Improving FHWA's Ability to Assess Highway Infrastructure Health

Development of Next Generation Pavement Performance Measures

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16. Abstract

This study was conducted as part of the Federal Highway Administration (FHWA) Task Order "Improving FHWA's Ability to Assess Highway Infrastructure Health." This portion of the study had the objective of developing a next generation pavement performance measure that provides an accurate and repeatable assessment of the functional condition of the roadway. The measure is to combine ride quality, cracking, and rutting or faulting and rely entirely upon data from the Highway Performance Management System (HPMS) database.

Over the course of the study, the effort shifted away from a single composite index of ride quality, cracking, and rutting or faulting to using these distresses individually. This report provides recommendations for collecting, processing, reviewing, and storing each of these distresses. Further recommendations are made with regard to assessing pavement condition based upon the stored values.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 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)

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List of Acronyms

Acronym	Definition
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
AFM	Automated faulting module
COV	Coefficient of variation
CRCP	Continuously reinforced concrete pavement
DOT	Department of Transportation
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
HPMS	Highway Performance Management System
IHS	Interstate highway system
IRI	International Roughness Index
JPCP	Jointed plain concrete pavement
LCMS	Laser Crack Measurement System
LTPP	Long-Term Pavement Performance
MAP-21	Moving Ahead for Progress in the 21st Century legislation
MEPDG	Mechanistic-Empirical Pavement Design Guide
NCHRP	National Cooperative Highway Research Program
PCC	Portland cement concrete
PHT	Pavement Health Track
PMS	Pavement Management System
QC/QA	Quality control / quality assurance
TWG	Technical Working Group
VTI	Swedish National Road and Transport Research Institute

Executive Summary

During the pilot study conducted as part of the project, "Improving FHWA's Ability to Assess Highway Infrastructure Health," Interstate 90 through South Dakota, Minnesota, and Wisconsin was evaluated in order to 1) identify and validate approaches for categorizing bridge and pavement condition as good/fair/poor that potentially could be used for the Interstate Highway System (IHS) and subsequently the National Highway System (NHS) across the country, and 2) provide a proof of concept for a methodology to assess and communicate the overall health of a corridor with respect to bridges and pavements. The results of the pilot study are contained in Federal Highway Administration (FHWA) publication FHWA-HIF-12-049. (18) This report may be accessed at:

http://www.fhwa.dot.gov/asset/pubs/hif12049/hif12049.pdf.

The pilot study demonstrated that the good/fair/poor approach is not only feasible for pavements, but also implementable at this time using pavement roughness. Additionally, the use of the Highway Performance Monitoring System (HPMS) distresses plus structural capacity based on deflections was shown to be feasible, but additional work is required before they can be implemented.

Accordingly, continuation of the good / fair / poor development effort with a focus on pavement condition indicators including the HPMS distresses was highly recommended and the basis for the current study. As an example, the fact that a pavement provides a smooth ride quality does not imply that it is structurally adequate and vice-versa. This being the case, it is critical that pavement condition be considered from multiple angles, akin to a doctor's visit, in order to properly and accurately assess the condition of the pavement network and hence facilitate the decision making process. Thus, continuation of the good/fair/poor development process was considered meritorious and, as noted earlier, highly recommended.

The level of confidence associated with the various pavement condition measures evaluated within the context of good/fair/poor from the pilot study is summarized in table ES.1:

Table ES.1 Confidence Levels for Pavement Condition Measures Evaluated

Condition Indicator	Confidence in Data
IRI	High
Cracking %	Low/Med
Cracking Length	Low
Rutting	Medium
Faulting	Low

Based on the findings from the pilot study, the following was recommended, which led to the decision of developing the next generation pavement performance measure which is the basis for the study detailed in this report:

- Undertake a study geared towards the incorporation of additional selected distresses into the good/fair/poor indicator, such as cracking and rutting in asphalt concrete (AC) pavements and cracking and faulting in Portland cement concrete (PCC) pavements.

The objective of the effort detailed in this report is to describe the development of a next generation pavement performance measure, which will enable the FHWA to more accurately and consistently assess the functional condition of portions of, or the entire, national highway pavement system. Based on the stated project parameters, the measure is to consider ride quality and pavement surface distresses (cracking and rutting or faulting) and it is to be entirely driven by HPMS data. Consideration of pavement structural condition is highly desirable, but the technology needed to collect data for network level evaluation is not ready at present for incorporation into the measure.

The effort involved the development of a Technical Working Group (TWG) to serve as a sounding board for ideas from the project team and as messengers to others in the industry regarding the work performed for this study. Members of the TWG included Edgardo Block (Transportation Supervising Engineer, Connecticut Department of Transportation [DOT]), Judith Corley-Lay (State Pavement Management Engineer, North Carolina DOT), Colin Franco (Associate Chief Engineer, Rhode Island DOT), Ralph Haas (Norman W. McLeod Engineering Professor and Distinguished Professor Emeritus in the Department of Civil Engineering, University of Waterloo), Rick Miller (Pavement Management Engineer, Kansas DOT), Brian Schleppi (Infrastructure Management Supervisor, Ohio DOT), Roger Smith (Herbert D. Kelleher Chair Professor Associate Department Head for Operations, Texas A&M University), Katie Zimmerman (President, Applied Pavement Technology, Inc.), Thomas Van (Pavement Management Engineer, FHWA), and Nadarajah Sivaneswaran (Highway Research Engineer, FHWA).

The effort to combine ride quality, cracking, and rutting or faulting into a single index was shifted based on the input of the TWG and the remainder of the effort concentrated on the individual condition indicators and in particular on the data requirements for each measure. For each pavement condition measure, the data requirements considered the following elements:

- Data collection.
- Data processing.
- Data QC/QA.
- Data storage.
- Condition rating.

Data collection covers the specific elements to be collected, the specifications of the equipment recommended to collect the data, the temporal and spatial recommendations for data collection, and the speed of data collection. Data processing identifies the specific tools used for processing the data and the recommendations associated with the algorithms for calculation. Equipment validation, calibration, and check recommendations performed as part of data collection are covered under data QC/QA. This section also covers the checks to be performed on the collected data. Data storage identifies what data should be stored in association with each condition indicator along with the summary interval over which the data is to be stored. The condition rating identifies the method for evaluating the pavement condition based on the stored data.

The data recommendations, which incorporate the input provided by the TWG, are summarized below. The overarching goal of these data recommendations is to lead to a complete and high-quality determination of pavement condition using data from the HPMS database, which in turn will lead to more accurate and consistent assessments of the functional condition of portions of or the entire national highway pavement system.

The condition ratings identified for each distress below were reviewed as part of a field validation effort that took place on May 7 through 9, 2013 along a portion of the Interstate 90 corridor in Minnesota. This section provided the widest variety of distress in the shortest distance. Each distress was reviewed separately with the review of cracking occurring on May 7th, rutting and faulting on May 8th, and ride quality on May 9th. The field validation included three members of the TWG (Colin Franco, Rick Miller, and Roger Smith), two participants from the FHWA (Robert Orthmeyer and Thomas Van) and one participant from the project team (Gonzalo Rada).

RUTTING DATA

The recommendations for collection, processing, reviewing, storing and evaluating rutting data are as follows:

- Data collection should cover a minimum width of 13 feet (3.96 meters).
- Data points within the profile should have a separation less than or equal to 0.4 inch (10 millimeters).
- The maximum longitudinal spacing between profiles should be 10 feet (3.05 meters).
- A 2-inch (51-millimeter) moving average filter should be applied to the transverse profile.
- The wireline method is recommended as the basis for the rut depth computation.

- The imaginary gage used to measure the depth to the pavement surface from the reference wireline should have a width of 1.2 to 1.5 inches (30 to 38 millimeters) is recommended for use in calculating the rut depth.
- The system validation should include a review of each component of the equipment as well as the operational aspects associated with typical data collection.
- Monthly checks should be conducted of the components throughout the data collection cycle.
- The processed rut depths should be reviewed for consistency in terms of both space and time.
- The data elements to be stored in the HPMS database associated with rut depth should include the average, minimum, maximum, and standard deviation rut depth and the cross-slope.
- The rut depth statistics should be stored at a base length of 0.1 mile (0.16 kilometer).
- The metadata for rut depth should include the items currently stored in the HPMS database along with the full transverse profile.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing.
- Rutting should be considered as an indicator of pavement condition as follows, which is based on the Mechanistic-Empirical Pavement Design Guide (MEPDG) and Pavement Health Track (PHT) tool threshold values (44, 45):
    - Good: Rut < 0.25 inch (6 millimeters).
    - Fair: 0.25 inch (6 millimeters) ≤ Rut ≤ 0.4 inch (10 millimeters).
    - Poor: Rut > 0.4 inch (10 millimeters).
- The field validation confirmed the appropriateness of the threshold between good and fair. The poor segments selected to be reviewed as part of the field validation appeared to have undergone a mill and fill repair since the measured rut depth data were obtained making it impossible to review the threshold between fair and poor.

RIDE QUALITY DATA

The recommendations for collection, processing, reviewing, storing, and evaluating ride quality data are as follows:

- The data collection interval should be 2 inches (51 millimeters) or less on asphalt concrete and 0.75 inch (19 millimeters) or less on Portland cement concrete.
- The height sensor should have a footprint with a width of 2.75 inches (70 millimeters).
- Ideally, the ride quality data collection would occur at the same time of day and time of year each time it is collected to minimize the impact of diurnal and seasonal variations.
- The full extent of the system, including bridges and pavement changes, is recommended for inclusion in the IRI calculation.
- The system validation should include a review of each component of the system, the system as a whole, the operator, and the operational aspects associated with data collection.
- Daily checks should be performed of the equipment during data collection.
- The processed data should be reviewed for variation both spatially and temporally.
- The IRI should be calculated and stored at a base length of 0.1 mile (0.16 kilometer).
- The date and time of data collection should be stored with the IRI for appropriate interpretation of these data.
- The metadata for the IRI should include those items already stored as well as the full longitudinal profile.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing.
- The recommended method for evaluating pavement ride quality condition based on IRI as established by FHWA is (41):
  - Good: IRI < 95 inches/mile (1.50 meters/kilometer).
  - Fair: 95 inches/mile (1.50 meters/kilometer) ≤ IRI ≤ 170 inches/mile (2.68 meters/kilometer).
  - Poor: IRI > 170 inches/mile (2.68 meters/kilometer).
- The field validation confirmed the threshold level between good and fair. No firm conclusions could be drawn regarding the threshold level between fair and poor.

FAULTING DATA

The recommendations for collecting, processing, reviewing, storing, and evaluating faulting data are as follows:

- The inertial profiler should be used for data collection and the equipment should be set to collect and store an elevation measurement every 0.75 inch (19 millimeters).
- Ideally, data will be collected at the same time of day and time of year.
- Additional research is required to ascertain a better understanding of the impact of changes in curling on faulting measurements.
- ProVAL version 3.3 (or later version) is recommended for calculation of faulting from the longitudinal profile data.
- ProVAL provides three joint detection methods within the module. The appropriate method for each agency should be reviewed to identify the most appropriate method(s) for use with their pavements.
- Both joints and cracks should be analyzed and reviewed for faulting on jointed concrete pavements; although additional research is needed to improve detection of cracks with faulting from the longitudinal profile data using automated methods.
- The system validation should include a review of each component of the system, the system as a whole, the operator, and operational aspects associated with typical data collection.
- AASHTO R57-10 provides specifications for daily checks to be performed of the equipment during data collection. These checks include checks of tire pressure, block check of height sensor, and a bounce test. A log should be maintained of these checks as a means to review the ongoing condition of the equipment.
- The data should be reviewed for variability over time and space.
- In order to be consistent with the recommendations for rutting and ride quality, the faulting data should be summarized to a 0.1-mile (0.16-kilometer) interval length.
- Data elements to store in the HPMS database should include:
  + Average faulting at 0.1-mile (0.16-kilometer) intervals.
  + Minimum fault, maximum fault, and standard deviation of faulting over the 0.1-mile (0.16-kilometer) interval.
  + Joint detection method.
  + Number of detected cracks and joints.
  + Joint spacing.

  + Date and time of data collection.

- The HPMS metadata includes the reporting interval, the method of data collection, and the type of equipment used for data collection. The full longitudinal profile collected at 0.75-inch (19-millimeter) intervals should be stored for future use as improvements are made in data processing capabilities.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing.
- Faulting should be considered as an indicator of pavement condition as follows, which is based on MEDPG and PHT threshold values (44, 45):
  + Good: Fault < 0.1 inch (3 millimeters).
  + Fair: 0.1 inch (3 millimeters) ≤ Fault ≤ 0.15 inch (4 millimeters).
  + Poor: Fault > 0.15 inch (4 millimeters).
- Based upon the field validation, the threshold values appear to be too strict. However, insufficient data were available to determine the appropriate levels for these thresholds and additional research will be required to set the thresholds.

CRACKING DATA

The recommendations for collecting, processing, reviewing, storing, and evaluating cracking data are as follows:

- An automated method for collection and processing of cracking is recommended for use in collecting cracking data.
- The HPMS data collection approach is recommended to include the percentage of cracking in the wheelpath and relative length of transverse cracking on asphalt surfaced pavements and the percentage of cracked slabs on jointed concrete pavements or percentage of punchouts on continuously reinforced concrete pavements. As noted in the HPMS manual, this includes both sealed and unsealed cracks.
- A 100 percent sampling rate for fully automated collection and processing is recommended to reduce the likelihood that outlier areas of condition will be missed in the evaluation.
- The base length for summarization of these data should be set to 0.1 mile (0.16 kilometer).
- The first step in quality control is system validation which should include a comparison of data collected by the equipment with those from a rating panel consisting of at least three members.

- The system validation should include a review of the equipment under varying operational aspects that may be expected as part of data collection.
- During data collection, checks should be performed of each component of the equipment to ensure their continued function.
- A minimum of 5 percent of the images should be manually checked for systematic errors in the data collection and processing with larger percentages being reviewed should systematic errors be identified.
- The metadata for the cracking should include those items already stored as well as the images collected. The current metadata for the HPMS database include the type of equipment used for collection of data and the method used to identify the pavement distresses.
- The images should be stored to allow for any required detailed review of the data.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing.
- Cracking should be considered as an indicator of pavement condition as follows:
  + PCC % Cracking (% of cracked slabs on jointed PCC or % of punchouts on CRCP)
    - Good: % Cracking ≤ 5.
    - Fair: 5 < % Cracking ≤ 10.
    - Poor: % Cracking > 10.
  + AC % Cracking
    - Good: % Cracking ≤ 5.
    - Fair: 5 < % Cracking ≤ 20.
    - Poor: % Cracking > 20.
  + AC Crack Length
    - Good: Length ≤ 265 feet/mile (50 meters/kilometer).
    - Fair: 265 feet/mile (50 meters/kilometer) < Length ≤ 1060 feet/mile (200 meters/kilometer).
    - Poor: Length > 1060 feet/mile (200 meters/kilometer).
- The field validation effort was unable to validate the thresholds associated with cracking. The angle of the sun with relation to the direction of travel along with the minimal cracking presence and low severity cracking on the validation segments made cracking difficult to observe. Additional work will be required to evaluate these cracking thresholds.

ADDITIONAL RESEARCH

The following items are recommended for future research to improve current capabilities in data collection and processing:

- Additional research is required to define appropriate thresholds of good / fair / poor with respect to a combination of rutting, cross-slope and speed of a facility that delineate safety considerations.
- Additional research is required to ascertain a better understanding of the impact of changes in curling on faulting measurements.
- Additional research is needed to improve the overall faulting measurement. In particular, the detection of joints and cracks which have little to no faulting within the longitudinal profile data using automated methods is nearly impossible. Potentially, the longitudinal profile data could be married to the cracking imagery to assist in identifying the cracks and joints within each segment.
- Additional research needs to be undertaken to review the threshold levels associated with evaluating condition based on faulting. The field validation identified that the threshold values are probably too strict, but based on the results of that effort, definitive levels could not be identified.
- Additional work is required to review the threshold levels associated with evaluating condition based on cracking. The field validation efforts related to cracking were inconclusive due to the difficulty of rating the distress and the general lack of cracking on the pavement reviewed.
- Additional consideration needs to be given to sealed cracks and length of ruts. These items are not currently considered by the HPMS guidelines.

1.0 Introduction

During the pilot study conducted as part of the project, "Improving FHWA's Ability to Assess Highway Infrastructure Health," Interstate 90 (I90) through South Dakota, Minnesota, and Wisconsin was evaluated in order to 1) identify and validate approaches for categorizing bridge and pavement condition as good/fair/poor that potentially could be used along the Interstate Highway System (IHS) and subsequently the National Highway System (NHS) across the country, and 2) provide a proof of concept for a methodology to assess and communicate the overall health of a corridor with respect to bridges and pavements. The results of the pilot study are contained in Federal Highway Administration (FHWA) publication FHWA-HIF-12-049. (18) This report may be accessed at:

http://www.fhwa.dot.gov/asset/pubs/hif12049/hif12049.pdf.

The pilot study demonstrated that the good/fair/poor approach is not only feasible for pavements, but also implementable at this time using pavement roughness. Additionally, the use of the Highway Performance Monitoring System (HPMS) distresses plus structural capacity based on deflections was shown to be feasible, but additional work is required before they can be implemented. It should be noted that other distress systems besides the HPMS were not considered for this study; although, these other methods for evaluating condition may provide a similar or more representative picture of condition.

Accordingly, continuation of the good / fair / poor development effort with a focus on pavement condition indicators including the HPMS distresses was highly recommended and the basis for the current study. As an example, the fact that a pavement provides a smooth ride quality does not imply that it is structurally adequate and vice-versa. This being the case, it is critical that pavement condition be considered from multiple angles, akin to a doctor's visit, in order to properly and accurately assess the condition of the pavement network and hence facilitate the decision making process. Thus, continuation of the good/fair/poor development process was considered meritorious and, as noted earlier, highly recommended.

The conclusions and recommended next step from the pilot study that help build the foundation for the current study include:

- The level of confidence associated with the various pavement condition measures evaluated within the context of good/fair/poor from the pilot study is summarized in table 1.1 as well as below:
  - There is a high-level of confidence with IRI given the acceptable correlation found in the study between the HPMS, State Department of Transportation (DOT) Pavement Management Systems (PMS) and field data sources.

- A medium-level of confidence exists for the rut depth data and additional investigation is required to resolve the bias issue between the HPMS or State DOT PMS data and the field data.
- For the remaining condition measures (cracking percentage, cracking length and faulting), additional work is required to standardize data collection and processing at the national level.

Table 1.1 Confidence Levels for Pavement Condition Measures Evaluated

Condition Indicator	Confidence in Data
IRI	High
Cracking %	Low/Med
Cracking Length	Low
Rutting	Medium
Faulting	Low

- Because of the high-level of confidence, pavement roughness in terms of IRI is feasible and the recommended measure for use as an initial good/fair/poor indicator. When used, the indicator should specifically mention this is ride quality condition, and not pavement condition.
- Because IRI does not provide a complete picture of pavement condition, other measures were considered in addition to or in combination with IRI, including selected distresses, structural capacity and remaining service life. However, given the level of confidence associated with these other pavement condition measures, significant work is required before they can be implemented.
  - Rutting data is important as an indicator of safety concerns as well as to the good/fair/poor indicator. However the rutting algorithm should be codified so that it can be applied consistently across the State DOTs. Based on this conclusion, an addendum to "Improving FHWA's Ability to Assess Highway Infrastructure Health Pilot Study Report" was issued titled "Improving FHWA's Ability to Assess Highway Infrastructure Health Pilot Study Report Addendum Rutting Bias Investigation." The addendum documents the investigation of the rutting bias between field data and the HPMS data observed in the pilot study. Based on the results of this investigation, rutting data requirements such as maximum longitudinal spacing, minimum number of points collected to characterize the transverse profile, gage width, and rutting algorithms were recommended which are further addressed in chapter 3.0.
  - Cracking data on asphalt concrete (AC) and Portland cement concrete (PCC) pavements and faulting data on PCC pavements cannot be used at present as inputs to a good/fair/poor indicator. Much investigation and standardization is required before they can be incorporated into the good/fair/poor indicator with a high-level of confidence.

+ Like cracking and faulting, pavement structural capacity using the RWD or other continuous deflection devices requires much work (both from a technology perspective and through some agreement within the pavement engineering community on appropriate condition thresholds) before this measure can be incorporated into a good/fair/poor indicator.
+ Given the need for consistent, high-quality data at the National level, use of the HPMS data set to drive the good/fair/poor indicator and possible associated flags is considered the best option at present and in the near future. However, this does not imply that improvements to the HPMS data are not possible and/or required. Using State DOT PMS data does not seem feasible at this time due to the differences between States. Collecting field data on the entire Interstate system likewise does not appear economically justified at this time.

Based on the above findings, a recommendation was made to undertake a study geared towards the incorporation of additional selected distresses into the good/fair/poor indicator, such as cracking and rutting in AC pavements and cracking and faulting in PCC pavements which led to the decision of developing the next generation pavement performance measure which is the basis for the study detailed in this report.

The objective of the effort detailed in this report is to describe the development of a next generation pavement performance measure, which will enable the FHWA to more accurately and consistently assess the functional condition of portions of, or the entire, national highway pavement system. Based on the stated project parameters, the measure is to consider ride quality and pavement surface distresses (cracking and rutting or faulting) and it is to be entirely driven by HPMS data. Consideration of pavement structural condition is highly desirable, but the technology needed to collect data for network level evaluation is not ready at present for incorporation into the measure.

After work on the project was initiated, the focus of the effort shifted from a single composite index to using each of the distresses individually. The individual distresses provide very different information about the condition of the pavement section. For example, ride quality does not provide any information about the structural performance of the section; however, it provides a great deal of information about how a user feels about the pavement condition.

The benefit of using the individual distresses is that they provide a clearer picture of the pavement condition with an understanding that the pavement may be sufficient structurally, but have a functional problem that should be corrected or that the pavement is sufficient functionally, but requires a structural repair.

Structure of this Report

The remainder of this report focuses on stakeholder involvement and the resulting data requirements.

- Chapter 2 describes the stakeholder involvement.
- Chapter 3 describes the field validation effort to evaluate the thresholds associated with each distress.
- Chapter 4 describes the rutting data recommendations.
- Chapter 5 presents the ride quality data recommendations.
- Chapter 6 presents the faulting data recommendations.
- Chapter 7 describes the cracking data recommendations.
- Chapter 8 documents the final recommendations.

2.0 Stakeholder Involvement

Towards accomplishment of the stated project objective, a Technical Working Group (TWG) was formed to provide technical review and input as the effort progressed, provide stakeholder perspective, act as a "sounding board," and serve as "messengers" to industry on the results of this project. Members of the TWG included Edgardo Block (Transportation Supervising Engineer, Connecticut DOT), Judith Corley-Lay (State Pavement Management Engineer, North Carolina DOT), Colin Franco (Associate Chief Engineer, Rhode Island DOT), Ralph Haas (Norman W. McLeod Engineering Professor and Distinguished Professor Emeritus in the Department of Civil Engineering, University of Waterloo), Rick Miller (Pavement Management Engineer, Kansas DOT), Brian Schleppi (Infrastructure Management Supervisor, Ohio DOT), Roger Smith (Herbert D. Kelleher Chair Professor Associate Department Head for Operations, Texas A&M University), Katie Zimmerman (President, Applied Pavement Technology, Inc.), Thomas Van (Pavement Management Engineer, FHWA), and Nadarajah Sivaneswaran (Highway Research Engineer, FHWA).

The first TWG meeting was held on August 23, 2012 via webinar. During this initial meeting, the TWG was provided with an overview of the "Improving FHWA's Ability to Assess Highway Infrastructure Health" study that led to the decision of developing the next generation pavement performance measure. The referenced study began in October 2010 in anticipation of the next authorization having a performance management focus. The Moving Ahead for Progress in the 21st Century (MAP-21) legislation passed in July 2012 confirmed the increased emphasis and importance of the proposed measure. Moreover, development of the measure was to build from and complement the work already completed by AASHTO.

The scope of work and approach to development of the next generation pavement performance measure was also discussed during the initial TWG webinar. Highlights of the input provided by the TWG members are presented below:

- Prior to actual development of the measure, it is imperative that the audience and objective(s) of the functional composite index be clearly established. Other items to consider in relation to audience and objective(s) included the definition of index levels:
  - + Pavement ride quality is primarily intended for roadway users.
  - + Pavement distresses are geared for treatment, intervention and planning activities.
  - + Pavement deflection is intended for project/engineering level planning activities.

