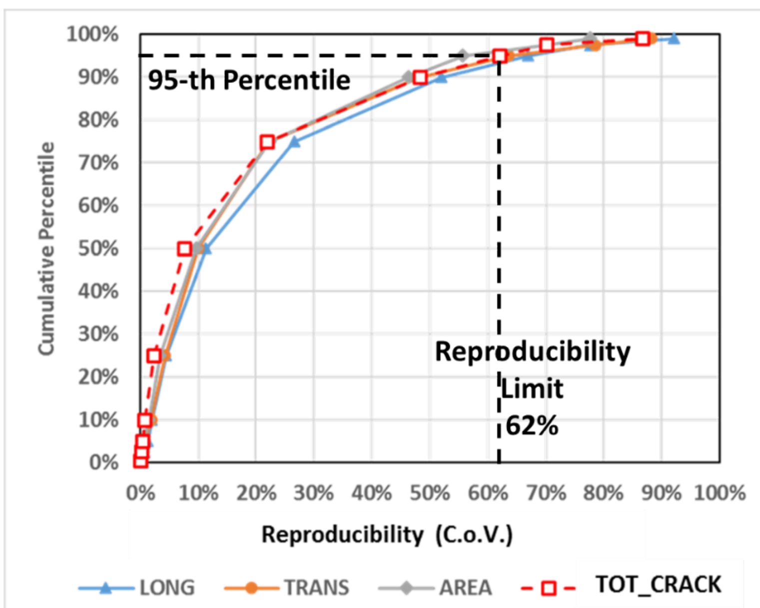

Figure 4.1. Example of establishing a reproducibility limit for cracking extent (TOT_CRACK) as measured by the 95-th percentile of C.o.V. between two ARAN systems.

<u>Determining expected ranges of values</u>

The need for determining an expected range of values for ARAN-reported pavement condition indicators was identified earlier during 2016, when abnormally high IRI values were measured using the then newly introduced 3-D ARAN systems .. In addition, the literature search indicated that some agencies included the expected ranges for IRI, cracking, and rutting in their quality management plans. In order to establish expected typical ranges of ARAN output values for Connecticut, the research team utilized historical PMIS network data for the period between 2008 and 2016. For each condition indicator or measurement in question (e.g., IRI, rut depth, cross slope, etc.), the annual distributions of ARAN values across the network were analyzed to determine cumulative percentiles (or probability of occurrence). In order to visualize annual variability, values for selected critical percentiles (0.5^{th}, 2.5^{th}, 25^{th}, 50^{th}, 75^{th}, 97.5^{th} and 99.5^{th} percent) were plotted as a time series.

Figure 4.2 provides an example of the trends for critical percentiles for mean IRI values for each year from 2008 through 2016. On the right side of the plot, the average values (mean of the nine average yearly data points) for each percentile are shown. One can notice that on average for the nine years, 99 percent of the Mean International Roughness Index (MRI) values, (the average of IRI values for the left and right wheelpaths) between the 0.5th and 99.5th percentile, range between 40 and 435 in/mi. Therefore, based on the information depicted in the plot of Figure 4.3, the MRI values most likely to occur (i.e., expected range for acceptance) would be between 40 and 450 (rounded up from 435) in/mi. This also means that not more than one percent of the network would be expected to have average IRI values below 40 or above 450. When they do occur, the relevant sections should be flagged and reviewed at the project level.

As an example of the usefulness of this type of analysis, note that for year 2015 in Figure 4.2, the MRI plotted above the 75th percentile appear to be abnormally high relative to the other years. In fact, two and one half percent of the MRI values are greater than 480 in/mile, well above the expected maximum of 450.

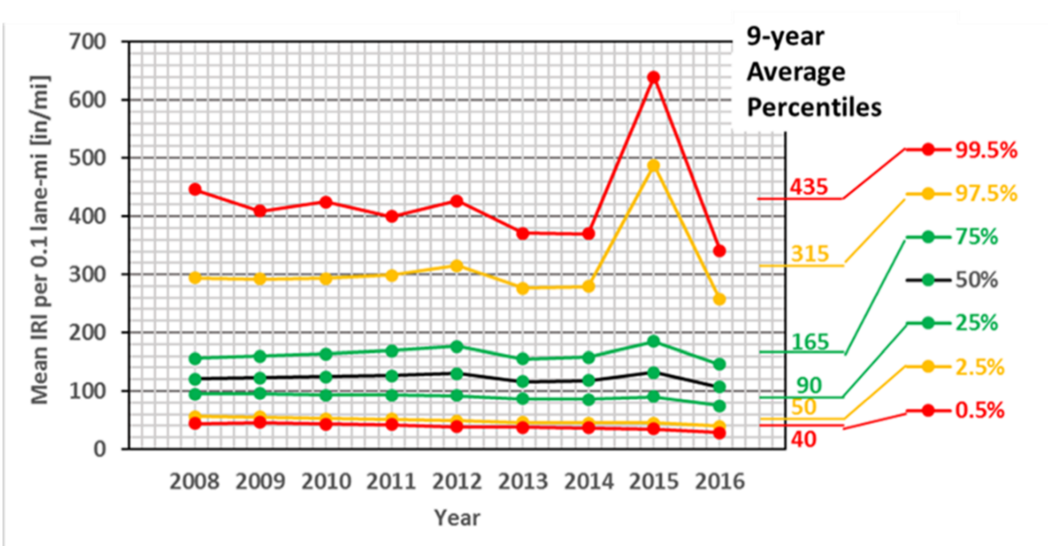

Figure 4.2. Example of determining average percentiles, using 2008-2016 CTDOT PMIS data for MRI.

Summary of Precision and Reproducibility of ARAN Data from SPR-2297

The data used for QC/QA analysis under this project was obtained from pavement surveys performed with two CTDOT ARAN vans (Van 8 and Van 9). Those two vehicles were run simultaneously for one time on an approximately 80-mile long selection of routes (hereafter called the Big Loop) in central Connecticut, and for five times on 2.5 lane-miles of Thornbush Rd., Wethersfield, CT, and Brook St., Newington, CT. While all the details on the aforementioned surveys can be found in the SPR-2297 final report, Tables 4.1 and 4.2 provide summaries of length, number of runs, and average repeatability and reproducibility for three condition indicators, (mean IRI, total cracking, and mean rut depth.) for the surveyed sections described above.

When comparing variations shown in Table 4.1, one can notice that there is much better reproducibility for mean IRI and total cracking on the shorter sections. Nevertheless, all three sections exhibited a significant spread of section C.o.V. values over the segment lengths, which is expressed by the 95% upper confidence level values being twice or even three times as high as the mean C.o.V. value for a segment. Notably, the small variation in mean rut depth per 0.1-mile section should be considered within the context of the overall low level of rutting (maximum 0.5 in) reported by the ARAN systems during the SPR-2297 project. Also, rutting has traditionally not been a major distress encountered within Connecticut, compared to, for instance, the extent of environmentally induced cracking.

Table 4.1. Summary statistics for reproducibility of CTDOT ARAN measurements using SPR-2297 study data.

Section ID	Section Length [miles]	Number of 0.1-mile segments (=Number of measurements per van)	Reproducibility as measured by		
			C.o.V. of Mean IRI per 0.1 lane-mile (mean [95%UCL*])	C.o.V. of Average Total Cracking per image (10 lane-m) per 0.1 lane-mile (mean [95%UCL])	Absolute Difference in Mean Rut Depth [in.] per 0.1 lane-mile (mean [95%UCL])
Big Loop	79.2	792*1 run = 792	4% (14%)	16% (55%)	0.005 (0.020)
Thornbush Rd.	0.6	6*5 runs = 30	<2% (<4%)	3% (11%)	0.009 (0.023)
Brook St.	1.7	17*5 runs = 85	<2% (<4%)	3% (11%)	No rutting

*95%UCL = 95-percent Upper Confidence Level value

In terms of precision, both CTDOT ARAN vehicles (Van 8 and Van 9) exhibited similar levels of repeatability. As can be seen in Table 4.2, with the sole exception of MRI on surfaces with poor ride quality (15% C.o.V. at 95% confidence) both the average and 95% upper confidence values of C.o.V. did not exceed 10 percent, . It is also interesting to note that repeatability C.o.V.

values in Table 4.2 are lower than reproducibility C.o.V. values in Table 4.1. This might indicate that both CTDOT ARAN systems produce similar random errors.

Table 4.2. Summary statistics for precision of CTDOT ARAN measurements using SPR-2297 study data.

Section ID	Section Length [miles]	Number of 0.1-mile segments (=Number of measurements per van)	Repeatability (Precision) as measured by		
			C.o.V. of Mean IRI per 0.1 lane-mile (mean [95%UCL*])	C.o.V. of Average Total Cracking per image (10 lane-m) per 0.1 lane-mile (mean [95%UCL])	Standard Deviation from Mean Rut Depth [in.] per 0.1 lane-mile (mean [95%UCL])
Thornbush Rd.	0.6	6*5 runs=30	8% (15%)**	5% (9%)	0.013 (0.025)
Brook St.	1.7	17*5 runs = 85	3% (7%)***	Low cracking	No rutting

*95%UCL = 95-percent Upper Confidence Level value
**Poor ride quality with mean IRI>170 in/mi
**Good to Fair ride quality with mean IRI<=170 in/mi

It is also of interest to compare the quality parameters derived from the SPR-2297 project with those employed by other agencies. Information contained in the report titled, *Practical Guide for Quality Management Condition Data Collection* (*Pierce et al., 2013*) was used for reference. As shown in Table 4.3, the resolution of reported sensor-measured data by ARAN in Connecticut is much better (smaller values) than that prescribed in federal regulations and other agencies that are referenced. As far as precision and accuracy thresholds are concerned, the SPR-2297 data in Connecticut produced very similar values or at least within the range of values required by the reference agencies.

Table 4.3. Comparison of quality parameters for pavement data

Performance Indicator	Source	Reported Measurement Resolution	Precision	Accuracy or Reproducibility
IRI	SPR2297	0.1 in/mi	<6%	<4%
	Other Agencies	1 in/mi (HPMS, Oklahoma) 0.6 in/mi (LTPP)	5% (Oklahoma)	5% (Oklahoma)
Crack Lengths	SPR2297	0.1 ft	<20%	<20%
	Other Agencies	Not Available	10% (Oklahoma) 30% (Pennsylvania)	10% (Oklahoma) 30% (Pennsylvania)
Rut Depths	SPR2297	0.01 in	<0.03 in	<0.03 in

	Other Agencies	0.1 in (HPMS) 0.04 in (LTPP, AASHTO)	0.08 in (Oklahoma) 0.12 in (British Columbia)	0.08 in (Oklahoma) 0.12 in (British Columbia)

Summary of Identified Sources of Variability in CTDOT ARAN Data

Identifying factors influencing variability

Under Task 3 of this Project, the CTI team investigated factors influencing precision and reproducibility of ARAN measurements performed earlier under Project SPR-2297. In order to determine factors influencing the variability of ARAN measurements, the datasets were analyzed for outliers. Where outliers occurred, sites were checked to find if the factors of influence that were determined the SPR-2297 study existed, such as, for example:

- low ARAN travel speeds
- variable lateral position within the lane
- pavement surface type
- high vs. low surface distress rating
- high vs. low ride quality rating
- certain geometric characteristics of the road.

Factors for precision and reproducibility of IRI measurements

The IRI measurements were collected on the 80-mile long Big Loop and the two short sections (total 2.5-lane-mile length) used for the repeatability runs. In terms of precision, better results were achieved on short sections than on longer ones, as shown previously in Table 4.1. In addition, the variability between the two CTDOT ARAN systems was lower on surfaces with good and fair ride quality (IRI<170 in/mi) than on surfaces with poor ride quality (IRI higher than 170 in/mi). One of the most influencing factors on reproducibility was found to be average speed per 0.1-mile section. Note that it was revealed during the SPR-2297 project that most of the identified data collected at speeds lower than 30 mi/hr occurred before and after stops at intersections.

An analysis of outliers (about 5% of data) revealed that where extremely large differences of CTDOT ARAN IRI measurements occurred they were usually caused by the presence of localized roughness such as at transverse joints, locations of cracking of high severity, unadjusted manhole lids, and other unexplained reasons.

Factors for precision, repeatability and reproducibility of crack length measurements

Overall, both CTDOT ARAN systems (Van 8 and Van 9) exhibited high precision of reported total crack lengths, as well as individual crack classes (longitudinal, transverse, and area) with average run-to-run variations within 20 percent of mean. However, it was found that both precision and repeatability varied significantly between crack severities and lane zones. In addition, the reproducibility of ARAN-reported crack length values appeared to be better on the shorter 2.5-mile long segments (3% average difference between vans for total cracking) as compared with the 80-mile long Big Loop (16% average difference). The run-to-run variation was higher (worse precision) for high-severity crack lengths and for cracks identified within lane zones near the pavement edges.

An analysis of outlier differences between CTDOT ARAN vans for reported cracking on the Big Loop revealed that a lateral shift between surface images, as captured by the two ARAN systems, when cracking was near the pavement edges was the cause in many cases. This shift likely leads to non-detection of cracks. The other differences were due to the inherent variability in crack classification (either by orientation or by lane zone) and in rating (by width) associated with the Roadware Vision detection algorithm. A more detailed discussion on this matter is provided in the SPR-2297 final report.

<u>Factors for precision and reproducibility of rut depth measurements</u>

An analysis of differences between rut depth datasets produced by the two CTDOT ARAN systems during project SPR2297 revealed very high levels of both precision and reproducibility. It was noticed, nevertheless, that the variation in rut measurements (St. Dev.) increased slightly with an increase in mean rut depth reported per 0.1-mile section. The SPR 2297 final report provides a more detailed discussion on the effect of precise vertical measurements and adequate post-processing of transverse profile for the computation of rut depths.

Estimates of Precision and Reproducibility Limits using SPR-2297 Data

Using the methodology described earlier (also, see Figure 4.2), the maximum acceptable levels of within- and between-variability, or precision and reproducibility limits, respectively, were calculated for 0.1-mile average IRI, cracking, and rutting values as collected and reported by the CTDOT ARANs. These limits were based on the data produced during the SPR-2297 project at a time when no formal validation or verification process for data quality acceptance had been established.

The limits derived in the following sections for IRI, Cracking, and Rutting were used to develop Table 4.1 “Deliverables, Protocols and Quality Standards for Automated Data Collection,” in the DQMP document. It is believed that the precision and reproducibility of ARAN data will be improved when the quality control and acceptance procedures described in the DQMP document and its appendices are put into practice.

<u>IRI</u>

The average IRI for each 0.1-mile section is reported in inches per mile separately for the left and right wheelpaths. Not more than 5 percent of the surveyed sections would be expected to exhibit precision or reproducibility variation higher than the maximum acceptable values shown in Table 4.4.

Table 4.4. IRI thresholds as measured by standard deviation from a mean of five runs

Ride Quality	Precision Limit		Reproducibility Limit	
	St. Dev. for	St. Dev. for	St. Dev. for	St. Dev. for

	Left WP IRI [in/mi]	Right WP IRI [in/mi]	Left WP IRI [in/mi]	Right WP IRI [in/mi]
Good and Fair (IRI<170 in/mi)	18	22	20	25
Poor (IRI≥170 in/mi)	25	35	14	17

Cracking

Historically, data for cracking orientation, location within pavement lane zones, and severity are reported in the Connecticut PMIS as average total length per 10-m long pavement surface image (ft/10 lane-m) for each 0.1 lane-mile surveyed. The PMS reports generated by the Roadware Vision software, however, provide total lengths per 5 lane-meters and per 0.1-mi section. Furthermore, the Federal Rule CFR 23 *(USG, 2017)* requires reporting cracking in percentage of wheelpaths' area. Therefore, in order to minimize confusion, Table 4.5 shows variability in terms of C.o.V. Since all limits are 95th percentile values, not more than 5 percent of measurements are expected to exceed these thresholds. Note that these limits were developed for pavement sections where both CTDOT ARAN systems reported non-zero crack lengths.

Table 4.5. Crack length precision and reproducibility thresholds.

Crack Type	Precision Limit, C.o.V.	Reproducibility Limit, C.o.V.
Crack class by orientation (long., trans., area)	15%	50%
Crack location (wheelpath, non-wheelpath)	Wheelpath ≤35% Non-wheelpath ≤60%	Wheelpath ≤40% Non-wheelpath ≤60%
Crack severity (low, medium, high)	30%	30%

Rutting

The CTDOT rates distortion of pavement surfaces using average rut depth per 0.1 lane–mi segment for the left and right wheelpaths. During the SPR-2297 study, it was found that variability trends differed between wheelpaths. Therefore, Table 4.6 summarizes proposed precision and reproducibility thresholds separately for each wheelpath. Similar to IRI and cracking data, not more than 5 percent of surveyed sections are expected to exceed these limits.

Table 4.6. Rut depth precision and reproducibility thresholds.

Precision Limit	Reproducibility Limit

St. Dev. For Left WP Rut Depth [in]	St. Dev. For Right WP Rut Depth [in]	St. Dev. For Left WP Rut Depth [in]	St. Dev. For Right WP Rut Depth [in]
0.020	0.050	0.045	0.065

Proposed Expected Ranges for Quality Control

The expected ranges derived in the following sections for IRI, Cracking and Rutting were used to develop Table 4.2 "Data Review Criteria for Automated Condition Data Collection," in the DQMP document (*CTDOT, 2018a*).

<u>IRI</u>

Figure 4.3 presents annual trends for critical percentiles of the MRI distributions for the period of 2008 to 2016. On the right side of the figure, the 9-year average values of critical percentiles are shown. The analysis of the percentiles indicates annual consistency for 75 percent of the data, which represents sections not exceeding 165 in/mi. On the other hand, much larger fluctuations of MRI values can be observed for the remaining 25 percent of measurements. Note that the highest MRI value (99.5th percentile) reaches as high as 640 in/mi in year 2015 and as low as 340 in/mi in year 2016. The recommended expected range of MRI values of 40 to 450 (rounded up from 435) in/mi is based on 99-percent of measurements (between 0.5th and 99.5th percentile). All sections with MRI outside of the proposed range should be flagged and reviewed at the project level.