- It was suggested that the performance measure should contain the following pavement condition indicators:
  - + Ride quality (IRI).
  - + Pavement distresses.
- Consideration should also be given to separating pavement distresses into structural versus non-structural related distresses.
- IRI data should be submitted to FHWA in 0.1-mile (0.16-kilometer) increments and the segmenting performed at FHWA. Also, reporting of IRI data for speeds less than 40 miles-per-hour (64 kilometers/hour) should be considered for deletion due to issues with IRI at lower speeds. In general, collection of IRI in urban areas is a problem that should be addressed.
- In development of the individual and composite indices, careful consideration must be given to the data collection and processing protocols associated with the generation of the HPMS data, which are to drive the measure. Items to consider include temporal (frequency, time of year, etc.) and spatial (longitudinal as well as transverse, as appropriate) issues. Consideration should also be given to the ability of the State DOTs to collect the proposed data; e.g., will they be able to purchase the necessary equipment. Similarly, protocols for collection should address accuracy, precision, and resolution (data collection spacing and averaging intervals).
- It is also important that quality control/quality assurance (QC/QA) of the data used to populate the HPMS database be addressed, as these data will be used to drive the measure.

Minutes of the initial TWG meeting are contained in appendix A. Subsequent to the meeting and taking into consideration the input provide by the TWG members, the project team prepared a detailed work plan for development of the next generation pavement performance measure. This work plan considered the findings from the "Improving FHWA's Ability to Assess Highway Infrastructure Health: Pilot Study Report" along with the results of a literature review conducted by the project team on pavement performance measures and the input provided by the TWG during the initial meeting; the work plan is provided in appendix B and it includes the literature review as an attachment. The work plan consisted of the following five tasks:

1. Definition of data recommendations – these data recommendations were intended to lead to a complete and high-quality determination of pavement condition using data from the HPMS database.
2. Identification of individual condition indices – these indices included IRI, cracking and rutting or faulting.
3. Development of next generation pavement performance measure – this functional composite index was to be based on the individual condition indices.

4. Calibration and validation of new pavement performance measure – this was to be accomplished through a ground-truth exercise.
5. Preparation of report and implementation recommendations.

In the work plan the following definitions were also provided relating to the development of the measure:

> ***Audience***: The next generation pavement performance measure is being developed for and is intended solely for the use of the FHWA. However, it is anticipated that other highway agencies may have an interest in reviewing and considering the resulting measure for their own purposes.
>
> ***Objective***: The purpose of the next generation pavement performance measure is to enable the FHWA to more accurately and consistently assess the condition of portions (one or more States, corridors, etc.) or the entire national highway pavement system. The measure is to include not only ride quality, which is especially important from a users' viewpoint, but because ride quality does not necessarily provide a clear picture of pavement condition, it is to include pavement surface distresses (cracking and rutting or faulting).(18) Although pavement structural condition would be highly desirable, the technology is not ready at present for incorporation into the proposed measure.(18)

The detailed work plan for development of the next generation pavement performance measure was presented to the TWG on November 15, 2012 via webinar. Highlights of the input provided by the TWG members concerning the Task 1 data requirements are provided below:

- The value used to quantify the average rut depth should take into consideration the length of the segment. For short segments, the average value may be sufficient; however, for longer segments a measure of variability, such as standard deviation or percentiles should be considered to give a better representation of the segment.
- State DOTs are fiscally in bad shape. States have just finished implementing the HPMS reassessment and are not going to be enthusiastic about new changes, such as requiring 400 points in transverse profiles. This would require new equipment to be purchased by many States. If the next generation performance measure is intended solely for FHWA, States would have to endure a lot of change without seeing the benefit.
- The project team should assess the need for more detailed consistent data. Is the benefit from more detailed consistent data justified for what the data is being used for?
- Although there are many States using sophisticated technology, there are others using windshield surveys for network level data collection. For rutting data, many States are currently using five sensors for collection of transverse profile, which is quite far from the 400 points suggested. Although

the States may be able to close the gap between the current and suggested sensor configuration, they need to be shown the benefit of the investment.

- MAP-21 requires moving to performance-based measures. The goal would be to have States collect data uniformly so that the condition measures are uniform. This will need to be a long term commitment and an incremental process.
- Consideration needs to be given to the difference between what FHWA wants to use the collected data for (condition measure) and what States use the collected data for (treatment selection, etc.).
- Fully automated cracking surveys are still 5 to 10 years out technology wise, but there needs to be a focused initiative now.
- It was suggested to show the implications of the changes in data collection.

The input provided by the TWG members concerning the Task 2 individual condition indices and Task 3 next generation performance measure is summarized below:

- A possible drawback to a composite index is that the same score can reflect two (or more) pavements with very different conditions.
- The intended use of the proposed indices/composite index is important. If it is to simply be used as a reporting tool for Congress, a composite index may be sufficient, but individual indices can also provide useful information as a composite index can mask certain issues.
- Different distresses are used to indicate different concerns, such as safety (rutting), ride (IRI), or to manage programs and treatments (cracking). Different States have different concerns when it comes to distresses experienced.

The minutes of the second TWG webinar are contained in appendix C, and they include the input provided by the TWG members on the remaining tasks.

As a result of the second TWG webinar and after discussions with the FHWA, the focus was shifted from development of a composite functional index to instead on the separate, individual pavement condition measures (ride quality, rutting or faulting, and cracking) and in particular on the data recommendations for each measure. For each pavement condition measure, the data recommendations considered the following elements:

- Data collection.
- Data processing.
- Data QC/QA.
- Data storage.
- Condition rating.

Data collection covers the specific elements to be collected, the specifications of the equipment required to collect the data, the temporal and spatial recommendations of data collection, and the speed of data collection. Data processing identifies the specific tools used for processing the data and the recommendations associated with the algorithms for calculation. Equipment validation, calibration, and check requirements performed as part of data collection are covered under data QC/QA. This section also covers the checks to be performed on the collected data. Data storage identifies what data should be stored in association with each condition indicator along with the summary interval over which the data is to be stored. The condition rating identifies the method for evaluating the pavement condition based on the stored data.

The project team began working on the data recommendations in December 2012, and presented the drafts results to the TWG in February and March 2013 via webinar. The rutting and ride quality data recommendations were presented and discussed on February 21, 2013 via the third TWG webinar, while the faulting and cracking data requirements were presented and discussed on March 13, 2013 via the fourth TWG webinar. Highlights of the input provided by the TWG members during the third webinar are presented below:

Rutting:

- The purpose of this measure and data recommendations is for a national perspective, not selecting a treatment. Therefore, using larger base lengths for a national perspective is expected although as the base length gets larger, the usefulness of the data diminishes regarding identification of areas of both good and poor condition.
- Rutting poses a safety issue, which is important at the national level and therefore it cannot be averaged similar to IRI. At what point does it become a meaningful indication for national reporting? In addition to reporting the average, consider using standard deviation as well or another measure of variability to help indicate a safety issue.
- Good/fair/poor rutting condition is affected by travel speed and cross slope (and ability of ruts to hold water). It was suggested to look into these factors as part of the thresholds.

Ride:

- The recommendation for data to be collected in the same season each year is desirable. However, it is not likely that this ideal consistency can be delivered by the States due to practical considerations such as equipment availability issues, collection efficiency, etc. Although there can be a significant difference in IRI between seasons for JPCP, on a national scale how meaningful is this slight improvement in data quality?
- Ride quality can vary depending on functional class. One approach may be to maintain the same threshold values regardless of functional class, but have different target values for different functional classes.

Highlights of the input provided by the TWG members during the fourth webinar are presented below:

Faulting:

- One TWG member confirmed most of the ProVAL findings as presented by the project team with the exception that ProVAL does not perform well at detecting joints for pavements without faulting. This brought up for consideration how to find joints in those cases where there is no curling, warping, or drop-off, etc.
- It was recommended that mid-panel cracks should be incorporated in the review. These cracks often exhibit more faulting than the joints. However, using the auto-detection function in ProVAL, the nominal joint spacing is entered and the joint window used as the variation in location from the nominal joint spacing units are inches and even if the window is widened, it does not perform well at identifying those mid-panel cracks. It was suggested that there is still improvement needed in automated joint detection.

Cracking (Data collection):

- The presentation prompted discussion regarding the coefficient of variation (COV) for automated cracking data collection, which has not been documented. Automated data collection still presents variability based on the interpretation software, images, placement of vehicle on repeat runs, etc. Nonetheless, several of the participants felt that the COV of the automated data collection should be less than that for manual data collection.
- It was suggested to keep in perspective what the collected data are going to be used for (i.e. States PMS or as a condition measure). Although it would be beneficial if the data collected could also be used for State PMS, this is unlikely as different States have different needs.
- It was highlighted that this project was initiated to determine the health of the interstate highway system (IHS) using data currently available (i.e. HPMS data). The purpose now is to identify issues with HPMS data and make recommendations to address those issues in the case reporting any of these indicators becomes a recommendation. Although this might not help the States in terms of their PMS, the States will benefit from this effort and be prepared to comply with such recommendations.
- Several members expressed concern over the amount of QC/QA that would be performed on fully automated data collection if the data were only used for the national reporting or condition measures and not in the States' PMS.
- Concern over the use of HPMS data was also expressed, as it appears those responsible for the HPMS database are resistant to change because they want to enable development of a comparative data set. Therefore, advancements under AASHTO cracking standards will need to give consideration to the collection of cracking data for the HPMS database.

Cracking (Processing and QC/QA):

- Clarification was provided by the project team on the type of validation system to use, such as the Long-Term Pavement Performance (LTPP) program Falling Weight Deflectometer (FWD) calibration sites. It was suggested that cracking maps containing detailed information such as location, type, width, etc. be used. Concern was expressed regarding having to travel long distances to calibration sites with expensive equipment.
- The use of repeat runs was recommended in order to determine the COV for automated distress surveys. The repeat runs could be performed in conjunction with the validation runs in order to characterize the expected variability. The repeat runs should consist of a minimum of three, but that may not be adequate. The current profile standard is 10 repeat runs. It was also noted that the COV will be different for different automated equipment vendors as each uses different processing methods. However, it was also noted that repeat runs become expensive and hinder production rates, so there needs to be a balance between QC/QA and production.
- Another member of the TWG noted that Applied Pavement Technology developed QC/QA recommendations for automated data collection. The report with the QC/QA recommendations has been submitted to FHWA for review. It was suggested that FHWA be contacted to obtain a copy of the report in support of this effort.

The minutes to the third and fourth webinars are provided in appendices D and E, respectively.

The fifth TWG meeting was a teleconference held on May 13, 2013. The purpose of this teleconference was to discuss the field validation effort and comments of the TWG members on the final report. Highlights of input by the TWG members are as follows:

- The recommendation for a length on the sensor footprint for collection of longitudinal profile data should be removed. The footprint should have a specified width but not a length as the lasers in use collect tens of thousands of data points within a second.
- Other approaches to collection of distress data, particularly cracking, may provide a similar or more representative picture of condition than the HPMS approach. However, one of the requirements established for this project was to use HPMS data.
- The recommendation for 100 percent sampling of cracking should be codified to note that this recommendation is more for those who use fully automated collection and interpretation. Collection of a 100 percent sample using manual or semi-manual techniques is too onerous a process for the benefit of collection 100 percent of the condition.

- Additional consideration needs to be given to sealed cracks and length of ruts. These items are not currently considered by the HPMS guidelines.

The minutes for the final teleconference are provided in Appendix F to this report. The five TWG meetings are summarized in Table 2.1, including meeting date, topic addressed and appendix where the associated minutes are contained.

Table 2.1 Summary of TWG Meetings

TWG Meeting	Meeting Date	Topics Addressed	Related Appendix
1	August 23, 2012	Introduction	A
2	November 15, 2012	Work Plan	B and C
3	February 21, 2013	Rutting and Ride Quality	D
4	March 13, 2013	Faulting and Cracking	E
5	May 13, 2013	Field Validation and Final Report	F

The resulting data recommendations are presented over the remainder of this report, and they incorporate the input provided by the TWG during the five webinars. It is recognized that the data recommendations identified in this report may be a significant challenge to State DOTs. These challenges will result from the need to purchase expensive equipment associated with the data collection requirements or to upgrade existing equipment and/or data processing protocols to obtain the data as specified. However, the overarching goal of these data recommendations is to obtain a complete and high-quality determination of pavement condition using data from the HPMS database, which in turn will lead to the following:

- More accurate and consistent assessments of the functional condition of portions of or the entire national highway pavement system, and
- Improvements in the ability to assess the financial needs of the NHS on a consistent basis.

Moreover, implementing the recommended improvements in the HPMS data collection will lead to improvements in the collection and processing of pavement management data, as there is usually some “spill over” in data quality between these two data sets.

3.0 Field Validation

As part of the study, a field validation effort was conducted along a portion of the Interstate 90 pilot study corridor in Minnesota. The objective of this effort was to calibrate and validate the condition rating system identified within this report.

The panel performing the field validation effort included FHWA staff, members of the TWG, and a member of the project team. The team included Thomas Van (Pavement Management Engineer) and Robert Orthmeyer (Senior Pavement Engineer) from the FHWA; Colin Franco (Associate Chief Engineer, Rhode Island DOT), Rick Miller (Pavement Management Engineer, Kansas DOT), and Roger Smith (Herbert D. Kelleher Chair Professor Associate Department Head for Operations, Texas A&M University) from the TWG; and Gonzalo Rada (Senior Principal Engineer, AMEC Environment & Infrastructure, Inc.) from the project team.

The field validation needed to be conducted in a location that is both manageable, convenient to those attending, and not require additional data collection. Accordingly, the pilot study corridor identified in Chapter 1 was selected for the field validation effort due to the availability of existing data, project team familiarity with the corridor, and the willingness of the State DOTs along the corridor to support this study.

Data collection along this corridor was fairly comprehensive for this study. Data sets from the HPMS database were obtained from the FHWA for the 2009 and 2010 data collection cycles. These data were in the HPMS 2010+ data format. The States provided information from the pavement management system documenting inventory of the segments along the corridor, pavement condition, linear referencing system, and any available documentation on their pavement condition and pavement management system. Additionally, data were collected for the project including roughness, rutting, faulting, and cracking in HPMS 2010+ format along with right-of-way images and pavement surface images.(18)

Due to the availability of these data to the project team, the pilot study corridor was the starting point for selection of the area to be used for the field validation. This 874-mile corridor needed to be narrowed down to a manageable length for use in the field validation effort. Based on the observed condition variability and travel convenience, the field validation site was limited to the area between mileposts 15 and 230 in the eastbound direction of Interstate 90 in Minnesota.

As noted in Chapter 2, the focus of the study shifted from a single composite index to reviewing condition in terms of the individual distresses. Therefore, the field validation was conducted reviewing each distress separately. Specific segments were selected for each distress representing the range of conditions for that distress. The segments were also selected such that there was variation in the other distresses present to account for the impact these distresses might have in the assessment of the condition for a specific distress. For example, does the presence of rutting impact the rating of cracking within an asphalt-surfaced section. Tables 3.1, 3.2, 3.3, and 3.4 present the segments looked at with respect to ride quality, cracking, rutting, and faulting, respectively.

Table 3.1 Segments reviewed with respect to ride quality

Milepost		Surface	IRI, inches / mile	Rut, inches	Fault, inches	% Cracking	Crack Length, feet / mile
Begin	End						
16.2	16.3	PCC	180		0.132	6	
18.1	18.2	PCC	172		0.177	0	
18.5	18.6	PCC	174		0.158	11	
19.9	20.0	PCC	110		0.150	0	
20.2	20.3	PCC	102		0.000	0	
21.6	21.7	AC	64	0.08		0	90
25.3	25.4	AC	57	0.08		1	0
26.3	26.4	AC	100	0.07		0	0
32.2	32.3	AC	53	0.06		0	650
41.6	41.7	AC	53	0.09		0	70
69.9	70.0	AC	107	0.50		0	670
72.3	72.4	AC	108	0.50		0	400
73.9	74.0	AC	196	0.34		0	500
81.0	81.1	AC	54	0.25		0	740
83.0	83.1	AC	98	0.26		0	680
85.7	85.8	AC	114	0.26		0	420
103.9	104.0	AC	101	0.07		0	0
108.3	108.4	AC	110	0.27		0	110
112.0	112.1	AC	100	0.26		0	0
114.2	114.3	AC	58	0.28		0	0
118.3	118.4	AC	111	0.06		0	100
124.0	124.1	AC	56	0.04		0	50
128.8	128.9	AC	47	0.04		0	70

Milepost		Surface	IRI, inches / mile	Rut, inches	Fault, inches	% Cracking	Crack Length, feet / mile
Begin	End						
129.8	129.9	AC	51	0.04		0	340
134.9	135.0	AC	59	0.04		0	0
140.8	140.9	PCC	176		0.159	82	
148.4	148.5	PCC	61		0.000	0	
158.0	158.1	PCC	53		0.000	6	
160.5	160.6	PCC	52		0.000	0	
162.2	162.3	PCC	54		0.169	0	
165.7	165.8	PCC	99		0.000	0	
193.2	193.3	PCC	51		0.000	11	
193.4	193.5	PCC	58		0.154	11	
194.3	194.4	PCC	120		0.183	11	
211.7	211.8	PCC	106		0.156	6	
213.0	213.1	PCC	96		0.000	6	
216.2	216.3	PCC	62		0.157	6	
216.4	216.5	PCC	101		0.000	0	
224.8	224.9	PCC	51		0.000	0	
226.2	226.3	PCC	56		0.154	0	

Table 3.2 Segments reviewed with respect to cracking

Milepost		Surface	% Cracking	Crack Length, feet / mile	IRI, inches / mile	Rut, inches	Fault, inches
Begin	End						
16.6	16.7	PCC	6		112		0.166
18.1	18.2	PCC	0		172		0.177
18.5	18.6	PCC	11		174		0.158
19.9	20.0	PCC	0		110		0.150
20.2	20.3	PCC	0		102		0.000
25.3	25.4	AC	1	0	57	0.08	
25.4	25.5	AC	1	90	64	0.08	
26.6	26.7	AC	0	70	107	0.08	
32.2	32.3	AC	0	650	53	0.06	
32.3	32.4	AC	0	700	58	0.04	
36.7	36.8	AC	0	120	47	0.10	
38.1	38.2	AC	0	60	48	0.09	
44.2	44.3	AC	0	60	32	0.09	
44.4	44.5	AC	0	110	35	0.09	
60.9	61.0	AC	0	70	63	0.09	
65.6	65.7	AC	0	380	105	0.33	
69.9	70.0	AC	0	670	107	0.50	
72.3	72.4	AC	0	400	108	0.50	
81.0	81.1	AC	0	740	54	0.25	
83.0	83.1	AC	0	680	98	0.26	
85.7	85.8	AC	0	420	114	0.26	
110.7	110.8	AC	0	0	98	0.26	
115.6	115.7	AC	0	0	60	0.32	
127.3	127.4	AC	0	360	61	0.04	
129.8	129.9	AC	0	340	51	0.04	
131.5	131.6	AC	0	410	64	0.05	
149.0	149.1	PCC	0		53		0.000

Milepost		Surface	% Cracking	Crack Length, feet / mile	IRI, inches / mile	Rut, inches	Fault, inches
Begin	**End**						
150.8	150.9	PCC	0		52		0.000
153.4	153.5	PCC	0		59		0.000
158.0	158.1	PCC	6		53		0.000
162.2	162.3	PCC	0		54		0.169
176.0*	176.1	PCC	11		106		0.226
178.0*	178.1	PCC	11		108		0.000
193.2	193.3	PCC	11		51		0.000
193.4	193.5	PCC	11		58		0.154
194.3	194.4	PCC	11		120		0.183
201.8	201.9	AC	0	720	64	0.07	
202.5	202.6	AC	0	670	61	0.04	
204.5	204.6	AC	0	670	55	0.04	
204.8	204.9	AC	0	680	60	0.04	
205.4	205.5	AC	0	670	58	0.04	
205.6	205.7	AC	0	350	54	0.04	
205.9	206.0	AC	0	650	63	0.05	
206.0	206.1	AC	0	410	54	0.04	
207.8	207.9	AC	0	670	63	0.04	
210.1	210.2	AC	0	660	62	0.04	
210.9	211.0	PCC	6		95		0.195
211.7	211.8	PCC	6		106		0.156
213.0	213.1	PCC	6		96		0.000
216.2	216.3	PCC	6		62		0.157

*The segments at 176.0 and 178.0 were removed in the field due to the presence of construction.

Table 3.3 Segments reviewed with respect to rutting

Milepost		Surface	Rut, inches	IRI, inches / mile	% Cracking	Crack Length, feet / mile
Begin	End					
21.4	21.5	AC	0.10	55	0	50
32.2	32.3	AC	0.06	53	0	650
39.5	39.6	AC	0.08	34	0	90
65.6	65.7	AC	0.33	105	0	380
66.4	66.5	AC	0.47	73	0	70
66.8	66.9	AC	0.42	79	0	690
67.8	67.9	AC	0.41	106	0	320
68.8	68.9	AC	0.42	74	0	470
69.9	70.0	AC	0.50	107	0	670
72.3	72.4	AC	0.50	108	0	400
81.0	81.1	AC	0.25	54	0	740
83.0	83.1	AC	0.26	98	0	680
85.7	85.8	AC	0.26	114	0	420
104.2	104.3	AC	0.06	64	0	100
108.1	108.2	AC	0.10	105	0	60
108.2	108.3	AC	0.26	114	0	60
114.9	115.0	AC	0.26	64	0	0
115.6	115.7	AC	0.32	60	0	0
118.4	118.5	AC	0.04	105	0	80
127.3	127.4	AC	0.04	61	0	36

Table 3.4 Segments reviewed with respect to faulting

Milepost		Surface	Faulting, inches	IRI, inches / mile	% Cracking
Begin	End				
145.7	145.8	PCC	0.125	103	64
146.4	146.5	PCC	0.112	64	0
156.9	157.0	PCC	0.000	40	0
158.0	158.1	PCC	0.000	53	6
162.2	162.3	PCC	0.169	54	0
163.7	163.8	PCC	0.110	74	0
166.0	166.1	PCC	0.122	122	0
192.2	192.3	PCC	0.114	74	24
193.2	193.3	PCC	0.000	51	11
193.4	193.5	PCC	0.154	58	11
194.3	194.4	PCC	0.183	120	11
194.5	194.6	PCC	0.000	102	16
194.7	194.8	PCC	0.105	107	0
195.6	195.7	PCC	0.171	111	5
201.3	201.4	PCC	0.151	109	5
210.9	211.0	PCC	0.195	95	6
213.0	213.1	PCC	0.000	96	6
213.5	213.6	PCC	0.122	75	0
216.2	216.3	PCC	0.157	62	6
218.1	218.2	PCC	0.322	110	18

The segments presented in table 3.2 for evaluating cracking limit the ability to draw some conclusions. First, there is no variation in percent cracking on the AC pavements within this area of the study corridor. However, on the full length of the corridor there are a total of 55 asphalt-surfaced segments with more than one percent cracking and 12 asphalt-surfaced segments with more than five percent cracking. Due to their location, it was not possible to incorporate these segments into the field validation. Therefore, no conclusions may be drawn regarding percent cracking on AC pavements.

Additionally, while an effort was made to cover a broad range of conditions, there were insufficient data to draw conclusions on the effect of the interaction of distresses on condition rating.

The members of the review panel were asked to rate each segment in terms of good, fair, or poor based on the following definitions, as provided in the pilot study report (18):

- Good condition: Pavement infrastructure is free of significant defects and has a condition that does not adversely affect its performance. This level of condition typically requires only preventive maintenance activities.
- Fair condition: Pavement infrastructure that has isolated surface defects or functional deficiencies. This level of condition typically could be addressed through minor rehabilitation, such as overlays and patching.
- Poor condition: Pavement infrastructure that is exhibiting advanced deterioration and conditions that impact structural capacity. This level of condition typically requires structural repair, rehabilitation, reconstruction, or replacement.

Data collection was performed as a windshield survey during the week of May 6, 2013. Cracking and rutting were reviewed from the shoulder at slow speeds from a Chevrolet Suburban and a Chevrolet Silverado. Faulting review was performed based on the sound and feel from riding within these two vehicles at 50 miles/hour (80 kilometers/hour). The ride quality survey was performed from the Chevrolet Suburban at 50 miles/hour (80 kilometers/hour).

Collection of cracking data was performed on May 7th, faulting and rutting were collected on May 8th, and ride quality data were collected on May 9th. As with the pilot study, collection was performed in the driving lane in the eastbound direction of travel.

Concerns were raised by the panel members participating in the field validation effort as to the sun angle for collection of the cracking information. It was not possible to correct vehicle travel to improve visibility of cracking on the pavement sections reviewed. Rainfall occurred during the survey on the morning of May 8th allowing for the review of rutting to include an examination of the presence of pooled water. However, the rainfall was not present for the full length of the pavement reviewed for rutting. Additional rainfall occurred during the collection of the ride quality data on May 9th, but was not believed to have impacted the collection of these data.

Analyses of the collected data assumed that the field data collected for the pilot study were correct and were intended to review the threshold values for the condition rating associated with each distress. These analyses are presented within each of the following four chapters.

4.0 Rutting Data

The HPMS Field Manual defines rutting as the longitudinal depression occurring in the wheelpaths of a pavement with the potential for associated transverse displacement.(7)

Rutting results from vertical plastic deformation within the AC layers, lateral or transverse flow of the AC mixture, or mechanical deformation of the subsurface layers.(14) The root cause of these deformations may result from insufficient compaction or an improper mix design, if the rutting occurs within the asphalt layers. Rutting occurring due to mechanical deformation of the subsurface layers is generally believed to be caused by excessive loading or an inadequate pavement structure.(15)

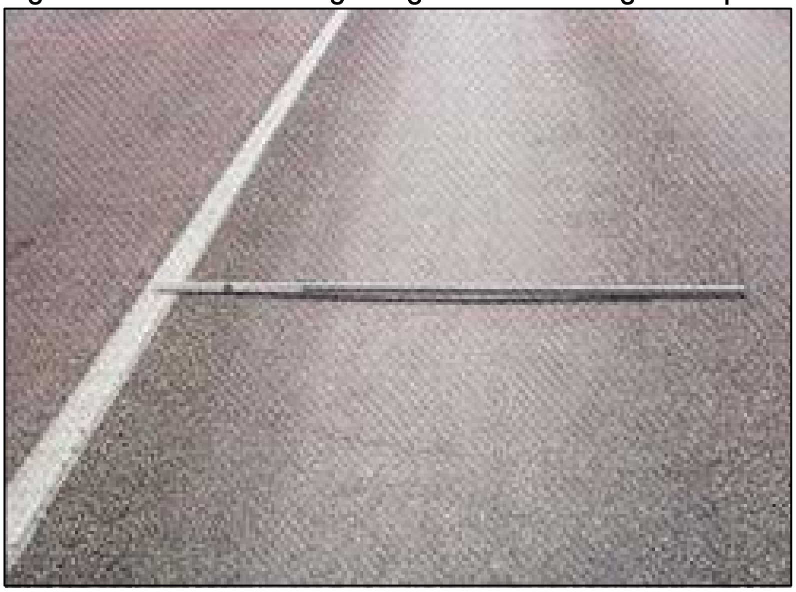
Any level of rutting provides an opportunity for water to pool on the pavement surface creating a safety issue. Cross-slope is a known factor contributing to the safety impacts of rutting on asphalt pavements.(21) VTI (Swedish National Road and Transport Research Institute) has done some work looking at the correlation between accident rate, speed, cross-slope and rutting and the results are not clear.(37) They speculated that driver behavior changed on rutted roads so this impacted the resulting accident rate. Florida DOT has done some work estimating drainage path given cross-slope and longitudinal slope, but they have not included rutting in that calculation.(21)

The HPMS database currently stores rutting as the average rut depth for both wheelpaths on the sample panel segments. The metadata for the HPMS database identifies whether the measurement was taken manually or automatically, the type of equipment used, the number of sensors used for automatic measurement, and the reporting interval. It also provides the posted speed limit for the segment. However, the current database provides no indication of the pavement cross-slope, which is important in evaluating the safety impacts of the measured rutting. Furthermore, the database provides no indication of quality control reviews performed on the data.

4.1 Data Collection Recommendations

There are a variety of devices available for collecting rut depth information. Historically, the most common device was a straightedge as shown in figure 4.1.(16) Over time, approaches were developed which provided a more complete picture of the rutting by collecting the full transverse profile such as the Dipstick™. Both of the straightedge and Dipstick™ types of devices require lane closures and traffic control and as such present a safety risk. Further, these types of measurements are slow forcing limited sampling of the rut depth. The advent of inertial profilers allowed for collection of sampled transverse profile data at highway speeds which may be used to estimate rut depth. More recently, sensors such as the one illustrated by figure 4.2 have been developed which collect up to 4,000 points across the transverse profile with a longitudinal sampling rate of up to 11,200 profiles per second.(17)

Figure 4.1 Use of straightedge for measuring rut depth



Source: FHWA.

Figure 4.2 LCMS Sensor used for collection of transverse profile

Source: Mandli Communications, Inc.

The specific elements considered associated with the collection of transverse profile data and hence rutting include the following items:

- Width of transverse profile.
- Transverse spacing of points / number of points within the profile.
- Longitudinal spacing between profiles.
- Cross-slope.
- Speed of data collection.

The width of the profile is related to the lane width but also to the processing of the rut depth values. A sufficient width is necessary to identify that the full lane-width is captured by the profile. The spacing of the transverse points relates to the number of points within the profile. This spacing needs to be adequate to provide sufficient definition to the shape of the road surface to calculate the full rut depth. The longitudinal spacing between profiles relates to the sampling frequency associated with the data collection. This spacing needs to be sufficient to provide an adequate representation of the occurrence of rutting along the segment being evaluated, but the recommendations should be set such that they are achievable by current equipment types. The speed and cross-slope are related to both the quality of the data collection and interpretation of the safety implications of the rut depth.

AASHTO has developed protocols related to the collection and processing of rut depth data. AASHTO PP70-10 covers the method for collecting transverse profile data. Some of the data collection recommendations presented later in this section were extracted directly from this protocol. Other data collection requirements were established based on work conducted as part of the FHWA study "Improving FHWA's Ability to Assess Highway Infrastructure Health," which was described in the introductory chapter to this report.

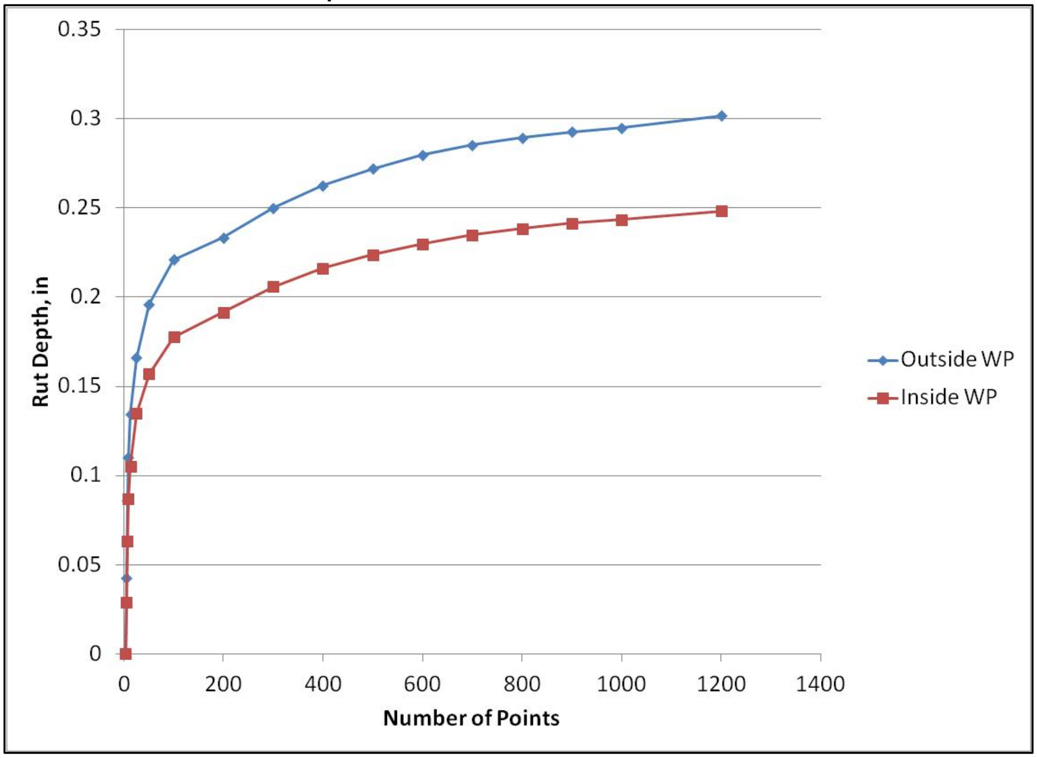
Among several other data collection efforts for the pilot corridor study, a multi-function automated pavement data collection vehicle was used to collect right-of-way images, roughness, rutting, faulting, and cracking data in accordance with HPMS 2010+ standards. The vehicle collected transverse profile data at 2-foot (0.61-meter) intervals along the corridor. The transverse profiles were collected using Laser Crack Measuring System (LCMS) sensors and consisted of 4,000 points collected over a width of just over 13 feet (3.96 meters). The equipment was identified as having a transversal resolution of 0.04 inch (1 millimeter) and a depth resolution of 0.02 inch (0.5 millimeter).

The recommended rutting data collection recommendations are as follows:

- From AASHTO PP70-10, the data points should cover a minimum width of 13 feet (3.96 meters). This width will help ensure that the full width of the lane is covered.
- From AASHTO PP70-10, the data points should have a separation less than or equal to 0.4 inch (10 millimeters). The pilot study data were used to evaluate the number of points within the transverse profile needed to evaluate the rut depth. Figure 4.3 illustrates the impact of the number of

points within the transverse profile has on the estimated rut depth. A range of points from 3 to 1,200 were considered. The figure illustrates that with the increasing number of points, the estimated rut depth increases with the degree of change in that value being greatly reduced once a minimum of 400 points is achieved. The AASHTO recommendation of 0.4 inch (10 millimeters) spacing between transverse profile points over a 13-foot (3.96-meter) lane width equates to roughly 396 points within the transverse profile.

Figure 4.3 Average rut depth based on varying number of points within the transverse profile

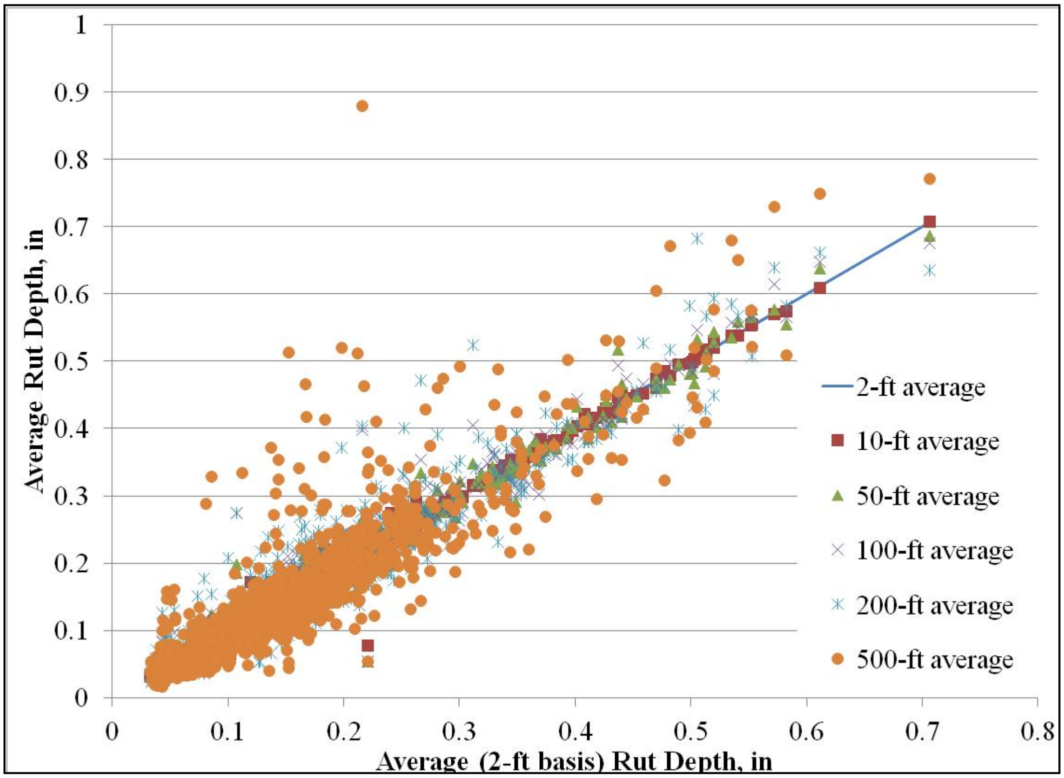


Source: AMEC and Cambridge Systematics, Inc.

- AASHTO PP70-10 recommends a maximum longitudinal spacing between profiles of 10 feet (3.05 meters). The pilot study data were analyzed to identify the appropriate longitudinal spacing for the transverse profile. As noted previously, the field data for the pilot study were collected at a longitudinal spacing of 2 feet (0.61 meter). The rut depths collected at the 2-foot (0.61-meter) interval were aggregated to a 0.1-mile (0.16-kilometer) interval. The profiles spaced at 2-foot intervals were sampled at intervals of 10 feet (3.05 meters), 50 feet (15.24 meters), 100 feet (30.48 meters), 200 feet (60.96 meters), and 500 feet (152.40 meters). These sampled data were also aggregated to 0.1-mile (0.16-kilometer) intervals. Figure 4.4 illustrates the impact of the longitudinal sampling on the rut depth in comparison to the values collected at 2-foot intervals (0.61-meter). Figure 4.5 provides the same data with the average rut depth from the 100-foot (30.48-meter), 200-foot (60.96-meter), and 500-foot (152.40-meter) sampling intervals eliminated from the graph. This figure shows that the data sampled at 10-foot (3.05-meter) intervals show considerably less scatter than the data sampled at longer intervals.

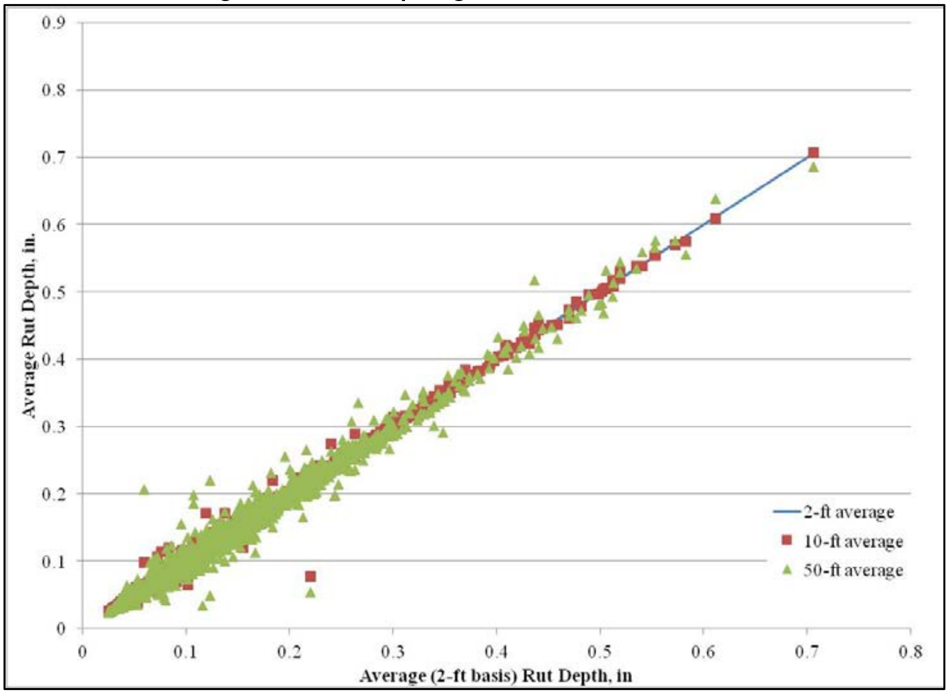
In order to meet the 10-foot (3.05-meter) longitudinal interval stipulated by AASHTO PP70-10, the equipment used for data collection must collect at least 9 profiles per second based on the equipment traveling at 60 miles-per-hour (96.6 kilometers/hour). This sampling rate is very achievable by the automated equipment that may be used to collect data.(17)

Figure 4.4 Average rut depth based on varying longitudinal sampling intervals



Source: AMEC and Cambridge Systematics, Inc.

Figure 4.5 Average rut depth based on 2-foot, 10-foot, and 50-foot longitudinal sampling intervals



Source: AMEC and Cambridge Systematics, Inc.

4.2 Data Processing Recommendations

The following items were considered in relation to data processing for the transverse profile:

- Filtering of the transverse profile.
- Straightedge width for rut depth computation.
- Gage width for rut depth computation.

The raw transverse profile data can be expected to be impacted by surface texture and noise from the data collection system. Applying a smoothing filter can eliminate the impact of these peaks and valleys. This processing approach removes the high frequency information from the profile data. This high frequency information is a result of macrotexture of the pavement surface leaving those data that are most relevant to calculation of the rut depth.

The width of the straightedge may impact the computed rut depth based on the shape of the profile. Some profiles may be lower in the center of the lane than on the edges; therefore, a straightedge that is less than the width of the lane is likely to result in a smaller estimated rut depth than one that encompasses the full width of the lane.

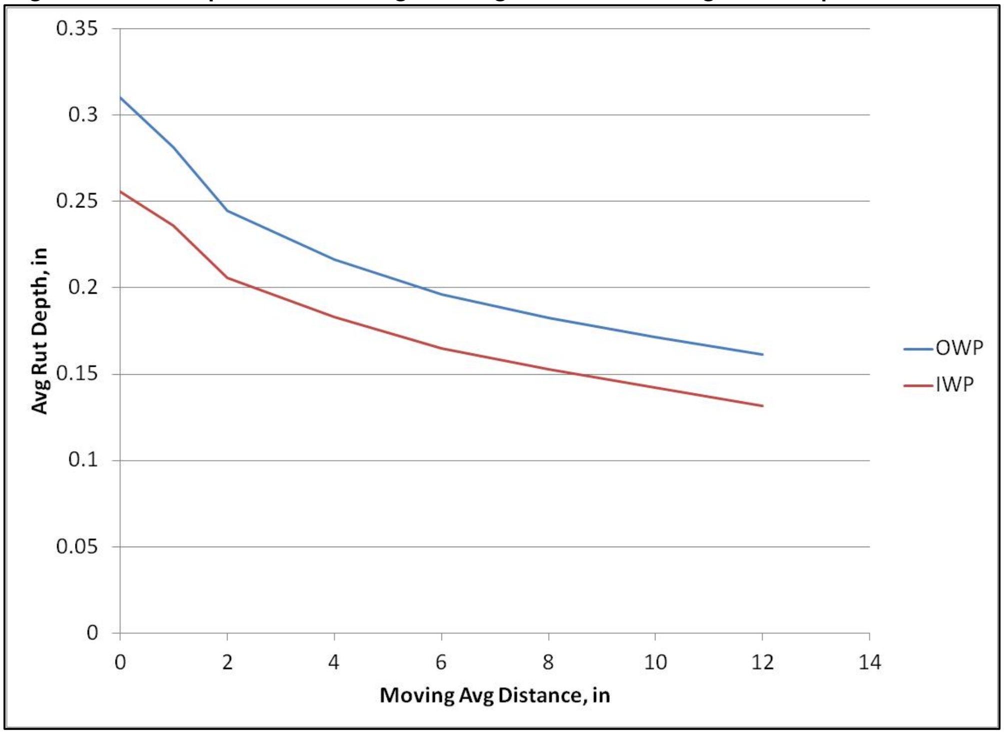
The gage is the imaginary ruler extending from the pavement surface to the straightedge used to measure the rut depth. A narrow gage may sit in a narrow crevice of the pavement surface (such as a crack) that does not impact vehicle travel. If the gage is too wide, then the gage would not measure to the bottom of ruts that do impact vehicular traffic.

AASHTO PP69-10 provides a specification for calculating rut depth from transverse profile. This information was considered in developing the recommendations for processing of transverse profile data. Additionally, the transverse profile as collected for the pilot study discussed in the prior section were used to perform additional analyses reviewing the impact of data filtration, straightedge width, and gage width on the estimated rut depth. The raw transverse profile data from the pilot study included 4,000 individual points for each profile.

The rutting data processing recommendations are as follows:

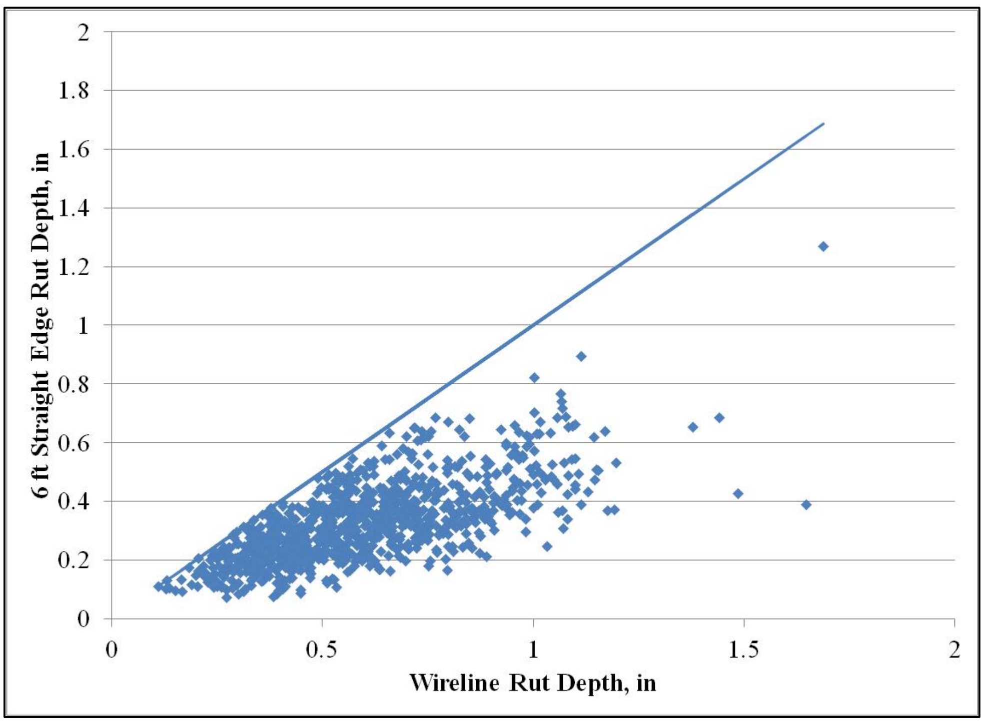
- As noted in AASHTO PP69-10, a 2-inch (51-millimeter) moving average filter should be applied to the transverse profile. The data collected for the pilot study were processed and the rut depth calculated using a moving average ranging in width from 0 to 12 inches (0 to 305 millimeters) in length. Figure 4.6 illustrates the impact of the moving average of varying lengths on the average rut depth. In reviewing the graph, a change in slope is noted at approximately 2 inches (51 millimeters). This change in slope suggests that a moving average width of 2 inches (51 millimeters) will reduce error without overly masking the estimated rut depth.
- The wireline method is recommended as the basis for the rut depth computation. Figure 4.7 and figure 4.8 provide a comparison of the rut depth based on a 6-foot (1.83-meter) straightedge and the wireline method for the left and right wheelpath, respectively. In both figures the rut depth is larger based on the wireline method than the 6-foot (1.83-meter) straightedge. The graphs illustrate that there is a high degree of correlation between the rut depth based on a 6-foot (1.83-meter) straightedge and those based on a wireline; however, it is not possible to state how much larger the rut depth based on a wireline is than the depth based on a 6-foot (1.83-meter) straightedge from just the rut depth value. These figures suggest that the wireline method of evaluation provides a more complete method of estimation of the rut depth on asphalt pavements.

Figure 4.6 Impact of moving average on the average rut depth



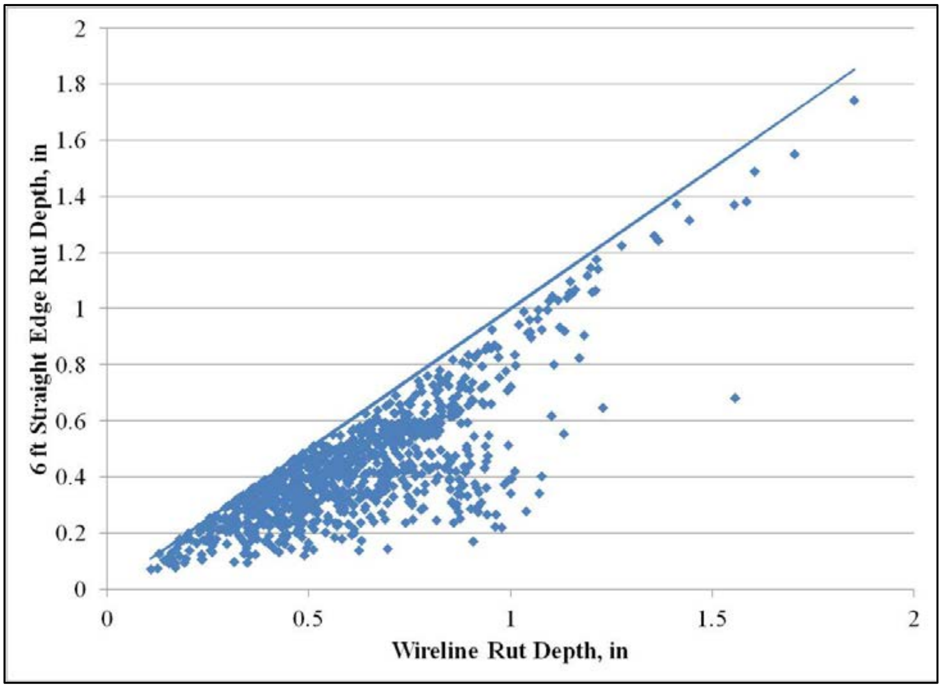
Source: AMEC and Cambridge Systematics, Inc.