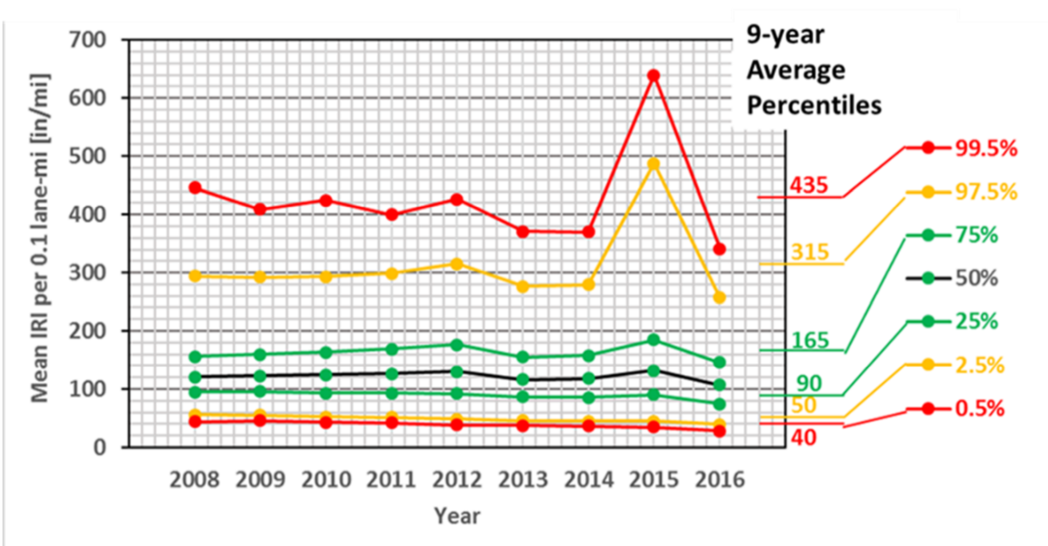

Figure 4.3. Annual trends for critical percentiles for distribution of MRI values from 2008-2016 PMIS.

<u>Cracking</u>

Figure 4.4 presents annual trends in critical percentiles (0.5, 2.5, 25, 50, 75, 97.5, and 99.5%) for cracking data in terms of average total crack length per image per 0.1-mi section reported across the State network. It can be seen that 99 percent of historically reported values (excluding year 2011) ranged between 0 and 290 ft/10 lane-m. Accordingly, all sections with reported cracking higher than 300 ft/10 lane-m (rounded-up) should be flagged and reviewed at the project level. It should be noted that due to significant changes made in the ARAN crack survey and detection technology during the past couple of years the annual trends reported prior to 2016 should not serve as a permanent benchmark for future network performance. The maximum expected range for cracking may need to be revised in the future, as additional data are available for analysis.

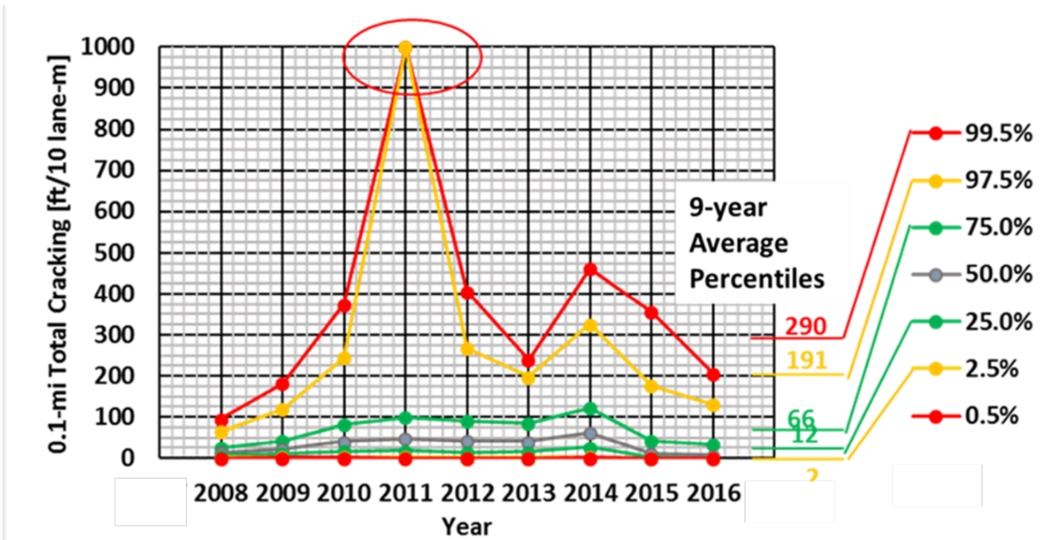

Figure 4.4. Annual trends for critical percentiles for distribution of crack length values from 2008-2016 PMIS.

<u>Rutting</u>

Figure 4.5 depicts the annual trends for critical percentile values of 0.1-mile average rut depths. It shows a peak in the 75 through 99-percentile values for years 2012 and 2013 (25% of rut depths reported above 0.2 in (99% within 1.1 in). On the other hand, the last three years (2014-2016) exhibit consistent distribution of rut depth with at least 99 percent of rut depths less than 0.45 in. Therefore, it is expected that 99 percent of the road network would exhibit rutting in the range between 0.03 and 0.45 inches. It is recommended that all sections with average rut depth per 0.1-mi larger than ~0.5 in be flagged and reviewed at the project level.

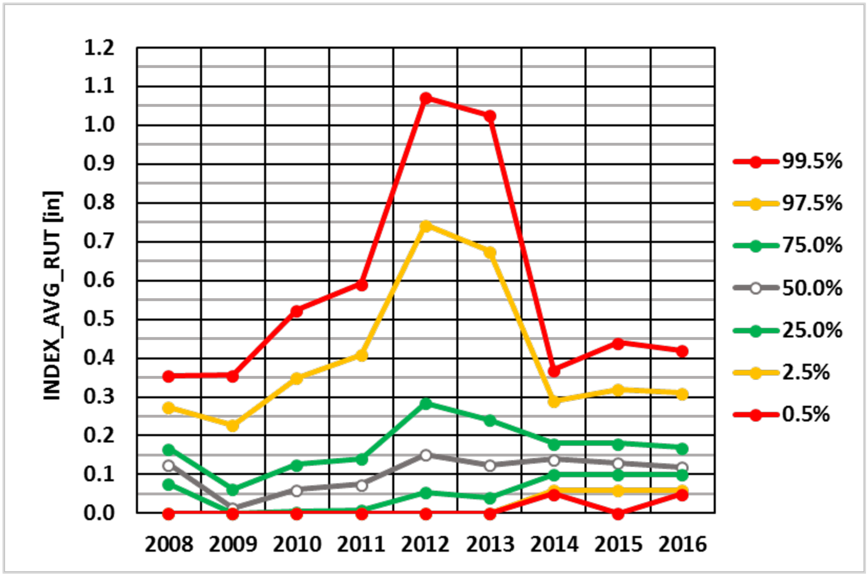

Figure 4.5. Annual trends for critical percentiles for distribution of rut depth values from 2008-2016 PMIS.

Chapter 5. Recommended Settings and Procedures for Validation and Verification Sites

The Federal Guide for Data Quality Management (Pierce et al., 2013) states that the quality management process should include 1) initial calibration and/or inspection of the equipment and 2) periodic validation of the collection method and/or equipment. Accordingly, two types of control sites are proposed to be used by the CTDOT: (1) validation sites to establish and monitor precision and accuracy of ARAN and reference survey methods and (2) verification sections to monitor repeatability and reproducibility if ARAN survey method. This Chapter describes the rationale for selection of validation sites and verification sections, whereas all details related to recommended settings and operations procedures on validation sites and verification sections are provided in the Manual for Quality Control of Pavement Condition Data collection (*CTDOT, 2018c*).

Recommended Settings and Procedures for Validation Sites

Table 5.1 summarizes the geometric characteristics (e.g., length, slope, and grade) and extent of surface distresses (e.g., roughness, cracking, rutting, and faulting) for the validation sites. These parameters were developed based on the relevant AASHTO and ASTM standard procedures (Table 5.2). It should be noted that these procedures are subject to revision, and are dependent on available resources, changes in federal requirements, state rules and regulations, safety, and other constraints that may become known in the future. Regional validation sites established with the cooperation of surrounding states is another option that could be considered in the future in order to pool resources. As a rule, all validation sites should be free of railroad crossings, bridge joints, utility covers, catch basins, and other localized roughness spots. In addition, one site can be used for multiple validation purposes (e.g., the same site for profile, rutting, and cracking measurement) if it meets multiple recommended parameters.