Figure 4.7 Comparison of 6-foot straightedge and wireline rut depths in the left wheelpath



Source: AMEC and Cambridge Systematics, Inc.

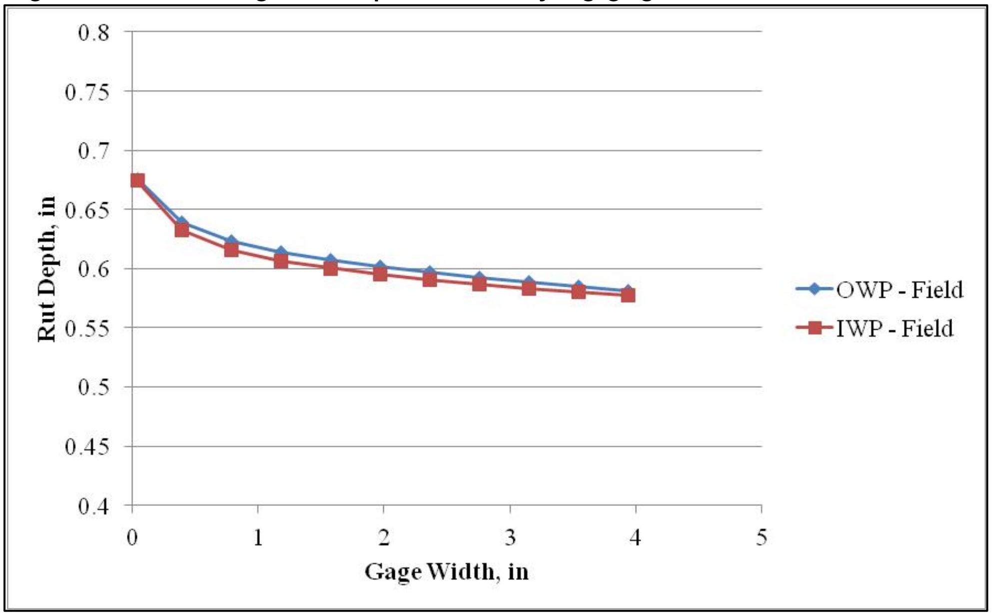
Figure 4.8 Comparison of 6-foot straightedge and wireline rut depths in the right wheelpath



Source: AMEC and Cambridge Systematics, Inc.

- A gage width of 1.2 to 1.5 inches (31 to 38 millimeters) is recommended for use in calculating the rut depth. In this study, the gage width was varied from 0.039 to 3.9 inches (1 to 100 millimeters) to review the impact this value had on the measured rut depth using the pilot study data. Figure 4.9 provides a clearer picture of the impact of gage width on the estimated rut depth for the transverse profile data provided by field data collection of the pilot study. Figure 4.9 illustrates that the initial increases in gage width provide a significant decrease in the estimated rut depth up to a gage width of 1.2 to 1.5 inches (31 to 38 millimeters). Beyond this width, the decreases are less significant. This change suggests that at the smaller gage widths, the rut depth is impacted by the noise and/or surface texture of the pavement that may be observed in the transverse profile. Based on this review, the optimal gage width is on the order of 1.2 to 1.5 inches (31 to 38 millimeters).

Figure 4.9 Average rut depth from varying gage widths



Source: AMEC and Cambridge Systematics, Inc.

4.3 Data Quality Control Recommendations

The following items were considered in relation to quality control of the transverse profile collection and processing:

- System validation.
- Equipment component checks.
- Processed data checks.

Quality control associated with collection of the transverse profile should begin with a validation of the system to be used for data collection. The system validation provides a means to check the overall operation of the equipment including the individual components and the operational aspects associated with the data collection. System validation is important to ensure that the data collection vehicle meets the quality requirements.

Component checks are quick checks that should be done on a regular basis throughout the data collection schedule. These identify that the equipment continues to operate within the bounds of proper limits throughout the data collection cycle.

Checks of the processed data evaluate the calculated rut depth. These checks identify errors that may have occurred in the data collection that were not caught by the equipment checks. These checks also identify errors in relational data such as maintenance or rehabilitation not recorded within the database.

AASHTO PP70-10 and AASHTO PP69-10 provide the basis for the quality control checks recommended here. Furthermore, the LTPP program has noted that checks of collected data are a key element in any quality control program.(19)

The rutting data quality control recommendations are as follows:

- The system validation should include a review of each component of the equipment as described in AASHTO PP70-10. As part of the approach described within this specification a number of operational aspects of the equipment will be reviewed including the distance measuring instrument, data point spacing, transverse measurement width, and vertical measurement resolution and accuracy. The system validation should also identify the impact of operational and environmental variables including sun angle and intensity, shadows, temperature, precipitation, surface texture, speed variability, cross-slope, vertical grade, roughness, and horizontal curvature.
- As part of data collection efforts, checks should be conducted routinely (at least monthly) of the components. These are performed in addition to the system validation checks and generally involve much simpler assessments of each component. As noted in AASHTO PP70-10 these checks involve regular data collection across a validation section and checks of the distance measuring instrument throughout the active data collection cycle. Typically, these checks would be performed on a monthly basis.
- As noted by the LTPP program, the processed rut depths should be reviewed for quality. This review should include checks of spatial and temporal variability. Based on the error limits identified within AASHTO PP69-10, a manual review of the transverse profile should be conducted if any of the following conditions are met:
    - Spatial change in rutting > 0.1 inch/foot (8 millimeters/meter).
    - Increase in rutting > 0.1 inch/year (2.5 millimeters/year).
    - Decrease in rutting > 0.05 inch (1 millimeter).

4.4 DATA STORAGE RECOMMENDATIONS

For data storage, the following items were considered:

+ Data elements to be stored in the HPMS database.
+ Base length interval.
+ Metadata to be stored.
+ Quality control review elements.

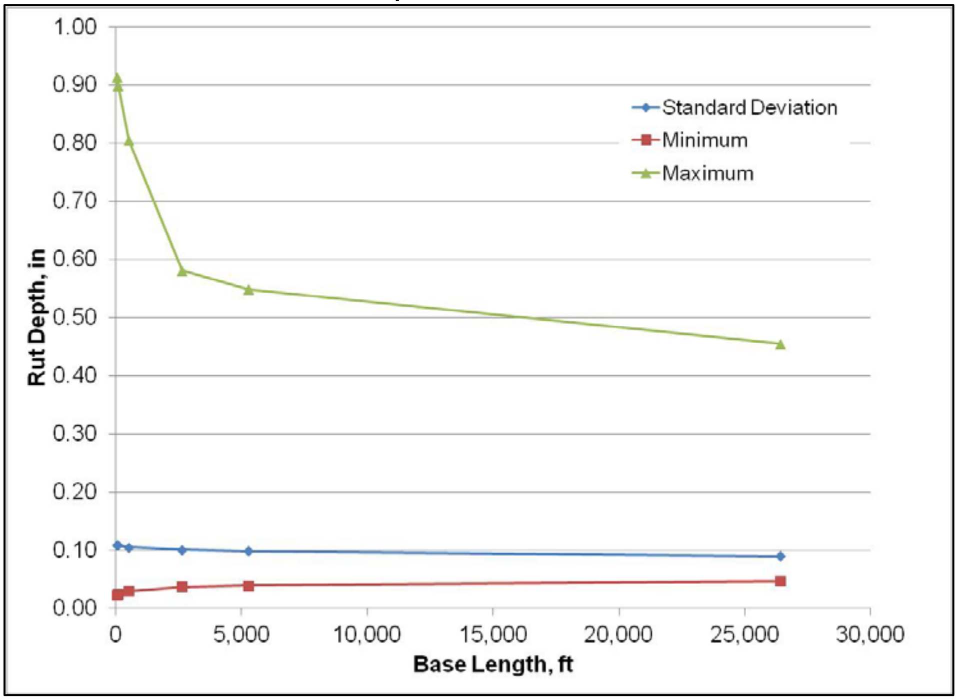
The appropriate data elements are required to allow for appropriate interpretation of the data. The segmentation refers to the distance over which the rut depths are averaged for storage in the HPMS database. As noted in the introduction, the anticipated use for these data is to evaluate condition of the nation's IHS. The data should be stored at a sufficiently small base length to allow for an understanding of the peaks and valleys of condition across that network, but not at such a small base length that it is impossible to interpret the overall condition. The metadata are used to describe the data stored in the main HPMS database and are essential in performing quality control reviews of the data obtained. Quality control review elements provide the user of the data with a means to evaluate the quality of the data and whether that data will meet the needs of their purpose.

The LTPP program has performed a study on methods for evaluation of rutting on asphalt pavements.(14) This study was reviewed to identify appropriate data elements to store. The pilot study data as previously described were used to evaluate the impact of segmentation.

The rutting data storage recommendations are as follows:

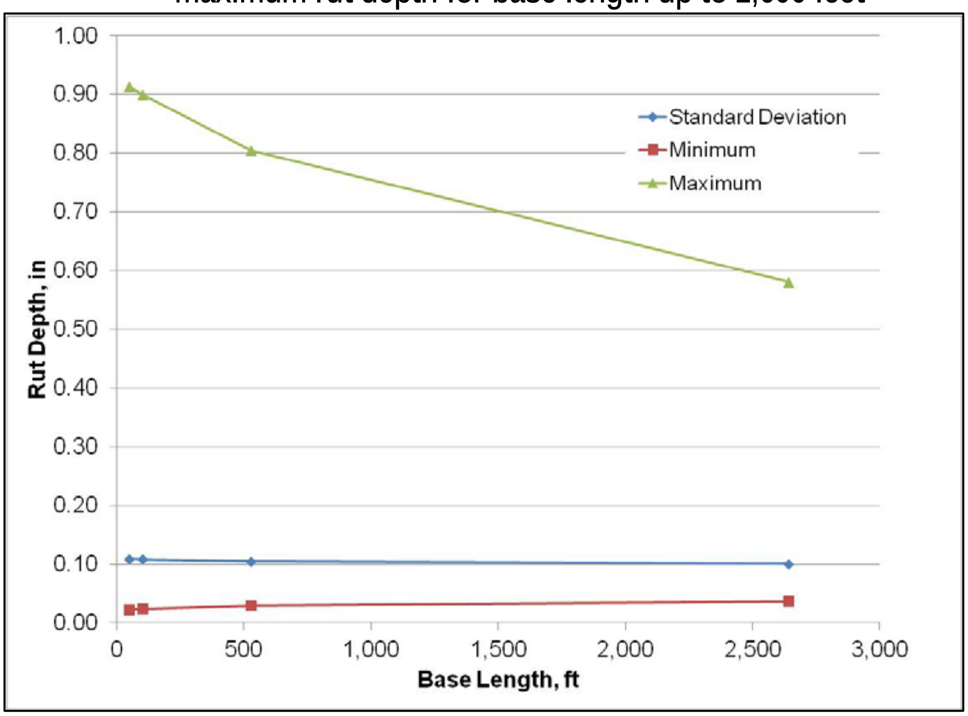
- The data elements to be stored in the HPMS database associated with rut depth should include the average rut depth and the cross-slope. In addition, the minimum rut depth, maximum rut depth, and standard deviation of rut depth over each interval should be stored as well. Rutting has been documented as allowing water to pool on the pavement surface.(14) The amount of water allowed to pool will be a function of the rut depth, the cross-slope, and the longitudinal slope. While this dependency is well understood, at present, there are no methods for calculating the depth of water ponding. The recent advent of the three-dimensional sensors for data collection will make this calculation much more possible than it has been in the past. For now, the cross-slope should be stored along with the rut depth to allow consideration of that element with the rut depth. In addition, the other statistics provide an understanding of the variability of rutting within a pavement segment and subsequently, an indication of the consistency of the potential for water ponding over a pavement segment.
- The base length of 0.1 mile (0.16 kilometer) is recommended for these data. The pilot study data collected at 2-foot (0.61-meter) intervals were used to review the impact of accumulating the data at various segment lengths from 50 feet (15.24 meters) to 5 miles (8,047 kilometers). Figure 4.10 illustrates the impact of base length to the standard deviation of the average rut depth, the minimum average rut depth, and the maximum average rut depth. Figure 4.11 is provided to illustrate the impact of changes in base length for the shorter base lengths shown in figure 4.10. As expected, the standard deviation decreases with increasing segment length as does the maximum rut depth while the minimum rut depth increases with increasing base length. The 0.1-mile (0.16-kilometer) interval is believed to provide a practical level of detail.

Figure 4.10 Impact of base length on standard deviation, minimum, and maximum rut depth



Source: AMEC and Cambridge Systematics, Inc.

Figure 4.11 Impact of base length on standard deviation, minimum, and maximum rut depth for base length up to 2,600 feet



Source: AMEC and Cambridge Systematics, Inc.

- The metadata for rut depth should include the items currently stored in the HPMS database. Additionally, the full transverse profile should be stored for future use. Storing the full transverse profile allows for the ability to recalculate rutting based on revised techniques should refinements be required in the future.
- Quality control elements should be added to the HPMS database to allow the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing. These elements could be as simple as providing a yellow flag where the data do not meet the spatial and temporal consistency limits previously identified and a green flag where they do.

4.5 CONDITION RATING

In combination with other factors such as cross-slope, speed, and macro-texture, rutting can lead to water ponding and hence the potential for hydroplaning, thus rutting is an important safety indicator. Studies have shown that as little as 0.1 inch (3 millimeters) of rutting may lead to the potential for hydroplaning of traffic or increased accidents.(39) Rutting can also be an indicator of the structural pavement condition; it occurs as a result of the accumulations of undesired permanent deformations within a pavement. Accordingly, in addition to the data recommendations provided above, a condition rating for rutting is also recommended in this section.

The FHWA Pavement Health Track (PHT) tool identifies a terminal value of rutting as 0.4 inch (10 millimeters).(44) This terminal value indicates a remaining service life of zero for a pavement with a rut depth of 0.4 inch (10 millimeters) or greater. The MEPDG also identifies a pavement with a rut depth greater than 0.4 inch (10 millimeters) as inadequate and a pavement with a rut depth equal to or less than 0.25 inch (6 millimeters) as adequate.(45) Therefore, these values were set as the delineator for between fair to poor and good to fair, respectively. The levels for condition for rut depth were set based on these threshold values as shown in table 4.1 along with the percentage of the pilot study corridor by condition level.

Table 4.1 Condition evaluation based on rut depth using a 0.1-mile base length

Condition	Distress Range	Percentage of Corridor
Good	Rut < 0.25 inch	96%
Fair	0.25 inch ≤ Rut ≤ 0.4 inch	3%
Poor	Rut > 0.4 inch	1%

The reasonableness of the rutting condition threshold values were reviewed through the field validation described in chapter 3 of this report. As noted in Chapter 3, a total of 20 0.1-mile (0.16-kilometer) segments were reviewed as part of the field validation effort. Of these 20 segments, seven were identified as having good condition, seven were identified as having fair condition, and six were identified as having poor condition with respect to rutting. Each of the six participating raters identified the condition of the pavement segment with respect to rutting.

The ratings were assigned a value of 3 for good, 2 for fair, and 1 for poor. These values were averaged across all six raters and then the average rating compared with the rating based on the thresholds shown in table 4.1.

Of the 20 segments reviewed, the average rating agreed with the rating based on the thresholds shown in table 4.1 50 percent of the time. However, as part of the review, the six segments identified as having poor condition were observed to have received a mill and fill since the data collection performed for the pilot study. If these six segments are eliminated, the level of agreement between the raters and the table 4.1 ratings rises to 71 percent.

The raters observed the condition as better than that shown by the table 4.1 ratings for three of the remaining four segments with disagreement. Comments on these three segments identified that the segment condition was worse near the end and one identified that it was difficult to see. The other segment, rated worse than the table 4.1 rating, was noted as having no noticeable water ponding and water over much of the surface. From these ratings, no changes are recommended to the threshold between good and fair.

Given the apparent construction on the six segments in poor condition, nothing may be observed about the threshold between fair and poor at this time.

Accordingly, based on the results of the field validation, the recommended threshold values for defining the good/fair/poor condition of a pavement should remain as preliminary as additional research needs to be undertaken to identify the combination of rut depth, cross-slope, and speed of the facility that delineate safety considerations. For example, 0.25 inch (6 millimeters) rutting on a high-speed facility with little to no cross-slope is of much greater concern than the same level of rutting on a low speed-facility and a high-degree of cross-slope.

5.0 Ride Quality Data

ASTM defines road roughness as the deviations of a pavement surface from a true planar surface that affects vehicle dynamics, ride quality, dynamic loads, and drainage.(22)

Roughness on pavements is generally a function of construction, climatic effects, and traffic loading.(23) Construction refers to three specific areas: 1) construction irregularities built into the surface, 2) construction deficiencies such as poor compaction, and 3) poor quality construction materials. Climatic effects refer to changes in temperature that cause warping and curling in concrete pavements. Climatic effects also cause changes in subgrade volume through frost heave or shrink and swell from moisture changes which result in irregularities that may be felt in the pavement surface.

Studies of data collected at the American Association of State Highway Officials (AASHO) Road Test show that subjective evaluation of pavements based on mean panel ratings was primarily influenced by roughness.(28) Furthermore, in 1996, FHWA conducted a survey of how highway users judge roadways. The survey identified that the most important issue for highway users is roadway condition in terms of pavement roughness (40). Clearly, ride quality is a key pavement performance indicator to highway users.

The HPMS database currently stores IRI as the statistic for evaluation of ride quality. The field manual identifies that these data should be collected for the full extent of the IHS on a two-year cycle. Furthermore, structures and railroad grades are expected to be included in the measurement of ride quality. The field manual specifies that the same lane and direction should be measured; however, the specific lane and direction are not identified. Metadata associated with ride quality data include the type of equipment used for data collection and the reporting or segmentation interval.

5.1 Data Collection Recommendations

Data collection for ride quality is primarily performed by an inertial profiler as illustrated in figure 5.1. One of the earliest devices used to evaluate ride quality was a straightedge slid along the surface of the pavement identifying deviations from that flat, planar surface. This type of evaluation was necessarily performed only as part of construction quality control due to its time consuming nature. A number of developments over the years have led to the inertial profiler which allows for evaluation of ride quality at highway speeds making this measurement more accessible for use in pavement management. The inertial profiler consists of a height sensor which measures the distance to the pavement surface, an accelerometer which measures the vertical movement of the vehicle and a distance measuring instrument to identify distance traveled in association with these vertical measurements.(24) With the advent of lasers with larger footprints, ride quality evaluation of pavements with difficult surface texture in particular concrete pavements with longitudinal tining has become more reliable.(4)

Figure 5.1 Typical inertial profiler

Source: Mandli Communications, Inc.

The following elements were considered in relation to data collection:

- Data collection interval.
- Sensor footprint.
- Temporal and diurnal variation.

The data collection interval specifies the distance between stored elevation points along the longitudinal profile. This interval must be sufficiently small to capture the full wave spectrum which impacts ride quality as it relates to the vehicles traversing the roadway. However, the interval must not be so small as to be beyond the capability of commonly available equipment capabilities.

The elevation profile may be influenced by the macrotexture of the pavement surface.(25) A small sensor footprint may fall between or on top of longitudinal tines of a PCC surface or between large aggregate in an open-graded AC surface course. Since it is unlikely that the footprint would always land between or on top of the surface macrotexture, this alternating measurement would add error to the longitudinal profile resulting in a higher estimation of roughness.

Curling and warping on jointed concrete pavements is commonly observed. This phenomenon may significantly impact the observed roughness of a pavement.(5) Curling occurs with changes in the temperature gradient of the pavement surface layer. The gradient is sensitive to changes in season and time of day with the lowest gradient observed in winter and the highest in summer.(6) Therefore, the amount of curl varies throughout the day with differing amounts of curl occurring over a year.

AASHTO has developed a series of standards related to ride quality data collection as follows:

- AASHTO M328-10 "Standard Specification for Inertial Profiler."
- AASHTO R54-10 "Standard Practice for Accepting Pavement Ride Quality When Measured Using Inertial Profiling Systems."
- AASHTO R56-10 "Standard Practice for Certification of Inertial Profiling Systems."
- AASHTO R57-10 "Standard Practice for Operating Inertial Profiling Systems."

For the purposes presented here, AASHTO M328-10 and AASHTO R57-10 are the primary standards referenced within this report.

The FHWA has initiated a series of studies to improve measurement capabilities associated with ride quality evaluation of pavements. Program TPF-5(063), "Improving the Quality of Pavement Profiler Measurement," is currently addressing a number of issues related to the implementation of the AASHTO provisional standards for ride quality data collection.(26) Reports from this study have been used to provide some of the guidelines.

Another study initiated by FHWA in 2002 reviewed the impact of diurnal and seasonal variations in concrete on ride quality measurements. The project, "Inertial Profile Data for Pavement Performance Analysis," collected longitudinal profile data on concrete pavements across the US at before sunrise, at sunrise, mid-day, and at sunset in all four seasons. A variety of other measurements were made including pavement temperature to estimate the impact of curling and warping behavior of jointed concrete pavements on ride quality data.(5)

The ride quality data collection recommendations are as follows:

- The data collection interval should be 2 inches (51 millimeters) or less in accordance with AASHTO M328-10. On concrete pavements where the data may be used for faulting measurement, the data collection interval should be 0.75 inches (19 millimeters) or less in accordance with AASHTO R36-12.
- A height sensor should be selected with a sufficient footprint to not be impacted by the surface texture. A recommendation has been made that the sensor footprint should have a width of at least 2.75 inches (70 millimeters).(27) This footprint may be achieved by a single laser with a width of 2.75 inches or by multiple small dots processed to obtain a single elevation value.

- Ideally, the ride quality data collection would occur at the same time of day and time of year each time it is collected to minimize the impact of diurnal and seasonal variations. This approach may not be practical, therefore, data should be reviewed with the idea that changes in IRI due to curling average approximately 10 inches/mile (0.16 meters/kilometer) with a difference as high as 40 inches/mile (0.63 meters/kilometer).(5)

5.2 DATA PROCESSING RECOMMENDATIONS

Longitudinal profile data are typically processed to determine IRI, which is the most often used pavement ride quality indicator. The standard for calculating the IRI is ASTM E1926. This standard provides much of the necessary detail for calculating the IRI. The one item not considered under data processing is which portions of the segment to include within the evaluation, e.g., areas such as bridges may have a significant impact on measured ride quality. Inconsistency in whether these and other structures are included in the IRI calculation may impact how condition is assessed by the FHWA on the IHS.

Longitudinal profile data were collected as part of the pilot study of the Interstate 90 corridor discussed under the rutting data. These data were collected along the full length of the pilot study corridor at 2-inch (51-millimeter) intervals. The data also included identification of the location of bridges and pavement changes which might impact ride quality. The data collected in Minnesota and South Dakota were used to estimate the impact of bridges and pavement changes on condition.

The ride quality data processing recommendations are as follows:

- The full extent of the system is recommended for inclusion in the IRI calculation. Table 5.1 presents the average, minimum, and maximum IRI values for data collected in Minnesota and South Dakota with and without bridges and pavement changes. The table illustrates limited impact in the data caused by bridges and pavement changes. The approach of incorporating these areas provides the most simplistic to data collection and processing. It also provides a more complete look of the ride quality along the system.

Table 5.1 Impact of bridges and pavement changes to IRI

State	Pavement Exclusions	IRI, inches/mile		
		Average	Minimum	Maximum
MN	All	80	23	427
	Bridges excluded	79	26	427
	Bridges and Pavement Changes excluded	78	26	427
SD	All	77	24	275
	Bridges excluded	73	24	263
	Bridges and Pavement Changes excluded	72	24	202

5.3 DATA QUALITY CONTROL REQUIREMENTS

The following items were considered with relation to data quality control:

- System validation.
- Daily / routine checks.
- Processed data review.

Quality control associated with collection of ride quality should begin with a validation of the system to be used for data collection. The system validation provides a means to check the overall operation of the equipment including the individual components and the operational aspects associated with the data collection. System validation is important to ensure that the data collection vehicle meets the quality requirements for the data use.

Component checks are quick checks that may be done on a regular basis throughout the data collection schedule. These identify that the equipment continues to operate within the bounds of proper limits throughout the data collection cycle.

Checks of the processed data evaluate the calculated IRI. These checks identify errors that may have occurred in the data collection that were not caught by the equipment checks. These checks also identify errors in relational data such as maintenance or rehabilitation not recorded within the database.

AASHTO R56-10 and AASHTO R57-10 provide the basis for the quality control checks recommended here. Furthermore, the LTPP program has noted that checks of collected data are a key element in any quality control program.(19)

The recommended ride quality data quality control requirements are as follows:

- The system validation should include a review of each component of the system as well as the system as a whole as specified in AASHTO R56-10. The standard also provides a means for reviewing the operator's capabilities with relation to data collection and operation of the equipment. This approach assumes that the operator is part of the system being validated.

- AASHTO R57-10 provides specifications for daily checks to be performed of the equipment during data collection. These checks include checks of tire pressure, block check of height sensor, and a bounce test. A log should be maintained of these checks as a means to review the ongoing condition of the equipment.
- As noted by the LTPP program, the processed data should be reviewed for variation both spatially and temporally. Based on AASHTO M328-10, the inertial profiler should be capable of distinguishing differences in IRI as low as 5 inches/mile (0.08 meter/kilometer). Therefore, the following changes should trigger a detailed review of the longitudinal profile for a segment:
  + Increase in IRI > 10 inches/mile (0.16 meter/kilometer) per year.
  + Decrease in IRI > 5 inches/mile (0.08 meter/kilometer).
  + Change in IRI between adjacent segments > 50 inches/mile (0.79 meter/kilometer).

5.4 DATA STORAGE RECOMMENDATIONS

For data storage, the following items were considered:

- Base length.
- Date and time of data collection.
- Metadata to be stored.
- Quality control review elements.

The base length refers to the distance over which the IRI is calculated for storage in the HPMS database. As noted in the introduction, the anticipated use for these data is to evaluate condition of the nation's IHS. The data should be stored at a sufficiently small interval to allow for an understanding of the peaks and valleys of condition across that network, but not at such a small interval that it is impossible to interpret the overall condition. The metadata are used to describe the data stored in the main database and are essential in performing quality control reviews of the data obtained. Quality control review elements provide the user of the data with a means to evaluate the quality of the data and whether that data will meet the needs of their purpose.

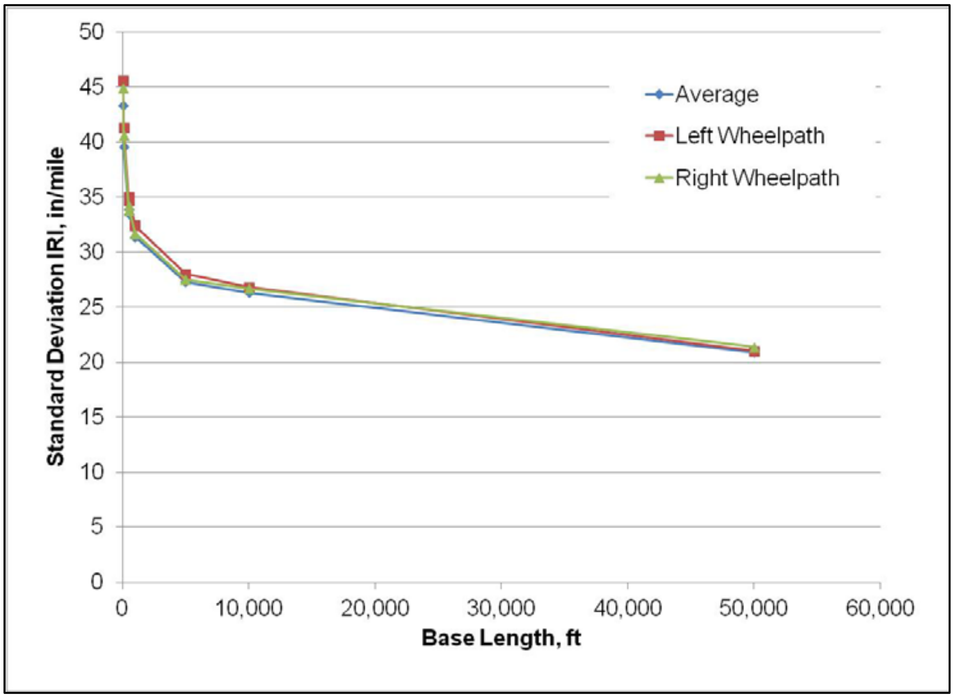
The pilot study data as previously described were used to evaluate the segmentation length.

The ride quality data storage recommendations are as follows:

- The IRI should be calculated to a base length of 0.1 mile (0.16 kilometer). The pilot study data were used to calculate IRI on segment lengths from 50 feet (15.24 meters) to 50,000 feet (15,240 meters). Figure 5.2 and figure 5.3 illustrate the impact of varying base length on the variability of data collected in Minnesota and South Dakota, respectively. Figures 5.4 and 5.5 have been provided to illustrate the impact of base length on variability for the shorter end of the graphs provided in figures 5.2 and 5.3, respectively. As expected, the standard deviation decreases with increasing segment length. The 0.1-mile (0.16-meter) interval is expected to provide an optimal level of detail.

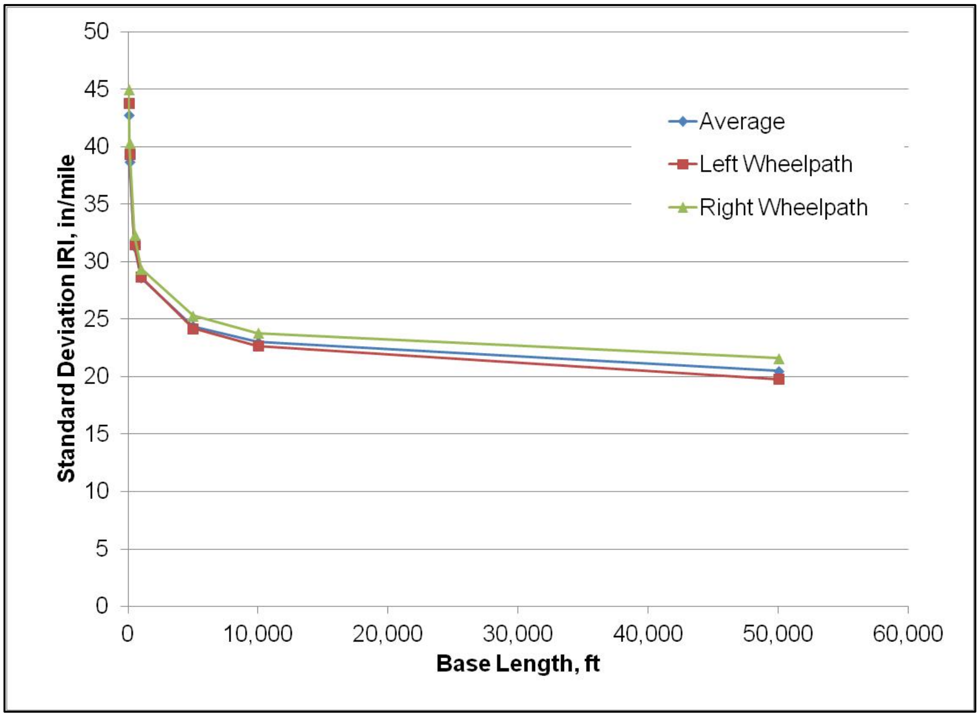
- As date and time of data collection may impact the resulting value, it is important that these data be stored for proper data interpretation.
- The metadata for the IRI should include those items already stored as well as the full longitudinal profile. The detailed longitudinal profile data should be stored to allow for review of the data. Additionally, storing the detailed data allows for re-calculation of the ride quality index in future years should any advances be made in this area.

Figure 5.2 Impact of base length on variation in IRI for data collected in Minnesota



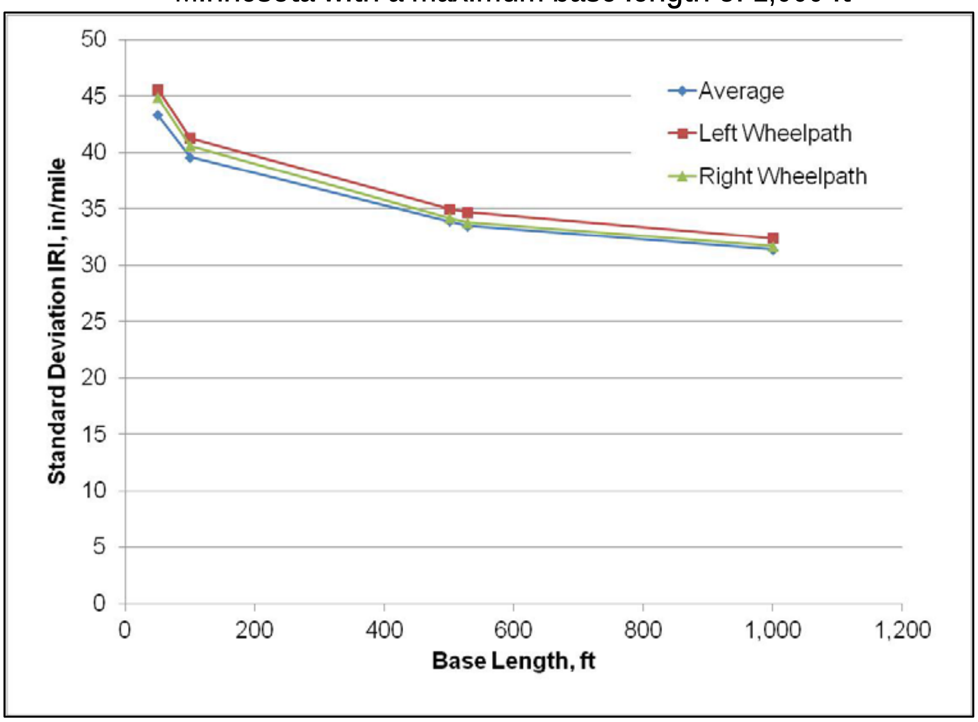
Source: AMEC and Cambridge Systematics, Inc.

Figure 5.3 Impact of base length on variation in IRI for data collected in South Dakota



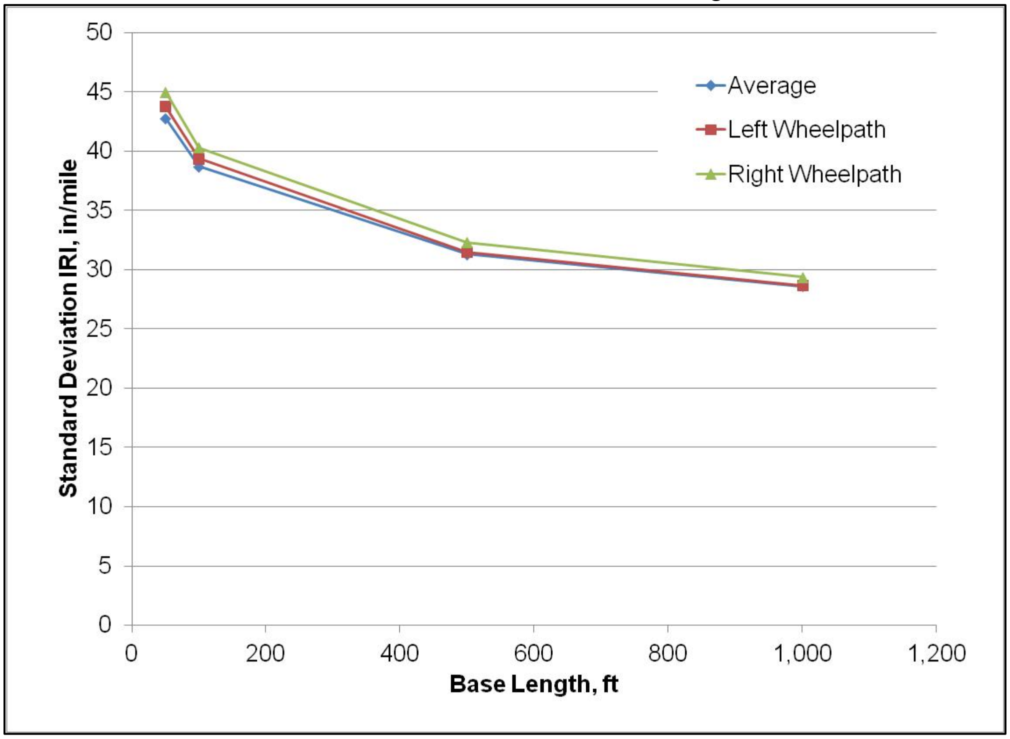
Source: AMEC and Cambridge Systematics, Inc.

Figure 5.4 Impact of base length on variation in IRI for data collected in Minnesota with a maximum base length of 1,000 ft



Source: AMEC and Cambridge Systematics, Inc.

Figure 5.5 Impact of base length on variation in IRI for data collected in South Dakota with a maximum base length of 1,000 ft



Source: AMEC and Cambridge Systematics, Inc.

- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing. These elements could be as simple as providing a yellow flag where the data do not meet the spatial and temporal consistency limits previously identified and a green flag where they do.

5.5 Condition Rating

As noted earlier, ride quality is a key pavement performance indicator to highway users and thus, a condition rating for IRI is also recommended in this section. However, unlike the other HPMS data elements addressed in this report, IRI says nothing about the structural capacity of the pavement, whether directly or indirectly. A poor riding pavement could be structurally sound and vice-versa. Accordingly, while an important and an accepted indicator, IRI cannot be used by itself to assess pavement condition; it needs to be used in conjunction with the other HPMS data elements addressed in this report, at least for the near future.

The method for evaluating pavement ride quality based on IRI as established by FHWA is shown in table 5.2 along with the percentage of the pilot study corridor by condition level. The level for unacceptable ride quality was first established by FHWA as part of the 1998 revision to the National Strategic Plan. The Plan was further revised to add the upper level for good ride quality in 2002.(41)

Table 5.2 Condition evaluation based on IRI using a 0.1-mile base length

Condition	Distress Range	Percentage of Corridor
Good	IRI < 95 inches/mile	72%
Fair	95 inches/mile ≤ IRI ≤ 170 inches/mile	26%
Poor	IRI > 170 inches/mile	2%

A total of 40 segments were identified for review of ride quality. Table 5.3 provides the breakdown of these segments by pavement type and condition rating.

Table 5.3 Breakdown of field validation segments by surface type and condition rating

Surface	Condition	Number of Segments
AC	Good	10
	Fair	9
	Poor	1
PCC	Good	9
	Fair	7
	Poor	4

Each of the ratings was given a numeric value from 1 to 3 with 1 being poor, 2 fair, and 3 good. These values were averaged and the rating assigned based on the average value. The average rating was then compared with the rating based on table 5.2. The raters did not agree with the table 5.2 rating for 13 of the segments. These 13 segments included four in poor condition, six in fair condition, and 3 in good condition. Comments provided by the raters on these 13 segments generally indicated that they were in borderline condition either good/fair or fair/poor.

No consistent differences were observed from the field validation that would warrant recommending a change in the threshold values presented in table 5.2.

6.0 Faulting Data

The HPMS Field Manual defines faulting as the vertical displacement at a joint or crack on concrete pavements.(7)

Two potential causes of faulting are: 1) loss of support due to pumping and 2) lack of adequate load transfer.(29) Under the action of live traffic, water entering a joint will erode the subgrade support near the joint removing some of the fine material. Without adequate load transfer across a pavement joint, the stress of traffic will cause high deflections of the slab, which in turn will cause degradation of the support on one side of the joint.

Joint faulting has an impact on the life cycle costs of a pavement in terms of required early rehabilitation and vehicle operating costs.(30) This impact to life cycle costs is primarily caused by the impact joint faulting has on ride quality as well as its indication of pavement structural condition deterioration.

The HPMS database currently stores faulting as the average of faulting collected on all joints within the segment. Faulting may be observed on cracks as well as joints in similar levels of significance.(31) However, the HPMS database only stores data from joints without regard to any faulting that may occur at cracks.

6.1 DATA COLLECTION RECOMMENDATIONS

Two types of equipment are available for collecting faulting data. The oldest and most commonly used one is the Georgia faultmeter, which is illustrated in figure 6.1. This approach is slow, requires traffic control; and subsequently, is not suited to network level measurement of faulting on concrete pavements. More recently inertial profilers have been employed in performing faulting measurements.(8) Using the inertial profiler for data collection allows network level data collection to be performed at highway speeds without the need for active traffic control.

The following data items were considered with relation to faulting measurement:

- Longitudinal interval between elevation points.
- Temporal and diurnal variation.

It is important to collect data at sufficiently small intervals that the joints may be found and appropriate levels of faulting measured.

Curling and warping on jointed concrete pavements is commonly observed. This phenomenon may impact the observed faulting at the joints of a concrete pavement.(5) Curling occurs with changes in the temperature gradient of the pavement surface layer. The gradient is sensitive to changes in season and time of day with the lowest gradient observed in winter and the highest in summer.(6)

Therefore, the amount of curl varies throughout the day with differing amounts of curl occurring over a year.

Figure 6.1 Fault measurement using Georgia faultmeter

Source: J.S. Miller and W.Y. Bellinger, Distress Identification Manual for the Long Term Pavement Performance Program (Fourth Revised Edition)¸FHWA-RD-03-031, Federal Highway Administration, McLean, VA, March 2003.

AASHTO R36-12 provides the specification for evaluating faulting using inertial profilers and provides the basis for some of the recommendations provided.

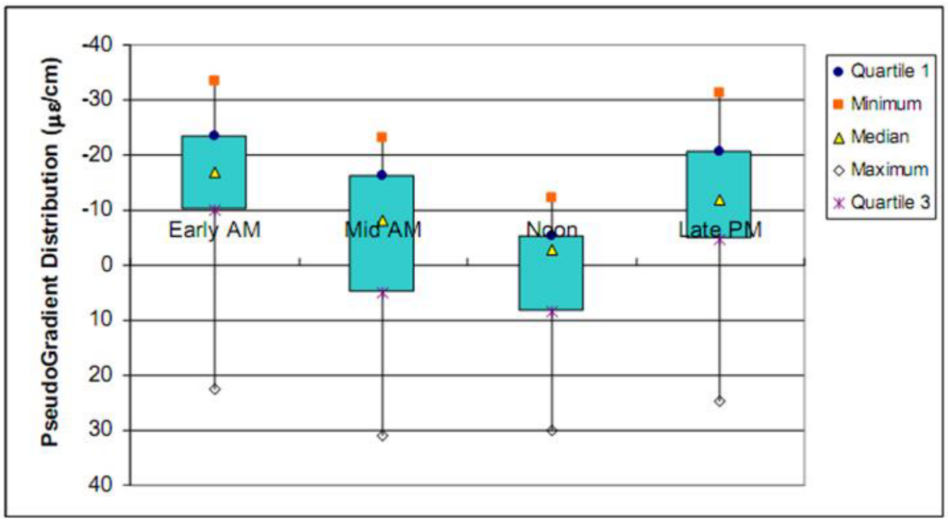
Another study initiated by FHWA in 2002 reviewed the impact of diurnal and seasonal variations in concrete on ride quality measurements. The project, "Inertial Profile Data for Pavement Performance Analysis," collected longitudinal profile data on concrete pavements across the US before sunrise, at sunrise, mid-day, and at sunset in all four seasons. A variety of other measurements were made including pavement temperature to estimate the impact of curling and warping behavior of jointed concrete pavements on ride quality data.(5)

The faulting data collection recommendations are as follows:

- The equipment should be set to collect and store an elevation measurement every 0.75 inch (19 millimeters) as identified in AASHTO R36-12. The development of the spacing is described more fully in ASTM STP 1555.(38)
- Ideally, data will be collected at the same time of day and time of year. Faulting is impacted by the curling and warping of the concrete slabs. Curling is affected by the temperature gradient within the concrete layer

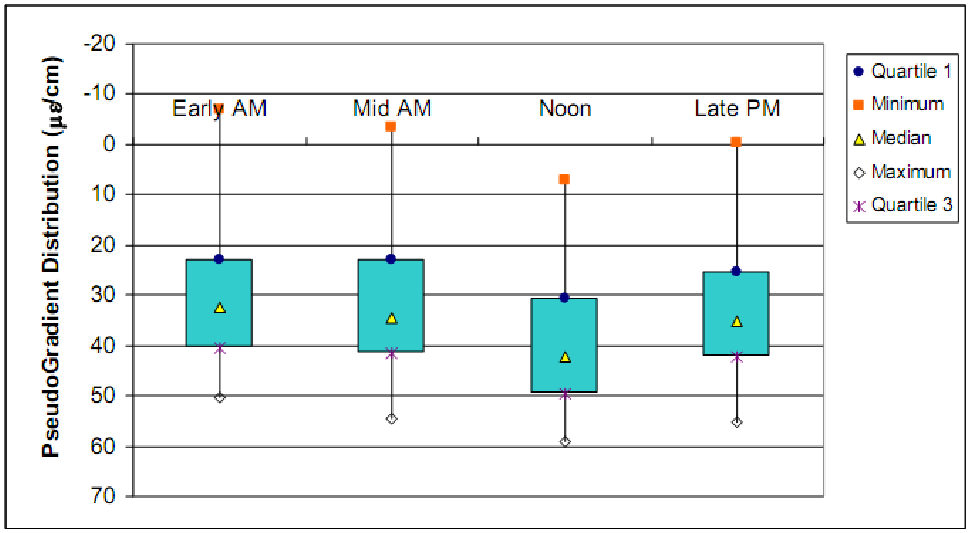
which varies throughout the year and the day. Figure 6.2 and figure 6.3 demonstrate the changes observed in the temperature gradient throughout the day. Further, as noted previously, the gradient changes by season with the lowest temperature gradient observed in winter and the highest in the summer.(6) It is acknowledged that this recommendation is difficult, if not impossible, to attain; however, every effort should be made to minimize differences in the degree of curling from one date to another. This is especially important since the specific amount of change in faulting based on changes in curling is not known. Additional research is required to ascertain a better understanding of the impact of changes in curling on faulting measurements.

Figure 6.2 Observed temperature gradient in a curled-up segment of jointed concrete (5)



Source: G.K. Chang.

Figure 6.3 Observed temperature gradient in a curled-down segment of jointed concrete (5)



Source: G.K. Chang.

6.2 Data Processing Recommendations

The following items were considered with relation to data processing:

- Faulting calculation algorithm.
- Joint spacing.
- Joint detection method.
- Crack / joint faulting calculation.

In order to obtain good estimates of the faulting, it is important to use an appropriate algorithm that has been fully vetted. It is difficult to determine faulting at a joint, if the joint location is not identifiable. Therefore, the joint spacing, joint detection method, and crack/joint calculation selection are instrumental in determining that the faulting is calculated for each joint.

AASHTO R36-12 has been developed to address the calculation of faulting from longitudinal profile measurements.

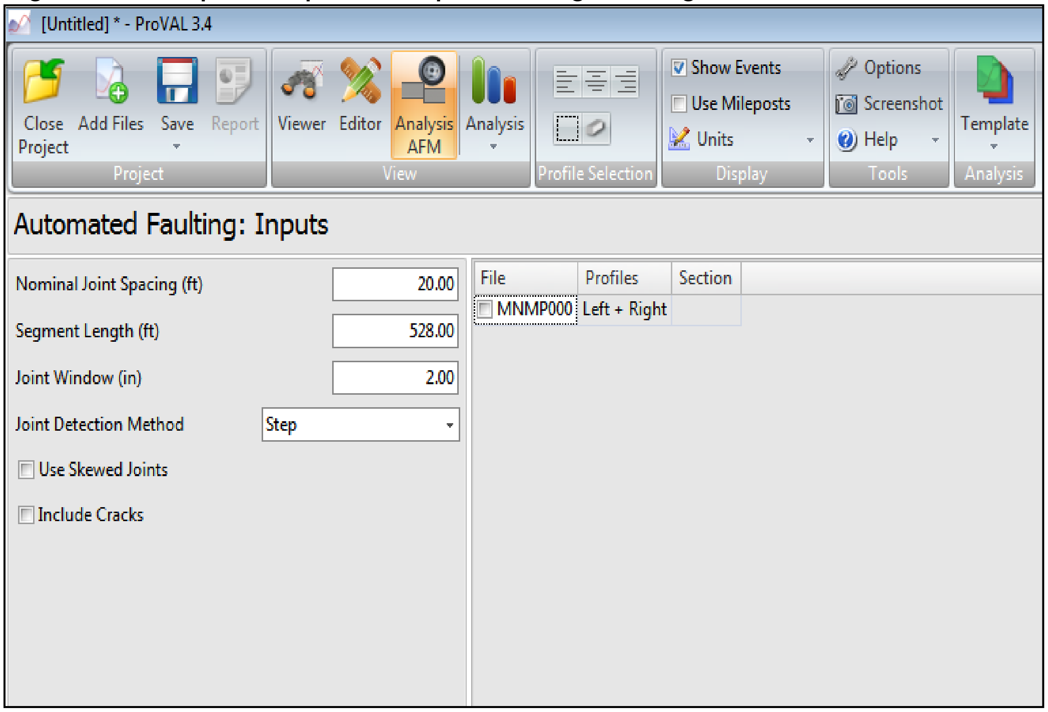
The FHWA has initiated a series of studies to improve measurement capabilities associated with ride quality evaluation of pavements. Program TPF-5(063), "Improving the Quality of Pavement Profiler Measurement," is currently addressing a number of issues related to the implementation of the AASHTO provisional standards for ride quality data collection.(26) As part of this study, the FHWA developed the ProVAL software for processing data from the longitudinal profiler. This software includes an automated faulting module (AFM) for the calculation of faulting on joints and cracks on concrete pavements.

Longitudinal profile data were collected as part of the pilot study of the Interstate 90 corridor discussed under the rutting study. These data were collected along the full length of the pilot study corridor at 2-inch (51-millimeter) intervals. Although the interval between the elevation points does not meet the requirement of 0.75 inch (19 millimeters) as specified in AASHTO R36-12, these data were used to identify the impact of the joint detection method on the faulting calculation. This longer recording interval for the data will impact the ability to detect the joints and cracks within the longitudinal profile data.