Table 5.1. Recommended site parameters for validation sites

Designated Data for Validation	Site Length	Longitudinal Grade	Cross Slope	Expected Distress Extent	Additional Requirements
Longitudinal Profile and IRI (High-Speed Roads 45-65 mi/hr)	0.4 mi	<2%	<3%	IRI=90 to 120 in/mi	Total crack length<300ft/0.1-mi
Longitudinal Profile and IRI (Low-Speed Roads 25-40 mi/hr)	0.4 mi	<2%	<3%	IRI=100 to 150 in/mi	Total crack length<300ft/0.1-mi
Transverse Profile	500 ft	<2%	<3%	n/a	CTDOT Drainage Index=3 to 5
Rut Depth	500 ft	n/a*	n/a	Average Rut Depth=0.25 to 0.5 in	CTDOT Distortion Index=4 to 6
Cracking	0.5 mi	n/a*	n/a	Total Crack Length=50 to 70 ft/10 lane-m	% Crack in Wheelpath=10% to 15%
Joint Faulting	1 mi	n/a*	n/a	Average Faulting=0.1 to 0.15 in	CTDOT Maximum Faulting in Right Wheelpath<1 in

*n/a = not applicable

Table 5.2. Summary of Relevant Standard Procedures for Operating on Validation Sites

Designated Data for Validation	Relevant Standard ID	Use
Longitudinal Profile and IRI	ASTM E2133-03	Operation of rolling inclinometer profiler for reference survey
	AASHTO R57-14	Operation of ARAN
	AASHTO R43-13	Quantifying roughness for reference and automated surveys
Transverse Profile	ASTM E1364-95	Operation of automated rod and level for reference survey
	ASTM E2133-03	Operation of rolling inclinometer profiler for reference survey
	AASHTO R57-14	Operation of ARAN
Rut Depth	ASTM E1364-95	Operation of automated rod and level for reference survey
	ASTM E2133-03	Operation of rolling inclinometer profiler for reference survey
	AASHTO R57-14	Operation of ARAN
	AASHTO R48-10	Quantifying rut depth for reference survey
	AASHTO PP69-14	Quantifying rut depth for automated survey
Cracking	AASHTO PP68-14	Operation of ARAN for collecting pavement images
	AASHTO R55-10	Cracking data storage for reference survey
	AASHTO PP67-16	Quantifying cracks for automated survey
Faulting	ASTM E2133-03	Operation of rolling inclinometer profiler for reference survey
	AASHTO R57-14	Operation of ARAN
	AASHTO R36-13	Detection of joints and quantifying faulting for reference and automated survey

Recommended Settings and Procedures for Verification Sections

The purpose of a verification section is to verify repeatability and reproducibility of ARAN sensor-related data (profile, IRI, joint faulting, and rut depth) during the collection season. It is recommended to run the ARANs on verification sections twice a month but not less than three times during data collection season. If a statistically significant change in repeatability or reproducibility (as compared with limits established on validation sites) occurs, a corrective action, such as a re-run on a validation site, may be required. Table 5.3 summarizes the recommended parameters to assist with selection of sections for verification runs. In general, all verification sections should be 0.5-mile long and provide for the ability to travel safely at 30 to 50 mi/hr. In addition, the sections should have no intersections, no traffic signals, no stop signs, and no localized rough segments.

Table 5.3. Recommended parameters for verification sections

Designated Data for Verification	Surface Type	Surface Condition Rating	IRI Limits in/mi	Rut Depth Limits, inches	Wheelpath Fatigue Crack Limits, percent	Faulting Limits, inches
IRI, Rutting, and Cracking	HMA	Good	<100	<0.2	<5	n/a
	HMA	Fair	120 to 150	0.25 to 0.35	10 to 15	n/a
Joint Faulting	JRCP	Fair or Good	n/a	n/a	n/a	> 0.2 in in Right Wheelpath

*n/a = not applicable

Chapter 6. Development of Data Quality Management Plan

This Chapter describes the process for the development of the DQMP and summarizes two ancillary addendum documents. The CTDOT DQMP document was primarily developed following the recommendations contained in the "Practical Guide for Quality Management of Pavement Condition Data Collection" (*Pierce et al., 2013*), which was developed under contract to FHWA. It was recognized, however, that the CTDOT required additional guidance on each of the procedures and actions related to quality of the collected pavement data. This was accomplished through the development of the two ancillary addendums. The first addendum "Photolog Field Data Collection Standard Operating Procedures" was created by the CTDOT Photolog unit to provide detailed guidance on operating the CTDOT ARANs, to document standard operating procedures for field data collection, and for processing pavement condition data in a manner that will provide optimum quality pavement condition information for use throughout the pavement community. The second addendum "Manual for Quality Control of Pavement Condition Data Collection" was developed by the CTI research team to detail the required procedures to be followed by CTDOT to achieve QC and Acceptance, as defined in the DQMP.

For this project, the three documents together provide a complete package for data quality management of pavement data collection surveys in Connecticut. In order to ensure meeting the FHWA regulations, as well as filing by the required date of May 18, 2018, the formal DQMP was developed in conjunction with a CTDOT study committee for this SPR project. The committee met several times between September 2017 and May 2018.

Description of DQMP

The main DQMP document identifies key activities, processes, and procedures for ensuring quality (*CTDOT2018a*). Table 6.1 contains a brief explanation for each of the DQMP sections.

Table 6.1. Summary of DQMP contents [May 2018 Draft]*(*CTDOT2018a*).

Section Title	Section Contents
Section 1 Quality Management Approach	Introduction and organization of the document.
Section 2 Pavement Data Collection Equipment and Business Processes	Automated equipment used by CTDOT for pavement data collection, and the business processes employed to produce quality data and information for use in FHWA HPMS, CTDOT performance measures, and paving and preservation programs
Section 3 Training, Qualification and Certification	Processes and protocols used to certify data collection equipment, equipment operators and the layout of standard reference validation sites.
Section 4. Deliverables, Protocols, and Quality Standards	The data collection deliverables subject to quality review, protocols used for collection, quality standards that are the measures used to determine a successful outcome for a deliverable, and criteria to describe when each deliverable is considered complete and correct. Deliverables are evaluated against these criteria before they are formally approved.
Section 5. Quality Control (QC)	The QC activities that monitor, provide feedback, and verify that the data collection deliverables meet the defined quality standards.

Section 6. Acceptance	The acceptance testing used to determine if quality criteria are met and corrective actions that must be taken for any deliverables not meeting the quality criteria.
Section 7. Quality Team Roles and Responsibilities	The defined quality-related roles and responsibilities for data collection, data reduction, review, acceptance, and reporting.
Section 8. Quality Reporting Plan	The documentation of all QM activities—including quality standards, QC, acceptance, and corrective actions—and the format of the final QM report.
Section 9. CTDOT Data Collection Quality Management Plan Endorsement	Signature page for endorsement of the CTDOT Data Quality Management Plan.

* The contents of the final DQMP approved by FHWA in August 2018 is contained in Appendix C

Description of Photolog Field Data Collection Standard Operating Procedures Manual

This document (*CTDOT2018b*) provides guidance to Photolog section personnel involved in field data collection and processing of the collected data. It describes the procedures for all field collection and office operations. Table 7.2 summarizes the content of the document.

Table 6.2. Summary of Standard Operating Procedures Manual (*CTDOT2018b*)

Section Title	Section Contents
Introduction	Foreword Background of the Photolog Unit and historical automated data collection in Connecticut
Platform, Environment & Equipment	Description of ARAN features and capabilities Description of ARAN subsystems and equipment
General Standards and Guidance	Summary of data acceptance standards currently used by Photolog Unit Safety requirements for ARAN & field operations Environmental requirements (weather and light conditions) for ARAN operation
Annual Pre-collection Season Preparations	Office preparations including data maintenance and backup Data structure requirements including routing file preparation ARAN equipment preparation and preventative maintenance Verification and control site preparations
Routine Office Procedures	Data processing guidelines including specifics on Road Vision software settings Data reporting and acceptance requirements
Routine Field Procedures	Morning setup requirements Daily collection procedures End-of-the-day routines
Control & Verification	Field collection control Recommended parameters for control and verification sites List of current verification sites
Resource Information	Contact information of all CTDOT personnel involved in data collection, processing, and use Contact information of vendor (FUGRO Roadware) List of fueling stations Checklist of incident report

Description of Manual for Quality Control of Pavement Condition Data Collection

The Manual (*CTDOT2018c*) describes recommended procedures and actions to ensure that the final product of the pavement data collection survey, i.e. Pavement Management Information System (PMIS) reports, adequately reflects pavement surface conditions of the State road network. The procedures and actions described in this manual are grouped in accordance with the three main phases of data flow, which are (1) pre-production, (2) production, and (3) post-production as indicated in Figure 6.1.

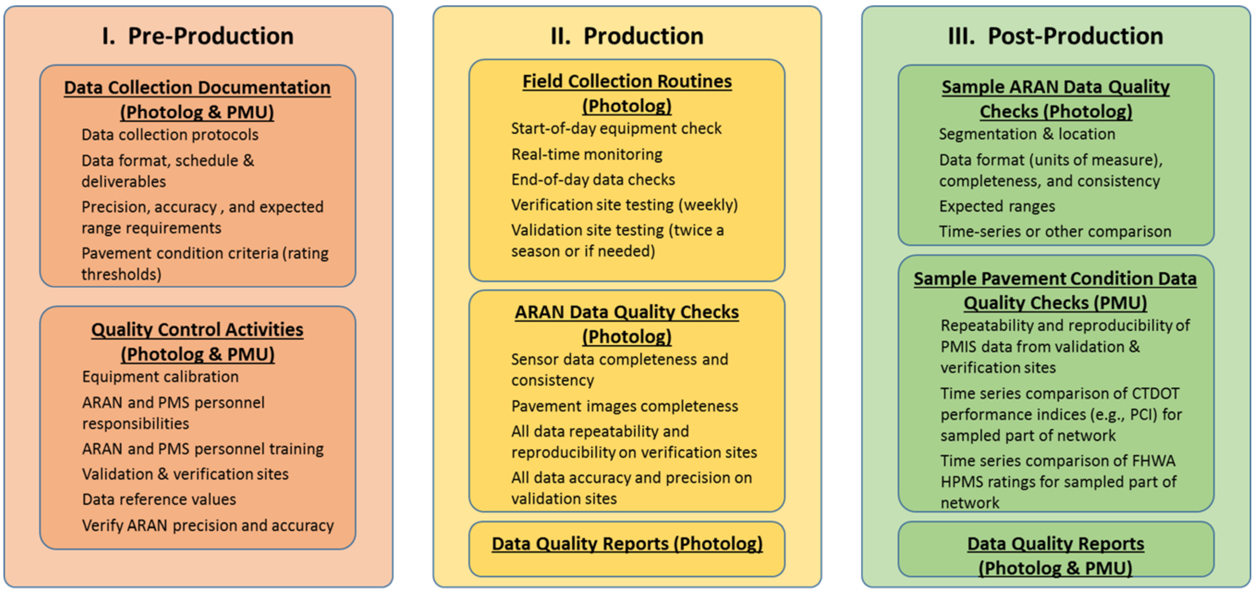

Figure 6.1. Quality Management Activities associated with three phases of pavement condition data collection (after Pierce and Zimmerman, 2015).

Table 6.3 summarizes the content of the Manual for Quality Control of Pavement Condition Data Collection.

Table 6.3. Summary of Manual for Quality Control of Pavement Condition Data Collection (*CTDOT2018c*)

Section Title	Section Contents
1. Purpose and Organization of The Manual	Purpose and organization of the manual including brief contents of the chapters

2. Pre-production Operations	Recommendations on data collection protocols including ARAN and Road Vision settings, as well as data formats Recommended validation site parameters for longitudinal and transverse profile, IRI, cracking, rutting, and faulting measurements Procedures for measuring reference values at validation sites, Procedures for operating the ARAN on validation sites Step-by-step routines for determining the precision, accuracy, and reproducibility for field measurement methods Procedure for determining expected ranges of values for ARAN surveys
3. Production Operations	Field collection procedures including start-of-day, daily collection, and end-of-day routines with reference to Photolog Standard Operation Procedures (*CTDOT2018b*) Procedures for validation site testing if required during production season Procedures for verification site testing including selection parameters and equipment operation guide Routines for ARAN data quality checks including data completeness and integrity, repeatability and reproducibility on verification sites, and corrective actions Data quality report format for ARAN data
4. Post-Production Operations	Quality acceptance criteria for post-production Procedures for quality acceptance of processed ARAN data and data from PMIS reports including sampling procedures Data quality report format for PMIS data
5. References	List of literature sources used in the Manual

Chapter 7. Conclusions and Recommendations

The SPR-2309 project targets preparation of the quality management plan for pavement condition data in Connecticut. The main document, the DQMP (CTDOT2018a), was prepared following FHWA guidelines, whereas two addendums focused on specifics of the CTDOT Photolog Unit's ARAN operating procedures (CTDOT2018b) and routines for establishing precision and reproducibility of ARAN data and monitoring pre-production, production and post-production quality (CTDOT2018c).

The literature review that was performed for this study showed an increasing number of agencies were performing some QC/QA activities to improve reliability of pavement data collection (Flintsch and McGhee, 2009; Pierce et al, 2013). However, even by 2013, the FHWA reported only a few agencies were found to have a comprehensive QMP in place for pavement condition surveys (Pierce et al., 2013).The FHWA study (Pierce et al., 2013) indicates that states are becoming more aware and concerned about quality, but that much greater emphasis should be placed on quality management for pavement management. FHWA notes in the Practical Guide that without a documented plan, such as a formal QMP, agencies are less likely to apply QM activities consistently from year to year, nor assess the effectiveness of the techniques used. Thus, a conclusion would be that the federal mandate for NHS QMPs in 2018 appears to be needed and timely.

It was found that, before the start of this Project, the CTDOT had no formal internal documents or guidelines on quality management for automated pavement condition data surveys. However, both collection and processing personnel showed a high awareness of the importance and need to develop such guidelines. Furthermore, since the kick-off of this project, the Photolog section implemented a number of steps to improve quality-related daily operations such as for example checklists of ARAN daily-required actions from start of day to end of day. It is likely that this awareness and these steps alone will improve quality control during the 2018 field data collection season.

In the absence of previously established validation sites, the data from ARAN repeatability runs obtained under the previous SPR-2297 study were used for an analysis of variability. Therefore, only precision and reproducibility of ARAN measurements is discussed herein. Required accuracy limits relative to reference values (ground truth) at validation sites are not provided, and must still be determined in the future at CTDOT, once validation sites are established.

The precision and reproducibility limits derived during this project for IRI, cracking and rutting were used to develop Table 4.1, "Deliverables, Protocols and Quality Standards for Automated Data Collection" in the DQMP document. It is believed that the precision and reproducibility of ARAN data will be improved when the quality control and acceptance procedures described in the DQMP document and its appendices are put into practice.

The expected ranges of IRI, cracking and rutting derived for this project from data collected for the previous study (SPR-2297) were used to develop Table 4.2, "Data Review Criteria for Automated Condition Data Collection" in the DQMP document. This information should be used by CTDOT to identify and check collected data that appears to fall outside of expected ranges. Any such identified data, as well as data that falls outside the limits for precision and reproducibility, could be suspect, and possibly indicate a need for some of the corrective actions listed in the DQMP Table 6.2, "General Acceptance Expectations and Deliverables" such as repairs of equipment, re-calibration of equipment, and/or re-collection of the data.

A specific recommendation regarding CTDOT's data collection process (in concurrence with observations made in other state studies) is that driving within the correct wheel paths is critical to maintaining quality control and meeting acceptance thresholds with vehicles collecting automated pavement data. Driver awareness of this critical action is mandatory. Keeping the ARAN vehicle within the prescribed lane position can be a challenge. Practice or training might be in order to improve overall quality levels.

It should be noted that due to significant changes made in the ARAN crack survey and detection technology during the past couple of years the annual trends reported prior to 2016 should not serve as a permanent benchmark for future network performance. In particular, the maximum expected range for cracking may need to be revised in the future, as additional data are available for analysis.

Recommendations on Further Research Related to Quality Management of ARAN Data

Due to the condensed time frame for this project, which was dictated by the federal regulations requiring the DQMP to be completed by May 20, 2018, a number of issues were identified that show a need for additional work. Some of these are the following:

- Investigate actual accuracy of IRI, cracking, rutting, grade, and cross-slope data with respect to reference values that will be established on CTDOT validation sites during the 2018 data collection season.
- Investigate the effect of the quality of pavement surface image and settings of the crack detection algorithm on precision and accuracy of crack measurements.
- Determine optimal thresholds for post-processing of raw roughness data collected under unfavorable operating conditions (low speed, steep speed gradient, sharp turns etc.).
- Re-evaluate PMIS reported data for 2016, 2017, and 2018 surveys and update benchmark values for forecasting pavement conditions on the Connecticut road network.
- Investigate and set reproducibility limits for time-series analyses, which can be used by CTDOT to perform year-to-year comparisons of pavement condition data.
- Evaluate the CTDOT Pavement Condition Index (PCI) for suitability on pavement sections where automated data cannot be collected at speeds above 30 MPH.
- Provide assistance to CTDOT with development of annual reproducibility and precision values at validation sites.
- Explore the use of Regional validation sites in cooperation with surrounding states as an option for pooling and sharing resources.

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Appendix A: State PMS Personnel Questionnaire (after McGee2009)

PART I: GENERAL QUESTIONS

1. Contact Information

   Participants

   Photolog: Lester King, Jim Spencer, Jin, Mike, Anthony

   PMS: John Henault, Jeannine

2. How long has the agency been collecting pavement condition data?

   Since 1996 (in current format)

3. How many lane-miles of roadway are surveyed?

   About 8,000 miles (13,000 km) x2 direction

4. What pavement condition data do you collect:

   Project Level: Surface Distress/ Smoothness/ Friction/ Structural Capacity

   Network Level: **Surface Distress**/ **Smoothness**/ ~~Friction/ Structural Capacity~~

5. Is the pavement data used to control pavement warranties, performance based contracts, and/or other public-private partnerships?

   Not in General. However, limited IRI data is used for sample smoothness projects (4 projects in 2017).

6. Do you use overall pavement condition index (Index name and components)?

   Yes. PCI (or historically, PSR) is combined from IRI, Rut, Crack, Environmental, and Drainage indices.

7. What surface distress do you collect?

   Cracking : Long., Trans., Alligator

   Rutting in both wheelpaths.

   Faulting

8. What collection methods are employed?

   Project Level: Walking Windshield **Automated** Semi-Automated

   Network Level: Walking Windshield **Automated** Semi-Automated

9. How often is network level data collected for

	Highway	Arterial	Collector/Local
Rural	**Annually**	**Annually**	**Annually (350 miles of local road is reported to HPMS)**
Urban	**Annually**	**Annually**	

10. What type of location referencing is used for pavement data collection activities?

<u>**GPS**</u> National Differential GPS <u>**Milepoints/Mileposts**</u>

Link-node Other

11. Do you collect data for a single or multiple lanes (Comment if needed)?

Most operational through lane (Lester).