The faulting data processing recommendations are as follows:

- ProVAL version 3.3 (or later version) is recommended for calculation of faulting from the longitudinal profile data. Starting with version 3.3, the ProVAL software provides an automated faulting measurement module. Within this module, the software will process the longitudinal profile data to estimate the faulting observed. Figure 6.4 displays the required inputs associated with the AFM. The ProVAL software currently implements Method A of AASHTO R36-12 for estimating faulting. Method A involves using a segment of profile consisting of approximately 8 feet (2.44 meters) centered around the joint. A series of points on the approach slab within the joint window is masked from the calculation. The remainder of the data from the approach slab side of the 8-foot (2.44-meter) calculation window is used to develop a straight line to define the approach slab elevation. Similarly, the data from the departure slab within the 8-foot (2.44-meter) window are used to develop a straight line. The lines are extended such that they overlap by approximately 9 inches (229 millimeters). The average difference between the lines within this 9-inch (229-millimeter) area is identified as the faulting for that joint.

Figure 6.4 Inputs required for processing faulting within ProVAL



Source: FHWA.

- Additional inputs required by ProVAL include the nominal joint spacing (the average as-constructed joint spacing on the section to be analyzed) and the joint window. The joint window is the area from the approach slab that is masked in the faulting calculation as described above. The unit for this item is inches.

- ProVAL provides three joint detection methods within the module. The appropriate method for each agency should be reviewed to identify the most appropriate method(s) for use with their pavements. The three methods are discussed below:
  - \+ The downward spike method performs anti-smoothing filtering of the longitudinal profile. The resulting profile is normalized using its root mean squares. Finally, all spikes with a value of -4.0 or less are identified as either a crack or a joint. The data are reviewed to eliminate multiple cracks or joints within a 1.64-foot (0.50-meter) window. In each case, ProVAL maintains the location with the deepest fault as the primary location.

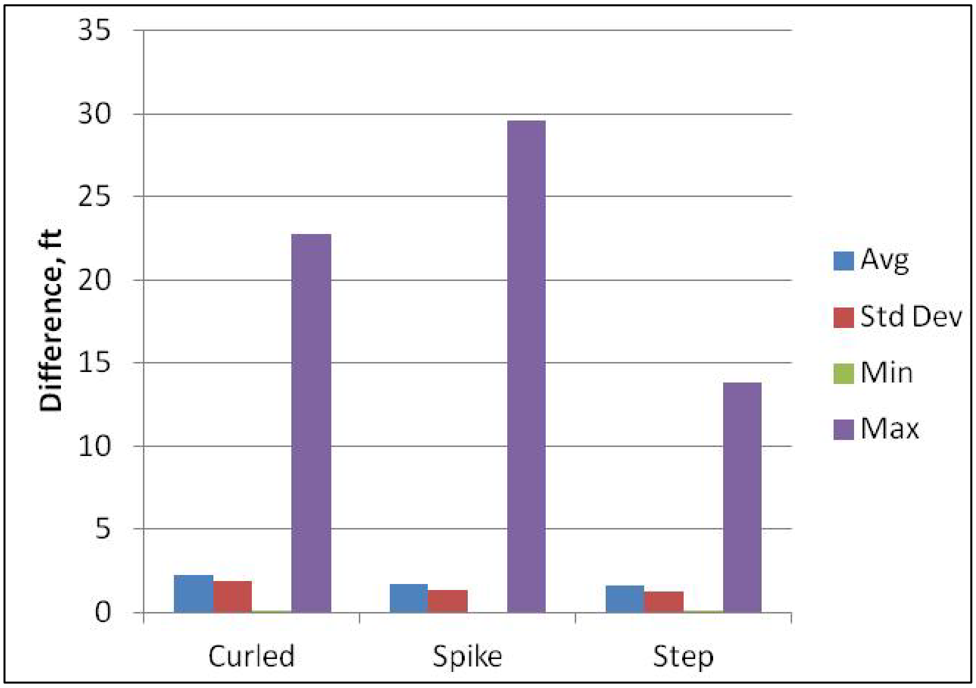
  - \+ The step detection method is identified as being appropriate when faulting is noticeable within the longitudinal profiles. Within the step detection method, locations are identified with a difference in elevation between points of 0.08 inch (2 millimeters) or larger. The data are reviewed to eliminate multiple cracks or joints within a 3-foot (0.91-meter) window. The locations are then classified as either cracks or joints.

+ The curled edge detection method is identified as most appropriate for segments with noticeable slab curling within the profile. Within this method, a bandpass filter is applied to the longitudinal profile data. Next, a 10-foot (3.05-meter) rolling straightedge is simulated along the filtered data. A joint or crack is identified as the location where the simulated rolling straightedge response exceeds 0.12 inch (3 millimeters). As with the downward spike method, multiple locations within a 1.64-foot (0.50-meter) window are eliminated and then the data are classified as either cracks or joints.

The data collected as part of the pilot study within Minnesota were reviewed along with the images collected from milepost 0 to milepost 20. The locations of the joints identified by each detection method were compared to those from the images. Figure 6.5 identifies the average, standard deviation, minimum, and maximum difference between each detection method and the actual locations using the images. The figure illustrates that the downward spike and step methods had the lowest average difference and lower standard deviations than the curled edge method.

Within each detection method, it was noted that some of the joints observed in the images within the 20-mile segment reviewed were not observed by the detection algorithm. The curled edge method missed 12 percent of the joints, the downward spike missed 5.1 percent of the joints, and the step method missed 5.7 percent of the joints. Based on these data, the downward spike and step detection methods provided the most consistent means of locating the joints within this 20-mile (32-kilometer) segment of the pilot study corridor. However, it is not expected that these provide the best method for all concrete pavements. It will be necessary for each State to perform a review of projects to identify the most appropriate joint detection method for the concrete pavements being evaluated within that State.

Figure 6.5 Difference in joint locations by detection method



Source: AMEC and Cambridge Systematics, Inc.

- In performing the faulting evaluation, a number of the joints were identified as cracks for the pilot study data. Therefore, it is recommended that both joints and cracks be included in the analyses. An LTPP study of faulting at joints and cracks has shown that faulting at cracks on concrete pavements may be significant.(31) However, the pilot study data used for computation illustrated that automated faulting calculation at cracks may be difficult as the joint detection methods do not appear as reliable at identifying the locations of cracks as they are at identifying joint locations. Additional research is needed to improve the detection of cracks using automated methods.

6.3 Data Quality Control

The following items were considered in relation to quality control of the collection and processing of faulting data:

- System validation.
- Equipment component checks.
- Processed data checks.

Quality control associated with collection of faulting should begin with a validation of the system to be used for data collection. The system validation provides a means to check the overall operation of the equipment including the individual components and the operational aspects associated with the data collection. System validation is important to ensure that the data collection vehicle meets the quality requirements for the data use.

Component checks are quick checks that may be performed on a routine basis throughout the data collection schedule. These identify that the equipment continues to operate within the bounds of proper limits throughout the data collection cycle.

Checks of the processed data evaluate the calculated faulting. These checks identify errors that may have occurred in the data collection that were not caught by the equipment checks. These checks also identify errors in relational data such as maintenance or rehabilitation not recorded within the database.

Because the recommendation is for faulting to be estimated based on data collected from an inertial profiler, the standards associated with the collection of longitudinal profile data are the primary source for quality control review of these data. AASHTO R56-10 and AASHTO R57-10 provide the basis for the quality control checks recommended here. Furthermore, the LTPP program has noted that checks of collected data are a key element in any quality control program.(19)

The faulting data quality control recommendations are as follows:

- The system validation should include a review of each component of the system as well as the system as a whole as specified in AASHTO R56-10. The standard also provides a means for reviewing the operator. As part of the system validation, perform a review of the equipment's ability to properly detect joint locations for a range of concrete pavements to be evaluated including different texture types, joint spacing and joint types.
- AASHTO R57-10 provides specifications for daily checks to be performed of the equipment during data collection. These checks include checks of tire pressure, block check of height sensor, and a bounce test. A log should be maintained of these checks as a means to review the ongoing condition of the equipment.
- The data should be reviewed for variability over time and space. Based on anticipated precision of data collection (8), the longitudinal profile should be reviewed more thoroughly should any of the following conditions be identified:
  - Increase in faulting > 0.08 inch/year (2 millimeters/year).
  - Decrease in faulting > 0.04 inch (1 millimeter).
  - Difference between segments > 0.10 inch (2.5 millimeters).

6.4 Data Storage Recommendations

For data storage, the following items were considered:

- Base length.
- Date and time of data collection.
- Data elements to be stored.
- Metadata to be stored.
- Quality control review elements.

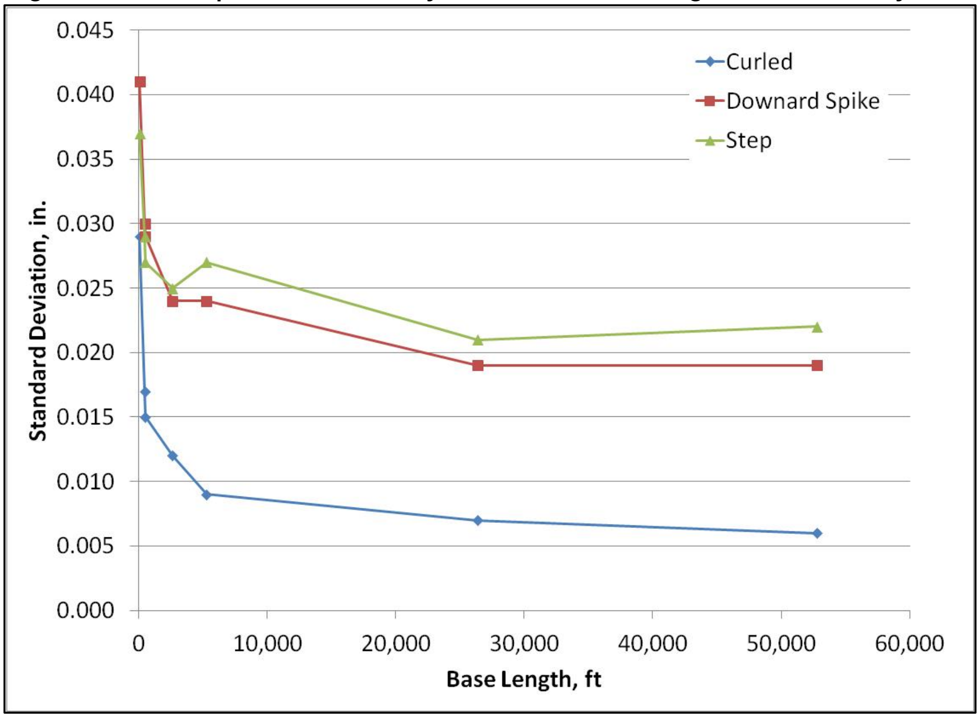
The appropriate data elements are required to allow for appropriate interpretation of the data. The base length refers to the distance over which the faults are averaged for storage in the HPMS database. As noted in the introduction, the anticipated use for these data is to evaluate condition of the nation's IHS. The data should be stored at a sufficiently small interval to allow for an understanding of the peaks and valleys of condition across that network, but not at such a small interval that it is impossible to interpret the overall condition. The metadata are used to describe the data stored in the main HPMS database and are essential in performing quality control reviews of the data obtained. Quality control review elements provide the user of the data with a means to evaluate the quality of the data and whether that data will meet the needs of their purpose.

The pilot study data previously discussed were used to evaluate the segmentation interval. Additionally, the AASHTO R36-12 specification was used to provide guidance on elements to be stored related to faulting.

The faulting data storage recommendations are as follows:

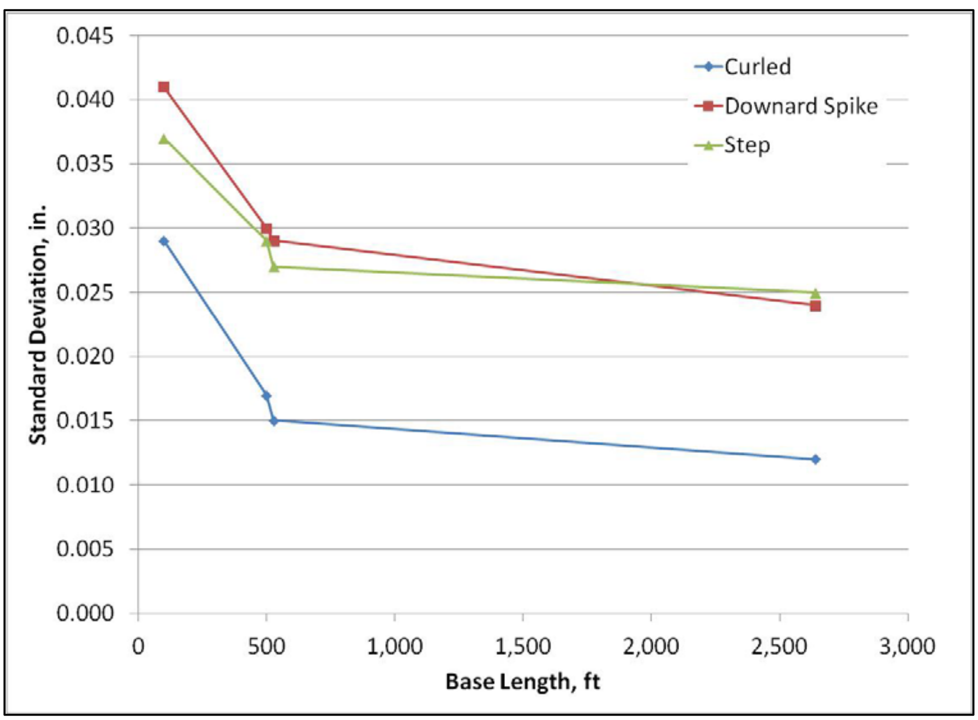
- The base length identifies the length over which the faulting data are summarized. Figure 6.6 illustrates the impact of base length on the variability associated with the faulting results for the corridor. As expected, the standard deviation is greatly reduced with longer segment lengths. Figure 6.7 is provided to illustrate the impact of base length on the variability with the longer base lengths removed allowing the reader to better view the variability associated with the shorter base lengths. In order to be consistent with the recommendations for rutting and ride quality, the faulting data should be summarized to a 0.1-mile (0.16-kilometer) interval length.

Figure 6.6 Impact of summary interval on faulting data variability



Source: AMEC and Cambridge Systematics, Inc.

Figure 6.7 Impact of summary interval on faulting data variability for base lengths up to 2,640 ft



Source: AMEC and Cambridge Systematics, Inc.

- Additional data besides the average faulting are required to appropriately interpret and review faulting. Data elements to store in the HPMS database should include:
  - Average faulting at 0.1-mile (0.16-kilometer) intervals.
  - Maximum and minimum values of faulting as well as the standard deviation of faulting within each 0.1-mile interval
  - Joint detection method.
  - Number of detected cracks and joints.
  - Joint spacing.
- As noted under data collection, the time of day and season may impact the measurement of faulting; therefore, in order to allow for proper interpretation of the data, both date and time of data collection should be stored for these data.
- The HPMS metadata includes the reporting interval, the method of data collection, and the type of equipment used for data collection. The full longitudinal profile collected at 0.75-inch (19-millimeter) intervals should be stored for future use as improvements are made in data processing capabilities.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing. These elements could be as simple as providing a yellow flag where the data do not meet the spatial and temporal consistency limits previously identified and a green flag where they do.

6.5 CONDITION RATING

It is important to recognize that faulting is already incorporated into the ride quality condition indicator. Faulting can also serve as an indicator of pavement structural condition. As noted earlier, some of the primary causes of faulting are loss of support due to pumping or lack of adequate load transfer.

Faulting should be considered as an indicator of pavement condition. The levels for condition were set based on the threshold values of the MEPDG and PHT tool as shown in table 6.1 with the percentage of the pilot study corridor by condition level. (44, 45)

Table 6.1 Condition evaluation based on faulting using a 0.1-mile base length

Condition	Distress Range	Percentage of Corridor
Good	Fault < 0.1 inch	53%
Fair	0.1 inch ≤ Fault ≤ 0.15 inch	26%
Poor	0.15 inch	21%

The faulting thresholds presented in table 6.1 were reviewed as part of the field validation. A total of 20 segments were reviewed for faulting. Of these 20, eight were in poor condition, seven were in fair condition, and five were in good condition.

As with the other distresses, the ratings were assigned a value of 1 for poor, 2 for fair, and 3 for good. These values were then averaged across all raters and compared with the ratings from table 6.1.

The average ratings agreed with the table 6.1 ratings for only 20 percent (4 total) of the segments reviewed. Of the 16 segments where the raters did not agree with the ratings from table 6.1, 14 were rated in better condition than that based on table 6.1 suggesting that the thresholds supplied in table 6.1 are too strict. These 16 segments included two in good condition, six in fair condition, and eight in poor condition. Five of the eight in poor condition were rated on average as good by the raters.

The thresholds should be reviewed based on a larger study to evaluate appropriate levels for rating the pavement condition.

7.0 Cracking Data

ASTM E1778 defines a pavement crack as a "fissure or discontinuity of the pavement surface not necessarily extending through the entire thickness of the pavement."(42) ASTM D6433 identifies cracking as one of the typical distresses that may be observed on pavement surfaces.(33) However, there are a broad array of definitions identifying types of cracks observed on pavement surfaces with these references providing just a few examples.(1,2,7,33,34)

Cracking occurs in pavement surfaces for a variety of reasons. As noted in ASTM D6433, cracks may occur due to excessive loading, climate factors, construction deficiencies or some combination.(33) The type of crack may provide an indication of the cause.

Cracking is commonly used as a key indicator of structural condition of a pavement section.(35) As indicated in ASTM D6433, the pattern of the cracking may provide an indication of the origin of the distress.(33)

One National Cooperative Highway Research Program (NCHRP) study has shown that over 95 percent of the States collect surface distress data.(13) Of the three States examined more closely, all three collect differing levels of detail of these data, suggesting that there will be a wide variety of surface distress data collection across the nation. In short, surface distress data are an important indicator of pavement condition, but there is a wide variety of opinion on the detail required to capture this information.

The HPMS database currently stores cracking data as the percentage of area with fatigue type cracking on asphalt surfaces, percentage of slabs with cracking on jointed PCC surfaces or percentage of punchouts on continuously reinforced concrete pavements (CRCP), and relative length of transverse cracking in feet per mile on asphalt surfaces. The manual identifies that this includes both sealed and unsealed cracks. For all cracking information, the HPMS metadata stores the method used for collecting the cracking data, the types of cracks stored within the percentage of cracking value, and the method used to define the types of cracks observed. The cracking data are collected on the sample panel locations and are optional for other areas where a sample panel section is a fixed segment of roadway that is monitored year to year and is used to represent the full extent of the system that is monitored.(7)

7.1 Data Collection Recommendations

There are a variety of methods for collecting cracking data on pavements. Manual surveys are commonly used for performing a detailed review of the pavement surface. These types of surveys involve the use of traffic control and are not practical for evaluation of large networks. Windshield surveys involve estimating cracking types and quantities while traveling along the network. In order to maintain speed along the highway being evaluated and evaluate a large network, the list of cracking types reviewed is necessarily shortened from the potential list shown in ASTM D6433. More recently collection of cracking data using automated surveys has become more achievable. Improved cameras and lighting techniques using lasers allow for identification of even narrow cracks.

The only element considered with relation to data collection recommendations was the type of equipment used.

The approach in terms of data collection is one of the key aspects of collecting cracking data. This approach needs to be accessible to all agencies, which need to perform the data collection and provide precise and accurate results.

The data collection approach was reviewed based on the available information about repeatability of the approach. The LTPP program has performed an evaluation of manual surveys for repeatability.(9) Additionally, data were provided by Mandli Communications regarding the repeatability of their equipment.(36)

An automated method for collection and processing of cracking is recommended for use in collecting cracking data.

The LTPP program showed coefficients of variation on asphalt surfaced pavements ranging from 9 percent for length of transverse cracking to 38 percent for fatigue cracking.(9) The observed precision is improved for cracking on concrete pavements ranging from 8 percent for length of transverse cracking to 22 percent for longitudinal cracking.(9)

The data from the automated collection was limited to one piece of equipment on asphalt pavement. Based on the experience of the LTPP program, asphalt pavement presents the greatest difficulty in terms of precision.(9) This equipment demonstrated a precision of 6 percent for load-related distress and a precision of 5 percent for non-load-related distress. The precision observed for transverse cracking was 9 percent.

It is recognized that the data presented here are representative of only one manufacturer. However, the vendor used to collect the data does not manufacture their own equipment, but rather they use components from a variety of manufacturers. The sensor used for collection of pavement images was a LCMS device as produced by Pavemetrics.

7.2 DATA PROCESSING RECOMMENDATIONS

The following elements were considered with respect to the processing of cracking data:

- Types of cracking.
- Sampling rate.
- Sample length.

There are a variety of ways to summarize cracking as indicated at the start of this chapter. The method used for summarizing the cracking needs to provide enough detail to capture effects related to climate and load separately. However, the method needs to be sufficiently simple as to limit errors associated with identifying the type of cracking observed. The sampling rate is important in collecting data that appropriately represent the cracking on the pavement section. Similar to the sampling rate, the sample size needs to be large enough to be representative of the pavement section but not so large as to distort the natural changes in conditions.

The current HPMS approach was used as the starting point for reviewing how cracks are identified. Additionally, the AASHTO protocols, PP67-10 and PP68-10, were reviewed for their potential use in obtaining cracking data to evaluate the condition of the IHS.

As part of the pilot study data collection along the Interstate 90 corridor through South Dakota, Minnesota, and Wisconsin, cracking data were collected in accordance with the HPMS protocol. Images were collected along the full length of the corridor and used to estimate the percentage of cracking in the wheelpath and relative length of transverse cracking on asphalt surfaced pavements and percentage of cracked slabs on concrete surfaced pavements. These data were collected using an LCMS sensor.

The cracking data processing recommendations are as follows:

- The HPMS data collection approach is recommended. Admittedly, one major component of this recommendation is based on the status quo of current HPMS data collection methods. The HPMS database currently reports the percentage of cracking in the wheelpath and relative length of transverse cracking on asphalt surfaced pavements including both sealed and unsealed cracks. The database currently houses the percentage of cracked slabs on jointed concrete pavements and percentage of punchouts on CRCP including both sealed and unsealed cracks in both cases. AASHTO PP67-10 currently divides the pavement surface into five zones based on location as it relates to the wheelpath. Cracking is reported in terms of type (pattern, transverse, or longitudinal) by zone. The HPMS approach for storing data captures load-related and non-load related distress information separately for asphalt surfaced pavements.
- A 100 percent sampling rate along with fully automated collection and processing is recommended to reduce the likelihood that outlier areas of condition will be missed in the evaluation. Table 7.1 provides the statistics associated with the two types of cracking collected along the Interstate 90 pilot study corridor. Based on these statistics, the average percent cracking condition could be estimated to a 95 percent level of confidence with evaluation of 10 percent of the 0.1-mile (0.16-kilometer) segments. However, in order to achieve a 95 percent level of confidence on the crack length, 50

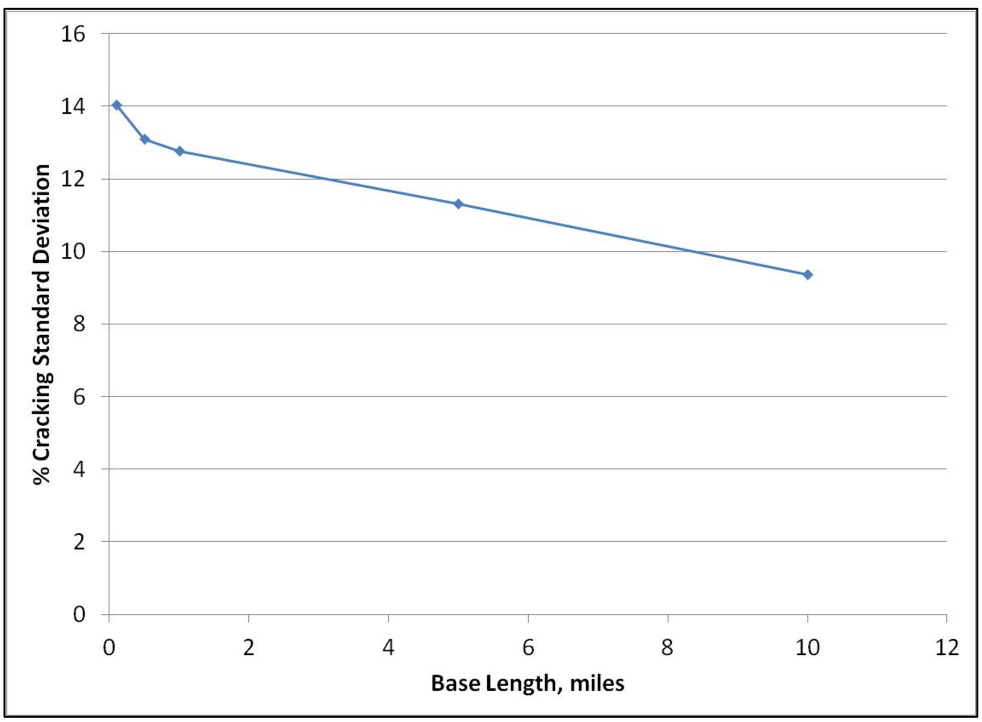
percent of the 0.1-mile (0.16-kilometer) segments must be evaluated. With automated sampling and processing, a 100 percent sampling rate may be achieved with little additional effort over a 50 percent sampling rate.