Outmost right lane (Jim)

12. Do you outsource collection of any pavement condition data?

No

PART II: QUESTIONS ABOUT QUALITY MANAGEMENT ACTIVITIES

13. Do you have a formal Quality Management Plan (QMP) for pavement data collection? Yes/<u>**No**</u>/ Sort of (Comment if needed)

14. Do you have a formal Quality Assurance Plan (QAP) for pavement data collection? Yes/<u>**No**</u>/ Sort of (Comment if needed)

15. What type of quality checks do you have in place for quality management purposes?

Activity	Analysis Criteria	How often	Note
Calibration of Equipment before collection	**Per FUGRO Specifications (Bounce Test? Plate Test?)**	**Annually** **Monthly**	**Full calibration by Fugro (=Preventive Maintenance** **DMI Calibration by Photolog unit**
Testing of **Known Control Segments** before collection	**N/A**	**N/A**	**Brooks St.** **Big Loop**
Ditto during production	**5% (or reasonable? Unclear) Change in Pavement Distresses and IRI**	**Monthly**	**Van-to van comparison** **Month-to-month comparison**
Testing of **Blind Control Segments** during production	**N/A**	**N/A**	**No**
Verification of Sample Data by independent consultant	**No**		**No**
Verification of post-survey processing software/procedures	**Road Vision Alerts and Warnings**		**No formal procedure**

Cross-measurements, i.e. random assignment of repeated segments to different teams/devices	**Yes**	**Monthly?**	**IRI&Rutting**
Statistical Routines • to identify **inconsistencies** in the data • to verify compliance with **expected range** • to check **missing data**	**No** **No** **RoadVision alerts and warnings**		
Comparison with existing time-series data	**Annually (Occasionally?)**		**No formal procedure**
Do you match automated results with manually established benchmark values **("ground truth")?**	**N/A**	**N/A**	**No**

16. What parameters do you use to determine accuracy of the data?

    No formal definition of accuracy. Occasional comparison with existing time-series

17. What percentage of data is checked for quality assurance?

No definite number or procedure. As of now, 5-m IRI data at speed under 25 mi/hr is removed from 160-m calculations.

18. What percentage of data must be corrected/resurveyed?

    5% on average (one year 10% was re-surveyed)

19. Based on your experience, what factor(s) have the greatest impact on the quality of pavement condition data?

Equipment (vehicle, hardware, software)

Unit of measure

Processing (unit conversion, post-processing)

Human Error (processing, unit conversion)

Training.

Timely detection of errors

PART III: PERSONNEL TRAINING

20. How many years of experience do Photolog personnel have on average?

    12 years

21. Do you require a formal certification for Photolog personnel? (Operation of ARAN, Data Processing, etc.)

    No

22. How do Photolog personnel receive initial and ongoing training?

    <u>On-job from experienced staff</u>/ In-house training program/ Formal education/ Professional certification/ Other

    <u>Note: both driver and operator gets the same training</u>

23. For how many hours per year do Photolog personnel receive ongoing training?

Not Applicable

PART IV: OPERATION PROCEDURES

24. Do you use a checklist of ARAN Standard Processes before, during, and after collection?

    Yes. Request from Jim Spencer

25. Do you check the following parameters when you "start the day"?

    Green lights on Accuracy; RMS Accuracy <0.03 Yes/Aware of that

    QC_Video.csv: < 5 dropped images **Aware of that/**

    At the end of the day

    GPS Mode: **<u>C/A (Course Acquisition</u>** **DGPS (Differential)**

    <u>Note: Differential is not used because it is time-consuming (??)</u>

26. Do you perform the following procedures every morning or start of collection event?

    Walk around ARAN: attention to DMI and RutBar enclosure **YES**

    Mechanical Checklist inspection **NO**

    Run Dummy file and review data for discrepancies **YES (twice a day)**

27. How often do you clean the ROW camera and LCMS laser glass?

    ROW camera –daily; LCMS – as needed

28. How do you ensure that ARAN moves at constant speed?

    Some drivers use cruise control, some are aware of its importance

29. How do you ensure that ARAN stays within the lane?

    N/A

30. Do you perform the following procedures during Video Collection?

Run report on ROW and pavement images several times a day. Y**es** (**warning message is generated automatically**)

Keep QC_Pcs_files.csv and QC_Video.csv open to collect PCS and no images dropped. **(N/A)**

31. How often do you review ACS (ARAN Collection System) settings and make sure they are appropriate for the specific project?

It is done annually by FUGRO during Preventive Maintenance

Photolog Unit DOES NOT change any settings.

32. How often do you review ROW camera and LCMS laser settings? **NEVER**

33. Do you perform the following procedures during daily collection?

Ensure that ROW/Pavement camera videos are displayed every mile of collection. **YES**

Ensure that the frame numbers are incrementing appropriately. **YES**

Ensure that 3D-DGPS is fixed at the start of each section. **YES**

34. Are you aware of/do you monitor the expected ranges of data in real time (IRI, rutting, cross-fall, grade)?

Graphical IRI trends are monitored during collection

Grade is displayed on the dashboard during collection.

35. Are you aware of/do you monitor the HDOP and VDOP numbers (dilution of precision of the GPS)?

The operators/drivers are aware of those parameters by do not monitor them. The automated warning is displayed when adequate collecting conditions are not met.

36. Do you perform the following End of Day Procedure? **YES**

1. Generating the daily folder & reports
2. Reviewing the QC_Video & QC_PCS files and sample images
3. Backing up the database
4. Exporting the data
5. Editing the .csv file on Frankie
6. Uploading the Daily folder to the FTP

37. How would you describe contribution of FUGRO, Inc. to your in-house process of pavement data collection?

FUGRO is vendor/supplier of ARAN hardware and software (Jim Spencer)

FUGRO is sole developer of Roadware Vision processing and reporting algorithms and routines (Jim and Jeannine)

CTDOT has limited ability to change some report templates (Jeannine)

CTDOT has not changed Cracking schema for as early as since 2010 (Jeannine, IRY)

Appendix B:

Additional Details on Pavement Data Collection Quality Management Processes Recommended and/or Used by Other States and Organizations

Addendum – Appendix to Literature Search

The following discussion demonstrates some of the QM commonalities and differences between the various organizations and states that primarily use Fugro Roadware equipment (except where indicated otherwise). Some organizations rely on vendors (e.g., Indiana, Virginia, Oklahoma), while others like Connecticut perform data collection and reduction in-house (Maryland).

FHWA Practical Guide for Quality Management of Pavement Condition Data Collection (from [1])

As background, for the purpose of uniformity, in outline format, FHWA recommends the following:

Foundation for quality

- Define methods, standards and protocols for
    - Distress types
    - Severity levels
    - Rating methods
        - Count, length, area, other
    - Condition value or index
        - Calculation method
- Quality Standards
    - Data Resolution (e.g., rut depth to nearest 0.1 in)
    - Accuracy (statistics, standard deviation, percent limits, other)
    - Repeatability
    - Responsibility
        - Staff roles
            - Tracking, documentation, data analysis, reports
    - Problem Resolution (corrective action procedures)

Quality Control (QC) (for data collection with automated equipment)

- Equipment Checks:
    - Manufacturer-recommended calibration
    - Manufacturer-recommended operations procedures
    - Manufacturer's data review procedures
- Vehicle Operator Personnel Training
    - Driver
    - Data collection operator
    - Data handling/processing
- Control of Variability
    - Identify manageable sources of variability
    - Maintain variability within acceptable limits

Account for random errors
Eliminate systematic errors
Make adjustments to minimize "controllable" variability
Perform equipment calibration
Test known "control" sections
At start of season
At pre-defined periodic intervals
At end of season
Test verification sections
Periodically
Follow daily startup procedures
Follow end of day procedures
Run software programs to check for:
Completeness
Reasonableness
Check data using:
previous data,
time series,
maximum allowable ranges,

Quality Acceptance (QA)
Establish acceptance criteria
Specify sample size for verification
Prepare QMP annually

Independent Assurance (IA)
Resample (e.g., 5-10%) data using a third party
Identify any random or systematic errors not already found during QC or QA

Virginia DOT (VDOT) (from [2])

Virginia is considered by many to be one of the pioneers and leaders in quality management for pavement data collection.

Standards Used:
International Roughness Index (IRI)
ASTM E950-09(2004) or later
Rutting
AASHTO PP-38-00 (2005) or later
Cracking
VDOT Distress Identification Manual V2.6 (Nov 1, 2012)
Faulting
AASHTO R36-13 (March 2014)

Data Collection
Asphalt surfaces
Longitudinal (L), Transverse (T), Alligator (A) cracks + (Patches, potholes, delamination, reflection Cracks, bleeding)

IRI
Rutting
Load Distress Rating (LDR) = fatigue cracking, patching, rutting, + other
Non-load Distress Rating (NDR) =T & L cracking, bleeding joint separation, + other
Critical Condition Index (CCI) = lower of LDR or NDR

Jointed Reinforced Concrete (JRC) surfaces
L, T + (divided slabs, blowups, patches, spalling, joint seal condition)
Faulting
IRI
Slab Distress Rating (SDR)

Continuously Reinforced Concrete (CRC) surfaces
T, clustered cracks + (punchouts, patches, spalling, joint seal condition)
IRI
Concrete Distress Rating (CDR)
Concrete Punchouts Rating (CPR)

Control Sites –

VDOT uses 14 control sites (8 asphalt, 3 JRC, 3 CRC), generally 1 mile in length. Sites are used to calibrate the distress rating process and to establish the precision and bias for the roughness and rutting.

Develop precision and bias statements for each vehicle, as well as the precision between all vehicles.