Table 7.1 Summary of Percent Cracking by Sampling Rate

Cracking Type	Average	Standard Deviation	Minimum	Maximum
% Cracking	5%	14.0%	0%	100%
Crack Length	1,861 feet/mile	3,502 feet/mile	0 feet/mile	23,580 feet/mile

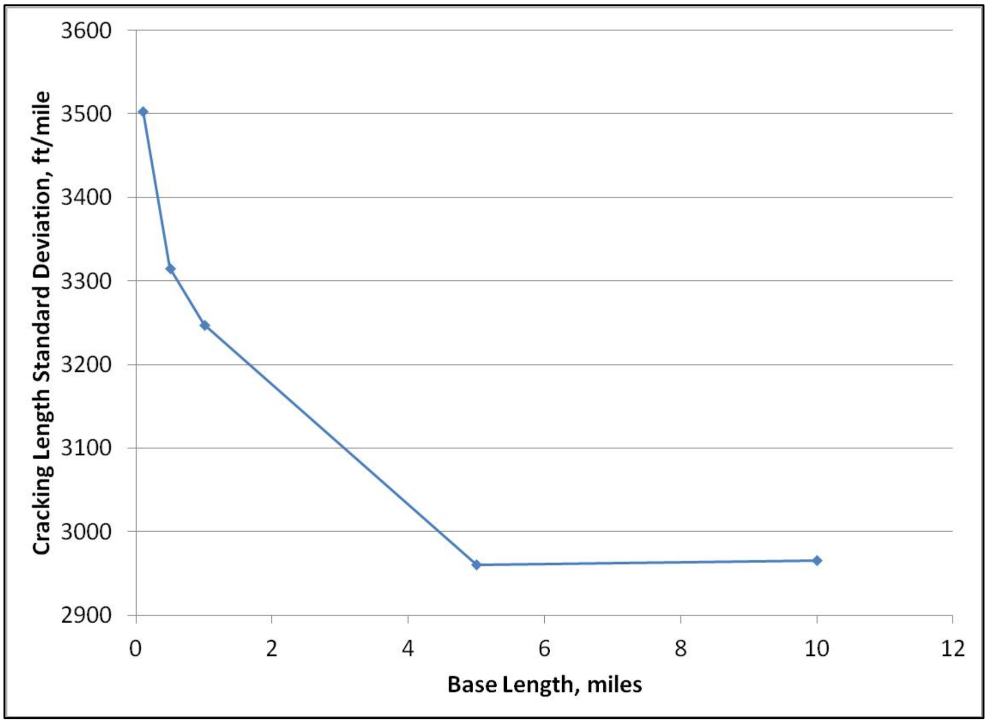
- The base length for summarization of these data should be set to 0.1 mile (0.16 kilometer). This length is consistent with the recommendations for ride quality, rutting, and faulting. Additionally, it allows sufficient detail to identify short areas of very good and very poor condition. The pilot study cracking data were used to estimate the impact of lengthening the base length beyond 0.1 mile (0.16 kilometer). Figure 7.1 and figure 7.2 identify the change in standard deviation by base length for percent cracking and crack length, respectively. These figures illustrate the large decrease in standard deviation at longer base lengths suggesting that for cracking shorter base lengths provide more data regarding the variability in pavement condition.

Figure 7.1 Change in variability of percent cracking by sample length



Source: AMEC and Cambridge Systematics, Inc.

Figure 7.2 Change in variability of cracking length by sample length



Source: AMEC and Cambridge Systematics, Inc.

7.3 DATA QUALITY CONTROL

The following items were considered in relation to quality control of the collection and processing of cracking data:

- System validation.
- Equipment component checks.
- Processed data checks.

Quality control associated with collection of cracking should begin with a validation of the system to be used for data collection. The system validation provides a means to check the overall operation of the equipment including the individual components and the operational aspects associated with the data collection. System validation is important to ensure that the data collection vehicle meets the quality requirements for the data use.

Component checks are quick checks that may be done on a regular basis throughout the data collection schedule. These identify that the equipment continues to operate within the bounds of proper limits throughout the data collection cycle.

Checks of the processed data evaluate the estimated cracking totals. These checks identify errors that may have occurred in the data collection that were not caught by the equipment checks. These checks also identify errors in relational data such as maintenance or rehabilitation not recorded within the database.

AASHTO PP67-10 and AASHTO PP68-10 provide the basis for the quality control checks recommended here. Additionally, the efforts of the LTPP program in reviewing the variability associated with distress data collection were used.(9) Furthermore, the LTPP program has noted that checks of collected data are a key element in any quality control program.(19)

The cracking data quality control recommendations are as follows:

- The first step in quality control is system validation which should be accomplished at the time of contracting with a vendor or purchasing equipment. The equipment validation will involve selection of at least one location for review. A panel rating team should review the site and map the cracks observed.(9) The site should consist of the segments of pavement with surface texture similar to what will be observed within the network to be rated.

  The validation site should be rated by a panel consisting of a minimum of three members which illustrates the differences in precision of distress rating that may be achieved by individual raters versus a panel.(43) The panel will perform a detailed survey including mapping of the cracks to identify type, location, severity, and extent. The map may then be used to review both the images and the automated processing of the data from the equipment. Next, the equipment should be used to perform multiple runs across the validation to evaluate the repeatability of the equipment simply due to the minor variations in operations between runs.

  AASHTO PP68-10 identifies a number of operational aspects to be reviewed as part of the system validation step. These should include the impact of sunlight/shade, surface texture, ambient temperature, and operational speed of the vehicle. It may be difficult to fully assess the impact of ambient temperature on the operation of the equipment; therefore, the manufacturer’s guidelines should be identified and followed.

- During data collection, checks should be performed of each component of the equipment to ensure their continued function. AASHTO PP68-10 proposes a method for continued quality control using a verification site which may be run at regular intervals throughout the data collection season to establish consistency in the equipment operations. The test method suggests that these checks should be performed at least once a month.

- The processed images should be reviewed for accuracy of the automated processing. Checks of the other distresses considered within this report may be automated, but the review of the images are necessarily manual in nature. Therefore, the review of these data should be limited to a “reasonable” amount which provides some assurance that the data are of good quality without becoming too burdensome to complete. No literature could be identified which provided a recommendation for the minimum of manual reviews related to automated processing of data. The recommendations here are general guidelines based on the authors' experience with distress data collection. Further investigation should be conducted to provide a better understanding of the precision and accuracy of automated processing of cracking data.

A minimum of 5 percent of the images should be manually checked for systematic errors in the data collection and processing. In the event that a systematic error is identified or the error rate identified from this review is larger than 15 percent, more of the images should be manually reviewed.

7.4 DATA STORAGE RECOMMENDATIONS

The following items were considered for storage of cracking data:

- Metadata to be stored.
- Quality control review elements.

The appropriate data elements are required to allow for appropriate interpretation of the data. The metadata are used to describe the data stored in the main HPMS database and are essential in performing quality control reviews of the data obtained. Quality control review elements provide the user of the data with a means to evaluate the quality of the data and whether that data will meet the needs of their purpose.

The cracking data storage recommendations are as follows:

- The metadata for the cracking should include those items already stored as well as the images collected. The current metadata for the HPMS database include the type of equipment used for collection of data and the method used to identify the pavement distresses.

  The images should be stored to allow for any required detail review of the data. Additionally, storing the detailed data allows for re-calculation of the cracking in future years should any advances be made in image processing.

- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing. These elements could be as simple as providing a yellow flag where the data do not meet the spatial and temporal consistency limits previously identified and a green flag where they do.

7.5 CONDITION RATING

Cracking is considered an important indicator of pavement condition and more specifically, of pavement structural condition. It is important, however, to recognize that it is an indirect indicator. For example, the presence of cracks in the wheel paths of AC pavements is clearly an indicator of structural deterioration likely resulting from the application of traffic loads. Similarly, the presence of transverse cracks in AC pavements indicates structural deterioration, but in this case likely resulting from environmental effects. Nonetheless, until traffic speed deflection measuring devices are ready for implementation, the use of cracking data is considered the best surrogate as an indicator of pavement structural condition.

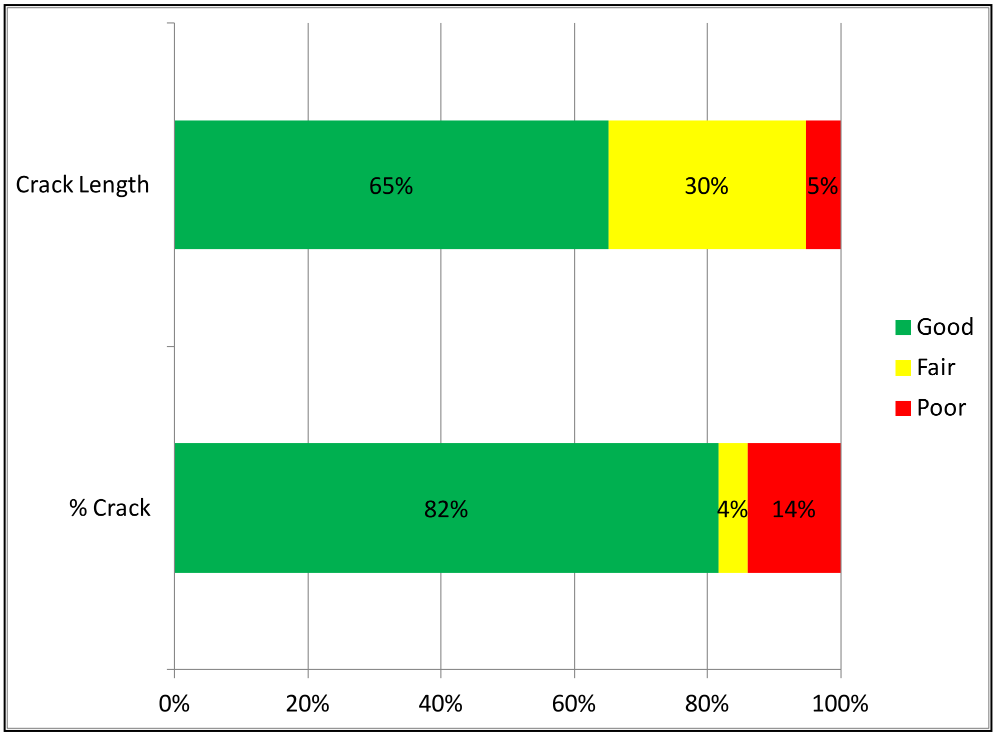
The MEPDG cracking threshold values were considered when setting the condition levels below. The condition associated with cracking, based upon collection of percent of crack slabs on jointed PCC, percentage of punchouts on CRCP and percentage of wheelpath cracking and length of transverse cracking on AC, is as follows:

- PCC % Cracking (Both percentage of cracked slabs on jointed PCC and percentage of punchouts on CRCP)
  - + Good: % Cracking ≤ 5
  - + Fair: 5 < % Cracking ≤ 10
  - + Poor: % Cracking > 10
- AC % Cracking
  - + Good: % Cracking ≤ 5
  - + Fair: 5 < % Cracking ≤ 20
  - + Poor: % Cracking > 20
- AC Crack Length
  - + Good: Length ≤ 265 feet/mile (50 meters/kilometer)
  - + Fair: 265 feet/mile (50 meters/kilometer) < Length ≤ 1060 feet/mile (200 meters/kilometer)
  - + Poor: Length > 1060 feet/mile (200 meters/kilometer)

Figure 7.3 illustrates the condition of the pilot study corridor in terms of these limits.

The field validation effort included review of the thresholds provided for cracking. A total of 17 segments were reviewed for cracking on PCC pavements. All of these segments were jointed PCC with no CRCP included in the review. Of these 17 segments, seven were in good condition, six were in fair condition, and four were in poor condition.

Figure 7.3 Condition of pilot study corridor in terms of cracking using a 0.1-mile base length



Source: AMEC and Cambridge Systematics, Inc.

As with the other distresses, the ratings were given values of 1 for poor, 2 for fair, and 3 for good. These values were then averaged to estimate an average rating for each segment. These average ratings agreed with the report ratings for eight of the 17 segments. Of the nine segments for which the ratings did not agree, one was in good condition, four were in fair condition, and four were in poor condition. The average rating for the segment in good condition was fair while the average rating for the other eight segments was good.

A total of 31 segments were reviewed for percent cracking on AC pavements. All of these segments were in good condition as noted in chapter 3. The AC pavements in the pilot study corridor had limited occurrence of wheelpath cracking making field review of this distress very difficult. Only two of the segments were not rated as good on average.

These same 31 segments with an AC surface were also reviewed for cracking length. Ten of the segments were in good condition and the remaining 21 were in fair condition.

As has been noted previously, the average ratings were obtained by assigning the ratings values and these values were averaged across each of the raters. The average ratings agreed with the report ratings for ten of the 31 segments (four in good condition and six in fair condition). Six of the segments in which the average rating did not match the report, the report-based condition was good and the raters identified them as fair condition. The remaining 15 segments were identified as fair condition by the report and the average rating was good.

The panel of raters noted that rating cracking was difficult due to the angle of the sun on the pavement surface in comparison with the direction of travel. Additional research is recommended to further review the thresholds for cracking recommended in this report.

8.0 Recommendations

As noted previously, the objective of this effort was to develop the next generation pavement performance measure. The objective was revised slightly to concentrate on the individual distresses that should contribute to the overall assessment of condition, namely, rutting, ride quality, faulting, and cracking.

A series of recommendations were developed related to collection, processing, quality control, storage, and condition rating for rutting, ride quality, faulting, and cracking. These recommendations are based on data collected along the Interstate 90 corridor through South Dakota, Minnesota, and Wisconsin as part of the pilot study for the FHWA project "Improving FHWA's Ability to Assess Highway Infrastructure Health." Where these data were insufficient to answer the questions about how the data should be collected, processed, reviewed, stored, and rated; published literature were used to fill in the gaps. All of the recommendations here were reviewed by the members of the TWG noted under the Stakeholder Involvement chapter. Additionally, the condition ratings were reviewed as part of the field validation described in chapter 3.

The following provides each of the recommendations regarding each distress.

8.1 Rutting Data

The rutting data collection recommendations are as follows:

- From AASHTO PP70-10, the data points should cover a minimum width of 13 feet (3.96 meters). This width will help ensure that the full width of the lane is covered.
- From AASHTO PP70-10, the data points should have a separation less than or equal to 0.4 inch (10 millimeters).
- AASHTO PP70-10 recommends a maximum longitudinal spacing between profiles of 10 feet (3.05 meters).

The rutting data processing recommendations are as follows:

- As noted in AASHTO PP69-10, a 2-inch (51-millimeter) moving average filter should be applied to the transverse profile.
- The wireline method is recommended as the basis for the rut depth computation.
- A gage width of 1.2 to 1.5 inches (30 to 38 millimeters) is recommended for use in calculating the rut depth.

The rutting data quality control recommendations are as follows:

- The system validation should include a review of each component of the equipment as described in AASHTO PP70-10. The review should include each component of the device and the operational aspects associated with typical data collection.
- As part of data collection efforts, checks should be conducted routinely of the components. As noted in AASHTO PP70-10 these checks involve regular data collection across a validation section and checks of the distance measuring instrument throughout the active data collection cycle. Typically, these checks would be performed on a monthly basis.
- As noted by the LTPP program, the processed rut depths should be reviewed for quality. This review should include checks of spatial and temporal variability. Based on the error limits identified within AASHTO PP69-10, a manual review of the transverse profile should be conducted if any of the following conditions are met:
  + Spatial change in rutting > 0.1 inch/foot (8 millimeters/meter).
  + Increase in rutting > 0.1 inch/year (2.5 millimeters/year).
  + Decrease in rutting > 0.05 inch (1 millimeter).

The rutting data storage recommendations are as follows:

- The data elements to be stored in the HPMS database associated with rut depth should include the average, minimum, maximum, and standard deviation rut depth and the cross-slope.
- The rut depth statistics should be stored at a base length of 0.1 mile (0.16 kilometer).
- The metadata for rut depth should include the items currently stored in the HPMS database. Additionally, the full transverse profile should be stored for future use.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing. These elements could be as simple as providing a yellow flag where the data do not meet the spatial and temporal consistency limits previously identified and a green flag where they do.

The recommended condition rating for rutting based on MEPDG and PHT threshold values is:

- Good: Rut < 0.25 inch (6 millimeters).
- Fair: 0.25 inches (6 millimeters) ≤ Rut ≤ 0.4 inch (10 millimeters).
- Poor: Rut > 0.4 inch (10 millimeters).

- The field validation confirmed the appropriateness of the threshold between good and fair. The poor segments selected to be reviewed as part of the field validation appeared to have undergone a mill and fill repair since the measured rut depth data were obtained making it impossible to review the threshold between fair and poor.

8.2 RIDE QUALITY DATA

The ride quality data collection recommendations are as follows:

- The data collection interval should be 2 inches (51 millimeters) or less in accordance with AASHTO M328-10. On concrete pavements where the data may be used for faulting measurement, the data collection interval should be 0.75 inch (19 millimeters) or less in accordance with AASHTO R36-12.
- A height sensor should be selected with a sufficient footprint to not be impacted by the surface texture. The recommended footprint will have a width of 2.75 inches (70 millimeters).(27) This footprint may be achieved by a single laser with a width of 2.75 inches or by multiple small dots processed to obtain a single elevation value.
- Ideally, the ride quality data collection would occur at the same time of day and time of year each time it is collected to minimize the impact of diurnal and seasonal variations. This approach may not be practical, therefore, data should be reviewed with the idea that changes in IRI due to curling average approximately 10 inches/mile (0.16 meter/kilometer) with a difference as high as 40 inches/mile (0.63 meter/kilometer).(5)

The ride quality data processing recommendations are as follows:

- The full extent of the system, including bridges and pavement changes, is recommended for inclusion in the IRI calculation.

The ride quality data quality control recommendations are as follows:

- The system validation should include a review of each component of the system as well as the system as a whole as specified in AASHTO R56-10. The standard also provides a means for reviewing the operator's capabilities with relation to data collection and operation of the equipment. This approach assumes that the operator is part of the system being validated.
- AASHTO R57-10 provides specifications for daily checks to be performed of the equipment during data collection. These checks include checks of tire pressure, block check of height sensor, and a bounce test. A log should be maintained of these checks as a means to review the ongoing condition of the equipment.
- As noted by the LTPP program, the processed data should be reviewed for variation both spatially and temporally. Based on AASHTO M328-10, the inertial profiler should be capable of distinguishing differences in IRI as low

as 5 inches/mile (0.08 meter/kilometer). Therefore, the following changes should trigger a detailed review of the longitudinal profile for a segment:

+ Increase in IRI > 10 inches/mile (0.16 meter/kilometer) per year.
+ Decrease in IRI > 5 inches/mile (0.08 meter/kilometer).
+ Change in IRI between adjacent segments > 50 inches/mile (0.79 meter/kilometer).

The ride quality data storage recommendations are as follows:

- The IRI should be calculated and stored at a base length of 0.1 mile (0.16 kilometer).
- Time and date of data collection should be stored with the IRI to allow for appropriate interpretation of the data.
- The metadata for the IRI should include those items already stored as well as the full longitudinal profile. The detailed longitudinal profile data should be stored to allow for review of the data.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing. These elements could be as simple as providing a yellow flag where the data do not meet the spatial and temporal consistency limits previously identified and a green flag where they do.

The recommended method for evaluating pavement ride quality based on IRI as established by FHWA is (41):

- Good: IRI < 95 inches/mile (1.50 meters/kilometer).
- Fair: 95 inches/mile (1.50 meters/kilometer) ≤ IRI ≤ 170 inches/mile (2.68 meters/kilometer).
- Poor: IRI > 170 inches/mile (2.68 meters/kilometer).
- The field validation confirmed the threshold level between good and fair. No firm conclusions could be drawn regarding the threshold level between fair and poor.

8.3 Faulting Data

The faulting data collection recommendations are as follows:

- The equipment should be set to collect and store an elevation measurement every 0.75 inch (19 millimeters) as identified in AASHTO R36-12. The development of the spacing is described more fully in ASTM STP 1555.(38)
- Ideally, data will be collected at the same time of day and time of year. It is acknowledged that this requirement is difficult, if not impossible, to attain;

however, every effort should be made to minimize differences in the degree of curling from one date to another. This is especially important since the specific amount of change in faulting based on changes in curling is not known.

- Additional research is required to ascertain a better understanding of the impact of changes in curling on faulting measurements.

The faulting data processing recommendations are as follows:

- ProVAL version 3.3 (or later version) is recommended for calculation of faulting from the longitudinal profile data. Starting with version 3.3, the ProVAL software provides an automated faulting measurement module. Within this module, the software will process the longitudinal profile data to estimate the faulting observed. The ProVAL software currently implements Method A of AASHTO R36-12 for estimating faulting.
- ProVAL provides three joint detection methods within the module. The appropriate method for each agency should be reviewed to identify the most appropriate method(s) for use with their pavements.
- Both joints and cracks should be analyzed and reviewed for faulting on jointed concrete pavements. The pilot study data used for the analysis presented in this report illustrated that automated faulting calculation at cracks may be difficult as the joint detection methods do not appear as reliable at identifying the locations of cracks as they are at identifying joint locations. Additional research is needed to improve the detection of cracks using automated methods.

The faulting data quality control recommendations are as follows:

- The system validation should include a review of each component of the system as well as the system as a whole as specified in AASHTO R56-10. The standard also provides a means for reviewing the operator. As part of the system validation, perform a review of the equipment’s ability to properly detect joint locations for a range of concrete pavements to be evaluated including different texture types, joint spacing and joint types.
- AASHTO R57-10 provides specifications for daily checks to be performed of the equipment during data collection. These checks include checks of tire pressure, block check of height sensor, and a bounce test. A log should be maintained of these checks as a means to review the ongoing condition of the equipment.
- The data should be reviewed for variability over time and space. Based on anticipated precision of data collection (8), the longitudinal profile should be reviewed more thoroughly should any of the following conditions be identified:
  + Increase in faulting > 0.08 inch/year (2 millimeters/year).

  - Decrease in faulting > 0.04 inch (1 millimeter).
  - Difference between segments > 0.10 inch (2.5 millimeters).

The faulting data storage recommendations are as follows:

- In order to be consistent with the recommendations for rutting and ride quality, the faulting data should be summarized to a 0.1-mile (0.16-kilometer) interval length.
- Additional data besides the average faulting are required to appropriately interpret and review faulting. Data elements to store in the HPMS database should include:
  - Average faulting at 0.1-mile (0.16-kilometer) intervals.
  - Minimum and maximum fault as well as the standard deviation of faulting over each 0.1-mile (0.16-kilometer) interval.
  - Joint detection method.
  - Number of detected cracks and joints.
  - Joint spacing.
  - Date and time of data collection.
- The HPMS metadata includes the reporting interval, the method of data collection, and the type of equipment used for data collection. The full longitudinal profile collected at 0.75-inch (19-millimeter) intervals should be stored for future use as improvements are made in data processing capabilities.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing. These elements could be as simple as providing a yellow flag where the data do not meet the spatial and temporal consistency limits previously identified and a green flag where they do.

Faulting should be considered as an indicator of pavement condition as follows, which is based on MEDPG and PHT threshold values (44, 45):

  - Good: Fault < 0.1 inch (2.5 millimeters).
  - Fair: 0.1 inches ≤ Fault ≤ 0.15 inch (4 millimeters).
  - Poor: Fault > 0.15 inch (4 millimeters).

Based upon the field validation, the threshold values appear to be too strict. However, insufficient data were available to determine the appropriate levels for these thresholds. Accordingly, additional research will be required to set the threshold values.

8.4 CRACKING DATA

The cracking data collection recommendation is:

- An automated method for collection and processing of cracking is recommended for use in collecting cracking data.

The cracking data processing recommendations are as follows:

- The HPMS data collection approach is recommended. Admittedly, one major component of this recommendation is based on the status quo of current HPMS data collection methods. The HPMS database currently reports the percentage of cracking in the wheelpath and relative length of transverse cracking on asphalt surfaced pavements. The database currently houses the percentage of cracked slabs on jointed concrete pavements and percentage of punchouts on CRCP. In all cases, these include both sealed and unsealed cracks.
- A 100 percent sampling rate using fully automated collection and processing is recommended to reduce the likelihood that outlier areas of condition will be missed in the evaluation.
- The base length for summarization of these data should be set to 0.1 mile (0.16 kilometer). This length is consistent with the recommendations for ride quality, rutting, and faulting. Additionally, it allows sufficient detail to identify short areas of very good and very poor condition.