ProVal (latest version) is used to process data for precision and bias statements

These sites are also used to calibrate distress rating

- IRI Repeatability needs to be within 95%
- Rutting repeatability needs to be +/- 5%
- Images need to identify 2mm wide cracks at highway speed
- LDR, NDR, SDR, CDR must fall within 10 index points from verification for at least 90% of samples
- CCI year-to-year comparison must be between +5 and -15 points

Network Road Surveys

100% of interstate and primary systems annually
20% of secondary system annually
Every 0.1 mile and a summary per each PM section

QC (by vendor)

Image quality
Sensor data
Linear referencing
Distress ratings
Shoulder ratings
Year-to-year comparison

IA (3rd party)

5% of deliverable checked via distress comparisons of random samples
High level review of entire deliverable
Year-to-year checks on matching management sections

Acceptance

Table 1. Acceptance Testing for Pavement Distress in Virginia

Deliverable Item	Acceptance (Percent Within Limits)	Acceptance Testing & Frequency
LDR	95%	Global database check for consistency, logic, completeness. Five percent sample inspection upon delivery.
NDR	95%	Global database check for consistency, logic, completeness. Five percent sample inspection upon delivery.
SDR	95%	Global database check for consistency, logic, completeness. Ten percent sample inspection upon delivery.
CDR	95%	Global database check for consistency, logic, completeness. Ten percent sample inspection upon delivery.
CPR	95%	Global database check for consistency, logic, completeness. Ten percent sample inspection upon delivery.
Right Shoulder #1 Type	90%	Five percent sample upon delivery. Comparison based on 0.1-mile results.
Right Shoulder #1 Width	90%	Five percent sample upon delivery. Comparison based on 0.1-mile results.
Right Shoulder #2 Type	90%	Five percent sample upon delivery. Comparison based on 0.1-mile results.
Right Shoulder #2 Width	90%	Five percent sample upon delivery. Comparison based on 0.1-mile results.
Left Shoulder #1 Type	90%	Five percent sample upon delivery. Comparison based on 0.1-mile results.

Left Shoulder #1 Width	90%	Five percent sample upon delivery. Comparison based on 0.1-mile results.
Left Shoulder #2 Type	90%	Five percent sample upon delivery. Comparison based on 0.1-mile results.
Left Shoulder #2 Width	90%	Five percent sample upon delivery. Comparison based on 0.1-mile results.

Table 2 identifies corrective actions that will be taken for any pavement condition data deliverables not meeting criteria. Final acceptance activities are performed by VDOT to determine if deliverables have met the established criteria shown in the table.

Table 2. Acceptance Testing for Pavement Condition Data in Virginia

Deliverable	Acceptance (Percent Within Limits)	Acceptance Testing & Frequency	Action If Criteria Not Met
IRI	90%	Weekly control, verification, and blind site testing. Global database check for range, consistency, logic, and completeness and inspection of all suspect data.	Reject deliverable; data must be re-collected.
Rut Depth	90%	Weekly control, verification, and blind site testing. Global database check for range, consistency, logic, and completeness and inspection of all suspect data.	Reject deliverable; data must be re-collected.
LDR	90%	Global database check for consistency, logic, completeness. Five percent sample inspection upon delivery.	Return deliverable for correction
NDR	90%	Global database check for consistency, logic, completeness. Five percent sample inspection upon delivery.	Return deliverable for correction
SDR	90%	Global database check for consistency, logic, completeness. Ten percent sample inspection upon delivery.	Return deliverable for correction

CDR	90%	Global database check for consistency, logic, completeness. Ten percent sample inspection upon delivery.	Return deliverable for correction
CPR	90%	Global database check for consistency, logic, completeness. Ten percent sample inspection upon delivery.	Return deliverable for correction
Location of Segment and Segment Begin Point	100%	Plot on base map using GIS. Global database check of accuracy and completeness.	Return deliverable for correction

Indiana DOT (from [3])

Note: Indiana DOT was not using Fugro Roadware equipment as of September 2015.

Indiana is one of the only states to previously perform a comprehensive research study dedicated to quality management of pavement data collection.

QC – performed in three phases in INDOT:

- a. Pre-project phase– to attain certification for accuracy and precision at equipment level
    - Laser, accelerometers, bounce test, distance calibration
- b. Data Collection phase– daily real-time QC checks
- c. Post-processing phase– back end in office for completeness and accuracy
- Field QC
    - Control sites – periodic re-collection
    - Equipment and bounce tests weekly
    - Real time graphs
    - Completeness checks every 2 hours
    - Daily report software
    - Operator's daily checklist
    - Real time image viewing
    - Back end test for completeness and accuracy
    - Logic checks on data for pavement type, lane, events etc.

QA – use random blind QA sites

- Completeness of delivered data
- Accuracy and reliability of:
    - roughness,
    - individual distress ratings
    - aggregate PCR

Certification of vehicles and for laser profile before data collection season
Tests on selected pavement sections (in the highway network)
Back end completeness consistency before importing to database

Quality Management Statistics

Check data for cleansing and integrity using Codd's Integrity Constraints, for example:

Rating = $1 - \frac{\quad}{\quad}$

Free of error

Example formula $Free\ of\ error\ rating = 1 - \frac{\quad}{\#}$

Completeness

Example formula $Completeness\ rating = 1 - \frac{\quad}{\#}$

Consistency

Example formula $Consistency\ rating = 1 - \frac{\quad}{\#}$

Oklahoma DOT (from NCHRP Synthesis 401[4] and [1] FHWA Practical Guide)

Note: Oklahoma DOT was not using Fugro Roadware equipment as of September 2015.

As of the publication date (2009) of Synthesis Report 401, ODOT established a 4-year contract with a data collection service provider to collect network-level data. The data are processed using a combination of automated and semi-automated techniques. The contract includes:

sensor data - (IRI, rutting, faulting, and macrotexture),

distress ratings - (type and severity) based on visual analysis of pavement video, and

geometric data - (longitudinal slope, crossfall, horizontal curve radii, and GPS coordinates). [4. p. 47]

Control Sites - four (4) 0.50-mi. long control sites. (two (2) - jointed concrete pavement, two (2)- asphalt pavement) located on a four-lane divided highway in the central part of the state.

Prospective contractors must collect the following on these four sites:

a. Video log images — downward-facing and two ROW views at intervals of 0.005-mi (or 200 images per mile for each view).

b. GPS data — latitude and longitude in degrees and decimals of a degree to six decimal places for the beginning of each 0.01-mi interval, for entire length of control site.

c. IRI data — IRI for the left and right wheel paths, and the average of both wheel paths at an interval of 0.01 mi. Use AASHTO PP 37-04, (but with a data summary interval of 0.01 mi and reported results in U.S. Customary units).

d. Rut depth data — for asphalt control sites, left and right rut depth, average, maximum, and the percent of rut depth measurements that are less than 0.5 in, for each 0.01-mi. interval in accordance with AASHTO PP 38-00, (using a minimum of eleven sensors, data summary interval of 0.01-mi, results reported in U.S. Customary units).

e. Faulting data — for jointed concrete control sites, the average, maximum, number of faults, and standard deviation for each 0.01-mi interval.

f. Geometric data — longitudinal grade, cross slope, and curve radii in U.S. Customary units for each 0.01-mi. interval.

g. Distress data — processed pavement distress ratings for the control sites using the Oklahoma DOT Distress Rating Guide. Aggregate and report distress data at 0.01-mi intervals.

QC, *- A* QC plan is developed by the data collection service provider and includes quality control checks at all stages of the data collection, processing, reduction, and delivery processes. Some of the quality control steps include

a. control and verification site testing,
b. inter-rater consistency testing, and
c. numerous checks of data quality and completeness. *[4, p. 47]*.

QA – QA of data supplied by the contractor, OKDOT implemented:

a. Control site testing –

- to identify factors that could affect the accuracy and repeatability of sensor data measurements,
- to evaluate the quality of the collected video.

b. Checks of distress ratings - on batches of submitted data using a modified version of the service provider's distress rating software. (*Note: these distress rating checks proved to be very time-consuming and labor intensive, such that ODOT contracted the review of the distress ratings for the third year of collection to a consultant.*)

c. Additional data quality assurance checks - of every data element in the pavement condition database.

Software - ODOT - developed Visual Basic quality acceptance tool operating within an Access database to rapidly and efficiently check the data delivered by the service provider. The software performs:

a. Preliminary checks – to verify "general" information, such as:

- district number,
- type of data entered in each field (e.g., integer versus characters),
- general section identification data,
- GPS values,
- pavement type,
- events (bridges, etc.),
- geometric values, and
- missing data.

b. Sensor checks - for all those data elements collected (using lasers or sensors to determine properties of the pavement section) that look for:

- duplicate records in adjacent sections,
- date,
- number of sensors used for rutting, and
- out-of-range values for IRI, rutting, faulting, and macrotexture.

c. Distress checks – to verify the specific distress for a given surface type to confirm that they are in accordance with ODOT distress rating protocols and within the expected values not only on an individual basis but also when considering various distresses in combination with one another.

d. Special checks - include more specific elements such as:

- maximum asphalt concrete patch length,
- number of railroad crossings and bridges, and
- nonmatching distress types (e.g., an asphalt concrete distress assigned to a concrete pavement). [4, p. 47-48]

GIS visualization and spatial analysis tools are also used for:

- detecting missing sections,
- inconsistencies in the location of some sections, and
- unexpected changes in pavement condition.[4, p. 138]

Table 3. Required accuracy, resolution, and repeatability of ODOT collected data (from [4], p. 13)

Data Element	Required Minimum Accuracy	Required Resolution (Measure to the Nearest)	Required Minimum Repeatability
Rut Depth	±0.08 in. compared to manual survey	0.01 in.	±0.08 in. run to run for three repeat runs
IRI	±5% compared to Dipstick or class 1 profiler	1 in./mi	±5% run to run for three repeat runs
Faulting	±0.04 inches compared to manual survey	0.01 in	0.04 in. run to run for three repeat runs
Distress Ratings	±10% compared to ODOT ratings	N/A	N/A
GPS Coordinates	±0.0005 degrees as compared to ODOT provided coordinates	0.000001 degrees	N/A

Louisiana Department of Transportation and Development (LaDOTD) (from [1] p. 120-129)

Note: as of Sept 2015, FUGRO Roadware equipment was being used

Surveys- A service provider delivers the following data to LaDOTD on a weekly basis (*)*:

a. ROW images

b. Raw data from the data collection vehicle's electronic sensors

- rutting
- IRI
- faulting, and
- GPS data

c. Equipment calibrations test results

- distress manifestation index
- rut measurement device, and
- video foot print

d. Electronic sensor verification results.

QC – Collected data are reviewed for completeness at the end of each day.

The service provider is responsible for checking all data/images prior to delivery to Louisiana DOTD.

The service provider must also rectify all issues discovered by Louisiana DOTD.

The service provider submits QC plans including:

a. preliminary activities
- developing the QC plan
- conducting personnel training/certification, and
- equipment calibration

b. control sites
c. data checks, and
d. final documentation delivery

The service provider's equipment is checked against an agency profiler and a Class I profiling instrument (e.g., Dipstick) before beginning testing.

During production, the service provider is required to use QC sections of known IRI, rutting, and faulting values.

Key personnel are identified in the data collection request for proposal, and the service provider is required to disclose all certifications and achievements in their proposal, including education background and achievements of key personnel.

All equipment is calibrated according to the manufacturer's recommendations.

The DMI is calibrated on segments with a known/surveyed length.

All operating procedures pertaining to data collection used by the service provider are documented.

Data verification by testing control sites or verification sites.

Repeatability – Minimum of three runs on each control site.

Consistency, Validity –

1.) Electronic data is compared to previous year's data collection.

2.) The service provider is mandated to re-collect control section data from the previous week's collection to verify that the equipment is in calibration.

In-vehicle, *real-time data checks* are performed for rutting, IRI, GPS, faulting, and DMI data to ensure that it is within the required tolerances.

Pavement distress data (i.e., images and processed results) are provided to the LaDOTD for review and evaluation. LaDOTD reviews approximately 5 percent of the control section length and segments the samples into 0.10-mi. increments. (For example, a control section with a 10 mi. length would result in 5 samples each 0.1 mi. in length).

Unlike the pavement images, the processed data is not sampled; instead, Microsoft Access queries are run to check for data inconsistencies. Electronic data checks include:

- Changes in *pavement type* from the previous year's survey.
- Changes in *pavement texture* from the previous year's survey.
- Sudden changes in *roughness* (major improvement/deterioration).
- Sudden changes in *rut depth* (major improvement/deterioration).
- High quantities of distress with low roughness values.
- High roughness values with low quantities of distress.
- A check for reasonableness of the maximum extent of distress.
- Review of all segments that are marked as a construction zone.
- Review of all segments that are marked as a lane deviation.
- Review all segments that are identified as a bridge, but the service provider data does not indicate a bridge location.
- Review control sections that are found to have a longer lengths than specified.
- Review control sections where the service provider did not collect the required 0.10 mi. lead in/lead out pavement length.
- Review pavement segments with incomplete data collection.

ROW images are checked by the Louisiana DOTD for clarity ensuring that there are minimal missed or skipped images proper lighting, and the correct stitching of pavement images

The data collection vehicle is checked daily for proper calibration, operation, and maintenance.

All calibration, operation, and maintenance efforts are performed in accordance with the manufacturer's recommendations, or as outlined in the standard operating procedures for the equipment.

Calibration, operation, and maintenance effort activities are documented in writing and submitted to the Louisiana DOTD.

Acceptance –The following items are checked by LaDOTD:

- Image clarity
- Image brightness/darkness

- Dry pavement—control section should not have any standing water during testing;
- Image replay—images should play sequentially and in the correct order.
- Missing images—there should be minimal or no missing images. Any control section that contains substitute images should be rejected.

The following items are checked by LaDOTD to ensure correct data collection:

- The beginning and ending of the control section are checked to ensure that the data collection vehicle started and ended at the correct location.

- The images for the first 0.10 mi. should be played and checked, while the distress images should be sampled throughout the entire control section.

- The lengths, as determined by the control section manual and the service provider, should coincide to be within less than 5 percent difference.

- Most control sections have a 0.10 mi. lead-in and lead-out. Only the ROW images are collected for the lead-in and lead-out.

NCHRP Synthesis #401, Quality Management of Pavement Condition Data Collection (from [4])

In summary, from the subject Synthesis report, and as evidenced by states described previously, typical Quality Management tools and methods used for quality control and acceptance are:

- Calibration/verification of equipment and methods before the data collection
- Testing of known control segments before data collection
- Testing of known control or verification segments during data collection, and
- Software routines for checking the reasonableness and completeness of the data.

Other promising quality management techniques that are not yet as commonly used include:

- Analysis of time-series data both at the project and network-level,
- Independent (quality control or acceptance) verification and validation of the pavement condition data by an independent quality auditor , and
- Use of blind site monitoring during the production quality acceptance process

A comprehensive *quality control plan* typically includes the following elements:

- Clear delineation of the responsibilities,
- Documented (and available) manuals and procedures,
- Training requirements for the survey personnel
- Equipment calibration and inspections procedures,
- Equipment and/or manual process verification procedures (e.g., testing of known control section) before starting production testing,
- Production quality verification procedures (e.g., testing of known or blind control sections during production testing), and
- Checks for data reasonableness and completeness.

Typical *quality acceptance* activities include:

- Establishing acceptance criteria (data accuracy and precision and reliability);
- Verification of the equipment/analysis criteria before data collection;
- Testing of known or blind (preferred) control or verification sites before and during data collection;
- Software data check for reasonableness, completeness, and consistency; and
- Time-series comparisons.

Other states likely to own, operate or contract FUGRO ARAN systems

The following states were contacted on September 9, 2017 via email. Most did not respond to the request for status information on Quality Management for data collection.

Pennsylvania DOT - PennDOT– Jason Vansickle – Contract ARAN

Arkansas DOT - ArDOT- Maxx Leach, Mark Evans – In-house ARAN

Maine DOT - Anne Carter – In-house ARAN

Missouri DOT - MoDOT– Brian Reagan – In-house ARAN

Vermont AOT - VTrans– Reid Kiniry - Contract

South Dakota DOT –SDDOT - Phil Clements – In-house

Iowa DOT – Matthew Haubrich- Contract

A couple of other states that may be using Fugro, who were not contacted are:

Michigan DOT – MDOT - Jason Redlinger – Contract ARAN

Oregon DOT - ODOT– John Coplantz – In-house and contract

References

[1] Linda M. Pierce, Ginger McGovern, and Kathryn A. Zimmerman. *Practical Guide for Quality Management of Pavement Condition Data Collection*. USDOT, FHWA, Washington D.C., February 2013.

[2] Quality Engineering Solutions, Inc. *Network-Level Pavement Condition Data Collection, Quality Management Plan*. Virginia Department of Transportation, Maintenance Division, Richmond VA, February 2015.

[3] Ghim Ping (Raymond) Ong, Samy Noureldin, and Kumares C. Sinha. *Automated Pavement Condition Data Collection Quality Control, Quality Assurance and Reliability – Final Report*. Report #FHWA/IN/JTRP-2009/17, Indiana Department of Transportation, Research, January 2010.

[4] Gerardo Flintsch, Kevin K. McGhee. *Synthesis Report 401, Quality Management of Pavement Condition Data Collection*. Transportation Research Board of the National Academies, Washington D. C., 2009.

[5] FUGRO. *ARAN 9000 Manual ver. 2.0- Fugro Roadware*. FUGRO, Mississauga, Ontario, Canada, November 2016.

[6] FUGRO. *ARAN 9000 Operation Guide ver. 2.2 – Fugro Roadware*, FUGRO, Mississauga, Ontario, Canada, February 2017.

Appendix C: Summary of Contents of Final CTDOT Data Quality Management Plan as Approved by FHWA CT Division on August 22, 2018

Section Title	Section Contents
Section 1 **Quality Management Approach**	Introduction and organization of the document.
Section 2 **Quality Team Roles, Responsibilities & Current Business Processes**	Quality-related roles and responsibilities and current business processes for data collection, data reduction, review, acceptance, and reporting for use in FHWA HPMS, CTDOT performance measures, and paving and preservation programs.
Section 3 **Certification for Persons Performing Manual Data Collection**	Processes used to certify and validate manual pavement condition raters and CTDOT's training procedures.
Section 4. **Equipment, Calibration, Certification or Validation Verification**	Detail and description of CTDOT's pavement data collection equipment processes and protocols used to calibrate, certify or validate and verify data collection equipment.
Section 5. **Quality Control (QC)**	The QC activities that monitor, provide feedback, and verify that the data collection deliverables meet the defined quality standards.
Section 6. **Deliverables, Protocols & Quality Standards**	The data collection deliverables subject to quality review, protocols used for collection, quality standards that are the measures used to determine a successful outcome for a deliverable, and criteria to describe when each deliverable is considered complete and correct. Deliverables are evaluated against these criteria before they are formally approved.
Section 7. **Data Acceptance Criteria and Error Resolution Procedures**	The acceptance testing used to determine if quality criteria are met and corrective actions that must be taken for any deliverables not meeting the quality criteria.
Section 8. **Quality Reporting Plan**	The documentation of all QM activities—including quality standards, QC, acceptance, and corrective actions—and the format of the final QM report.
Section 9. **DQMP Endorsement**	Signature page for endorsement of the CTDOT Data Quality Management Plan.