The cracking data quality control recommendations are as follows:

- The first step in quality control is system validation which should be accomplished at the time of contracting with a vendor or purchasing equipment. The equipment validation will involve review of a site based on a crack map prepared by a panel rating team. The crack map will be used to review both the ability of the images to capture the distress and the processing software to achieve the total cracking observed.
- The system validation should include a review of the equipment under varying operational aspects that may be expected as part of data collection. These should include the impact of sunlight/shade, surface texture, ambient temperature, and operational speed of the vehicle. It may be difficult to fully assess the impact of ambient temperature on the operation of the equipment; therefore, the manufacturer's guidelines should be identified and followed.
- During data collection, checks should be performed of each component of the equipment to ensure their continued function. AASHTO PP68-10 proposes a method for continued quality control using a verification site which may be run at regular intervals throughout the data collection season to establish consistency in the equipment operations.
- The processed images should be reviewed for accuracy of the automated processing. A minimum of 5 percent of the images should be manually

checked for systematic errors in the data collection and processing. In the event that a systematic error is identified or the error rate identified from this review is larger than 15 percent, more of the images should be manually reviewed.

The cracking data storage recommendations are as follows:

- The metadata for the cracking should include those items already stored as well as the images collected. The current metadata for the HPMS database include the type of equipment used for collection of data and the method used to identify the pavement distresses.
- The images should be stored to allow for any required detail review of the data. Additionally, storing the detailed data allows for re-calculation of the cracking in future years should any advances be made in image processing.
- Quality control elements should be added to the HPMS database to allow for the user to identify potential issues with the data being used and how these issues may impact the analyses they are pursuing. These elements could be as simple as providing a yellow flag where the data do not meet the spatial and temporal consistency limits previously identified and a green flag where they do.

The recommended condition rating for cracking is as follows:

- Unlike rutting and faulting, cracking is considered an important indicator of pavement condition and more specifically, of pavement structural condition. It is important, however, to recognize that it is an indirect indicator.

  The MEPDG cracking threshold values were considered when setting the condition levels below. The condition associated with the cracking is as follows:

  + PCC % Cracking (% of cracked slabs on jointed PCC and % of punchouts on CRCP)
    - Good: % Cracking ≤ 5.
    - Fair: 5 < % Cracking ≤ 10.
    - Poor: % Cracking > 10.
  + AC % Cracking
    - Good: % Cracking ≤ 5.
    - Fair: 5 < % Cracking ≤ 20.
    - Poor: % Cracking > 20.
  + AC Crack Length
    - Good: Length ≤ 265 feet/mile (50 meters/kilometer).

    - Fair: 265 feet/mile (50 meters/kilometer) < Length ≤ 1060 feet/mile (200 meters/kilometer).
    - Poor: Length > 1060 feet/mile (200 meters/kilometer).
- The field validation effort was unable to validate the thresholds associated with cracking. The angle of the sun with relation to the direction of travel made cracking difficult to observe. Additional research will be required to evaluate these thresholds.

8.5 RECOMMENDED FUTURE RESEARCH

The following items are recommended for future research to improve current capabilities in data collection and processing:

- Additional research is required to define appropriate thresholds of good / fair / poor with respect to a combination of rutting, cross-slope and speed of a facility that delineate safety considerations.
- Additional research is required to ascertain a better understanding of the impact of changes in curling on faulting measurements.
- Additional research is needed to improve the overall faulting measurement. In particular, the detection of joints and cracks which have little to no fauting within the longitudinal profile data using automated methods is nearly impossible. Potentially, the longitudinal profile data could be married to the cracking imagery to assist in identifying the cracks and joints within each segment.
- Additional research needs to be undertaken to review the threshold levels associated with evaluating condition based on faulting. The field validation identified that the threshold values are probably too strict, but based on the results of that effort, definitive levels could not be identified.
- Additional work is required to review the threshold levels associated with evaluating condition based on cracking. The field validation efforts related to cracking were inconclusive due to the difficulty of rating the distress and the general lack of cracking on the pavement reviewed.
- Additional consideration needs to be given to sealed cracks and length of ruts. These items are not currently considered by the HPMS guidelines.

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Appendix A. Minutes of First TWG Meeting

TECHNICAL MEMORANDUM

Date: August 28, 2012

To: Nastaran Saadatmand **FHWA Contract No.:** DTFH61-07-D-00030-T-10002
From: Gonzalo Rada **AMEC Project No.:** 6420101002.415
CC: Steve Gaj, Jonathan Groeger, Amy Simpson

Subject: FHWA Highway Infrastructure Health Assessment Study – Task 15 "Next Generation Pavement Performance Measure" Technical Working Group: TWG Meeting #1 Minutes

The objective of Task 15 under the FHWA Highway Infrastructure Health Assessment Study is to develop a next generation pavement performance measure that provides an accurate and repeatable assessment of the functional condition of the roadway. In support of this objective, a Technical Working Group (TWG) was formed to assist the project team.

The first TWG meeting – a webinar – was held on August 23, 2012, starting at 2:00 pm Eastern Daylight Time.

All eight invited TWG members participated in the initial webinar. They include:

- Edgardo Block, Connecticut DOT
- Judy Corley-Lay, North Carolina DOT
- Colin Franco, Rhode Island DOT
- Ralph Hass, University of Waterloo
- Rick Miller, Kansas DOT
- Brian Schleppi, Ohio DOT
- Roger Smith, Texas A&M University/TTI
- Katie Zimmerman, Applied Pavement Technology (APTech)

In addition to the TWG members, the following FHWA and project team members participated in the webinar:

- Steve Gaj, FHWA
- Gonzalo Rada, AMEC
- Jonathan Groeger, AMEC
- Amy Simpson, AMEC

The agenda for the initial webinar as well as highlights for each agenda item are provided below:

1. Welcome and Introductions

   Steve and Gonzalo welcomed the TWG members on behalf of the FHWA and the project team, respectively, and thanked them for their willingness to assist with the effort.

   As part of the introductions, the charge given to the TWG was as follows:

+ Provide technical review/input as project progresses
+ Provide stakeholder perspective
+ Act as a "sounding board" to bounce ideas around
+ Act as "messenger" to industry with project final results

An overview of the planned TWG activities was also provided under this agenda item, and they included:

+ Meeting 1 (Webinar) – review of project, pilot study results, discuss overall approach, provide input/ideas
+ Meeting 2 (Webinar) – Discuss detailed work plan
+ Meeting 3 (face-to-face in Washington DC) – discuss individual component recommendations, discuss FCI recommendations and plan for ground truth
+ Review of final report

2. Pilot Study Overview

An overview of the pilot study was presented by Jonathan, in order to provide the foundation for the effort in question. The overview included the project genesis, objectives, approach (including tracks 1 and 2), structure, stakeholder involvement, questions asked and answered, corridor statistics, data gathering (HPMS, State PMS and Field), tier 1 metric (validating IRI), tier 2 metric (functional condition index components), tier 3 metrics (structural condition), and overall observations and recommendations.

During the overview, which lasted approximately 40 minutes, the TWG members were provided the opportunity to ask questions on two occasions. The first at the conclusion of the pilot study data description and the second at the conclusion of the overview. These Q&A periods, but especially the second one, provided much interesting discussion, which is captured under agenda item 5 (TWG input).

3. Task 15 Next Generation Performance Measure SOW and Approach

Approximately 15 minutes were spent by Gonzalo addressing this agenda item. The topics discussed included the task goal, objective, scope of work and approach, including a more detailed discussion of Subtasks 15.2, 15.3 and 15.4 activities and their relation to the TWG activities.

The agenda provided as part of the presentation had the Task 15 scope of work and approach as two separate items, but they were treated as one agenda item during the webinar.

4. TWG Input

As part of the presentation, a slide containing possible input from the TWG was prepared and included the following items:

+ Comments on overall approach
+ Ideas on potential data collection protocols that may gain acceptance across the United States
+ Potential FCI models
+ Concerns/items to consider
+ Critical references

However, the use of the above referenced slide was not necessary as all TWG members actively participated in the webinar without the need for encouragement.

Highlights of the input provided by the TWG members are presented below:

+ When discussing the results of the IRI portion of the study Steve polled the TWG to see if they recommended performing a comparative analysis of IRI on two more corridors in regions other than the I-90 corridor. The TWG thought this a worthy undertaking.
+ Prior to actual development of the indices, it is imperative that the audience and objective(s) of the functional composite index be clearly established. During the webinar, FHWA was defined as the primary audience, but it should also be of use to the State DOTs. In addition, it was suggested that the index will be used to assess the functional condition of the pavement at the state and corridor level. Other items discussed in relation to audience and objective(s) included the definition of index levels:
    - Pavement ride quality: primarily intended for roadway users (but could have negative impact on preservation as is the case of structural indicators)
    - Pavement distresses: geared for treatment, intervention and planning activities.
    - Pavement deflection: intended for project/engineering level planning activities.
+ Related to the above bullet item, it was suggested that the functional condition index should contain the following pavement condition indicators:
    - Ride quality (IRI)
    - Pavement distresses.

  Consideration should also be given to separating pavement distresses into structural versus non-structural related distresses.
+ Specifically related to IRI, some members of the TWG thought IRI data should be submitted to FHWA in one-tenth mile increments and the segmenting performed at FHWA. Also, reporting of IRI data for speed sunder 40 miles-per-hour should be considered for deletion due to issues with IRI at lower speeds. It was commented that in general collection of IRI in urban areas is a problem that should be addressed.
+ In development of the individual and composite indices, careful consideration must be given to the data collection and processing protocols associated with the generation of the HPMS data, which are to drive the indices. Items to consider include temporal (frequency, time of year, etc.) and spatial (longitudinal as well as transverse, as appropriate) issues. Consideration should also be given to the ability of the State DOTs to collect the proposed data; e.g., will they be able to purchase the necessary equipment. Similarly, protocols for collection should address accuracy, precision, and resolution (data collection spacing and averaging intervals).
+ It is also important that quality control/quality assurance of the data used to populate the HPMS database be addressed, as these data will be used to drive the indices.
+ The following references were suggested by the TWG for review and consideration in development of the indices:
    - Brown, D.N., Measuring Pavement Condition Data for the Establishment of a Long-Term Pavement Performance Study on New Zealand Roads.
    - Haas, R., A. A. El Halim, K. Helali, S. Khanal, and C. Winiarz. Performance Measures for Highway Road Networks. Transportation Association of Canada. March 2012.
    - Harrision, et. al., Comparative Performance Measurement: Pavement Smoothness. NCHRP 20-24(37B).

  These references have been obtained and reviewed by the project team, and they have been incorporated into the project literature review.

The above input is consistent with the SOW and approach presented by the project team for development of the indices.

5. Wrap-up / Path Forward

   Members of the project team discussed the path forward, which is to prepare a detailed work plan for development of the individual and functional composite index. This work plan will be provided to the TWG and it will be discussed during the second TWG webinar, which will likely take place in October 2012.

   FHWA and the project team again thanked the TWG members for their willingness to help on this important undertaking as well as for their valuable input during the initial webinar. The webinar concluded at 3:45 pm Eastern Daylight Time.

Overall, the initial webinar was considered a great success and it laid out an excellent foundation for carrying out the remainder of the index development work.

Please let us know if you have questions, require clarification or would like to discuss the above.

Appendix B. Work Plan

Development of the Next Generation Pavement Performance Measure: Detailed Work Plan

PUBLICATION NO. None

Draft - October 2012

U.S. Department of Transportation

Federal Highway Administration

FOREWORD

This document outlines the detailed work plan to develop a next generation pavement performance measure that provides an accurate and repeatable assessment of the functional condition of the roadway. The measure will combine ride quality, cracking and rutting or faulting into a composite functional index (FCI). In addition, this measure is to rely entirely upon Highway Performance Monitoring System (HPMS) pavement data. The work plan considers the findings from the Federal Highway Administration (FHWA) work titled, "Improving FHWA's Ability to Assess Highway Infrastructure Health: Pilot Study Report" along with the results of a literature review on pavement performance measures and the input provided by the Technical Working Group (TWG) established specifically for the purposes of this effort. The work plan consists of five tasks: Task 1.Definition of data requirements, Task 2. Development of individual performance indices, Task 3. Development of next generation pavement performance measure, Task 4. Calibration and validation of new pavement performance measure, and Task 5. Preparation of report and implementation recommendations. The activities associated with each of the above tasks are detailed along with the proposed schedule for completion of the tasks.

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7. Author(s) Rada, G.R., Groeger, J.L., Visintine, B. and Simpson, A.L.		8. Performing Organization Report No.
9. Performing Organization Name and Address AMEC Environment & Infrastructure, Inc. 12000 Indian Creek Court, Suite F Beltsville, Maryland 20705		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-07-D-00030-T-10002
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration Office of Asset Management 1200 New Jersey Avenue, SE Washington, D.C. 20590		13. Type of Report and Period Covered Draft Work Plan 14. Sponsoring Agency Code

15. Supplementary Notes
The Contracting Officer's Representative (COR) was Mr. Jason Harrington, P.E. The Task Monitor was Ms. Nastaran Saadatmand, P.E.

16. Abstract
This document outlines the detailed work plan to develop a next generation pavement performance measure that provides an accurate and repeatable assessment of the functional condition of the roadway. The measure will combine ride quality, cracking and rutting or faulting into a composite functional index (FCI). In addition, this measure is to rely entirely upon Highway Performance Monitoring System (HPMS) pavement data. The work plan considers the findings from the Federal Highway Administration (FHWA) work titled, "Improving FHWA's Ability to Assess Highway Infrastructure Health: Pilot Study Report" along with the results of a literature review on pavement performance measures and the input provided by the Technical Working Group (TWG) established specifically for the purposes of this effort. The work plan consists of five tasks: Task 1.Definition of data requirements, Task 2. Development of individual performance indices, Task 3. Development of next generation pavement performance measure, Task 4. Calibration and validation of new pavement performance measure, and Task 5. Preparation of report and implementation recommendations. The activities associated with each of the above tasks are detailed along with the proposed schedule for completion of the tasks.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 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)

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INTRODUCTION

The objective of the effort addressed in this work plan is to develop a next generation pavement performance measure that provides an accurate and repeatable assessment of the functional condition of the roadway. The measure will combine ride quality, cracking and rutting or faulting into a composite functional condition index (FCI). In addition, this measure is to rely entirely upon Highway Performance Monitoring System (HPMS) pavement data.

Previous work by the Federal Highway Administration (FHWA) and the task order team (AMEC and Cambridge Systematics, Inc.) established the potential viability of this type of measure; this work is documented in "Improving FHWA's Ability to Assess Highway Infrastructure Health: Pilot Study Report." However, a more detailed treatment and investigation is warranted, hence the pursuit of this effort.

In developing this work plan, the task order team considered the findings from the above referenced pilot study along with the results of a literature review on pavement performance measures and the input provided by the Technical Working Group (TWG) established specifically for the purposes of this effort, which had its first meeting (a webinar) on August 23, 2012. The results of the literature review are contained in Appendix A, while the minutes of the initial TWG meeting are contained in Appendix B.

Prior to laying out the proposed detailed work plan and consistent with a TWG recommendation, both the intended audience and objectives of the next generation pavement performance measure are introduced here as they help provide a more clear context for development of the measure.

> ***Audience****:* The next generation pavement performance measure is being developed for and it is intended solely for the use of the FHWA. However, it is anticipated that other highway agencies may have an interest in reviewing and considering the resulting measure for their own purposes.
>
> ***Objective***: The purpose of the next generation pavement performance measure is to enable the FHWA to more accurately and consistently assess the condition of portions (one or more states, corridors, etc.) or the entire national highway pavement system. The measure is to include not only ride quality (AASHTO Tier 1 measure), which is especially important from a users' viewpoint, but because ride quality does not necessarily provide a clear picture of pavement condition, it is to include pavement surface distresses (cracking and rutting or faulting; AASHTO Tier 2). Although pavement structural condition (AASHTO Tier 3) would be highly desirable, the technology is not ready at present for incorporation into the proposed measure.

With the above audience and objective in mind, the major tasks proposed for development of the next generation pavement performance measure are as follows:

1. Definition of data requirements,

2. Development of individual performance indices,

3. Development of next generation pavement performance measure,

4. Calibration and validation of new pavement performance measure, and

5. Preparation of report and implementation recommendations.

The activities and schedule associated with each of the above tasks are detailed in the next section of this document.

WORK PLAN

Task 1. Definition of Data Requirements

As stated earlier, the next generation pavement performance measure is to be driven entirely by HPMS pavement data – ride quality (IRI), cracking and rutting or faulting. For the measure to truly accomplish its intended objective, however, enhancements to the HPMS data collection processes are required in order to ensure not only consistent and uniform data from one State DOT to another, but also accurate and repeatable data. The need for high quality data in the HPMS database is of paramount importance to the development of the composite FCI if it is to truly serve its intended objective; otherwise, as the old adage goes, "garbage in, garbage out." Those changes cover the range of activities from data collection to processing to QC/QA to storage, and they are detailed under this task.

> The objective of this task is to establish data requirements that will lead to complete and high-quality pavement condition data in the HPMS database. Establishing the data requirements will not be a significant challenge given current technology, but their implementation will be due to the impacts on State DOTs. The impacts include not only the possible purchase of expensive equipment, but also changes in current data collection, processing, QC/QA and storage practices and the associated implications. These changes will not happen overnight, rather it is envisioned that it will take a five-year transition phase or greater for the State DOTs to comply with the data requirements to be developed.

a. Data Collection

Significant differences presently exist on how State DOTs collect data for input to the HPMS database. For example, some State DOTs collect IRI data that is reported at 0.1-mile intervals while others report IRI data on segments greater than 15-miles, and this can and does have an impact on the composite FCI. Longer reporting intervals tend to average pavement roughness, while shorter intervals tend to show rougher or smoother intervals. Similarly, some State DOTs use 4,000 or more transverse elevation points to determine rut depths, while others use just three or five points. Again, this can and will have a significant impact on the composite FCI.

Accordingly, the objective of this subtask is to define clear data collection requirements and protocols that address the following items:

- Data collection elements; e.g., IRI, structural cracking, non-structural cracking, rutting and faulting.
- Data collection equipment specifications; e.g., longitudinal elevation data to be used in faulting determinations must be collected at an interval not to exceed 5-mm, transverse profile measurements should contain at least 1,000 points for rut depth determinations, etc.
- Equipment calibration and/or check requirements prior to data collection.

- Data collection temporal requirements; e.g., time/season of year (spring, summer, fall or winter) and time of day (morning, afternoon or night) when data should be collected.

- Data collection spatial requirements; e.g., transverse profile measurements should be collected every 50-ft and should contain at least 1,000 data points for rut depth determinations, while longitudinal profile measurements should be recorded at 1-inch intervals and reported at 0.1-mile intervals for IRI purposes.

- Data collection speed requirements; e.g., the minimum speed for the collection of IRI data should exceed 40 mph and instructions on what to do when those requirements cannot be met, as could be the case in urban areas.

Each of the above requirements/protocols apply to the HPMS pavement data elements; i.e., IRI, cracking, rutting and faulting. In the development of these requirements/protocols, the project team will pursue the following approach:

- Review information gathered as part of the literature review, which is contained in Appendix A to this work plan.

- Take advantage of project team data collection experience that been has gained over the past 20+ years on projects for the FHWA, State DOTs and other agencies.

- Pursue unpublished reports and/or information for ongoing projects; e.g., the FHWA Data Collection Guide for HPMS Pavement Data Items.

It is recognized that the resulting requirements/protocols will impose a significant burden on most or all State DOTs, especially given current financial constraints, but unless high quality data are collected the usefulness of the HPMS database for generating the composite FCI is significantly compromised.

It is also recognized that the referenced data collection requirements may need to be phased over time for a number of reasons (e.g., State DOTs readiness), accordingly an implementation plan will also be an outcome for this subtask.

b. Data Processing

As was the case with the collection of the raw data, processing of the data collected can vary significantly from one State DOT to another. In most cases this is driven by the business needs of and experience of each DOT. This can be impacted by the vendor who performs their data collection or which provided the equipment to the State DOT. For example, the tools provided by one vendor use a 6-ft straightedge with a 40-mm ruler gauge width to compute rutting, while another vendor may use the same straightedge but with a 50-mm ruler gauge width or the wireline method. Again, these changes in processing tools will affect the computation of the composite FCI. However, it is felt that the processing tools provided by the vendors could be revised without much impact if clear processing requirements are established. In other cases, tools that have been developed with the support of state or federal agencies, which are not provided by the vendors, could be used. An excellent example is the FHWA-sponsored ProVal software for the processing of longitudinal profile data and the computation of IRI and/or faulting.

Accordingly, the objective of this subtask is to establish specific data processing requirements. These processing requirements apply to all HPMS pavement data elements and may include:

- Use of specific processing tools such as the earlier referenced ProVal software.
- More generic requirements such as the separation of structural and non-structural distresses from pavement images.
- Use of specific algorithms such as the use of wire line method for the computation of rut depths.

The project team's approach to establishing the data processing requirements will be the same as described under Subtask 1.a – i.e., rely on literature review findings, project team's experience and unpublished reports and/or information from on-going projects.

Unlike data collection, the data processing requirements are not expected to have a significant impact on State DOTs, other than the issues associated with the transition from one approach to another and adaptation. However, like data collection, it is possible that data processing requirements may need to be phased over time, concurrent with the associated data collection, and hence an implementation plan also needs to be an outcome from this subtask.

c. Data Quality Control/Quality Assurance

Implementation of the data collection and processing requirements under the previous two tasks will go a long way towards ensuring uniform and consistent quality data. Nonetheless, it is vital that both the raw and processed data undergo QC/QA to ensure that is indeed the case. QC/QA elements are already contained in the HPMS database, but there is certainly room for improvement. For example, the use of time-history data is an excellent QC/QA tool. More specifically, comparison of say, this year's processed data (IRI, distress, rutting and faulting) versus that from two years ago, can quickly identify data issues; e.g., IRI decreased from two years ago to today, but no maintenance and rehabilitation (M&R) is indicated in the HPMS database, so either there is a data issue or missing M&R data. Moreover, implementation of the time-history QC/QA check can easily be automated and implemented.

Accordingly, the objective of this subtask is to review the QC/QA elements presently contained in the HPMS database as well as other information readily available and formulate a QC/QA plan for implementation by State DOTs as well as within the HPMS database. Fortunately, much work has been done in the development of QC/QA tools, so some of the specific items that will be considered and reviewed as part of this subtask include:

- Existing HPMS database QC/QA elements.
- QC/QA elements and tools available from the data collection vendors.

- QC/QA elements and tools developed by highway agencies. The FHWA ProVal as well as the many QC/QA elements developed under the Long-Term Pavement Performance (LTPP) program are excellent examples.

- Information resulting from the literature review performed in support of this effort, which is contained in Appendix A to this report.

The outcome from the above review will be a list of candidate HPMS data QC/QA elements and tools for further consideration based on the following criteria:

- Demonstrated usefulness and value of the QC/QA elements and tools in achieving high quality data.

- Ease of adaptation of QC/QA elements and tools by the State DOTs and within the HPMS database.

As part of this subtask, the project team will also address implementation of those QC/QA elements and tools by the State DOTs as well as within the HPMS database. Other than transition and adaptation issues, no significant challenges are envisioned as part of the implementation.

d. Data Storage

By the time Subtasks 1.a through 1.c have been completed, the most critical HPMS data issues will have been addressed except for one: the storage of pavement condition data within the HPMS database. While it is not the intent of the project team to address the HPMS database schema, it will nonetheless address issues that cascade from the previous subtasks including:

- Incorporation of new data elements; e.g., computed parameters.

- Implementation of new data QC/QA elements and tools as well as the possible incorporation of the outcomes from these elements and tools into the database; e.g., data quality flags.

The outcome from this subtask will be a list of recommend changes and/or enhancements to the HPMS database schema.

Task 2. Development of Individual Performance Indices

Once the data requirements and protocols have been clearly established, the next task in the work plan entails the development of the individual pavement performance measure indices for IRI, cracking, rutting and faulting.

To begin with, the project team will first consider the definition of these indices in the very simplistic terms of good/fair/poor (G/F/P) categories. For example, the

> The objective of this task is to develop individual performance condition indices for IRI, cracking and rutting or faulting. Because implementation of the Task 1 data requirements may take five-years or more, it is possible that two sets of indices could be proposed – one for use now and the other five-years later.

thresholds for pavement roughness (IRI) could be defined as follows:

Category	IRI Threshold, in/mile
Good	< 95
Fair	95 ≤ IRI ≤ 170
Poor	> 170

Similarly, the thresholds for rutting could be defined as follows:

Category	Rutting, in
Good	< 0.1
Fair	0.1 ≤ Rutting ≤ 0.40
Poor	> 0.4

The resulting G/P/F categories will then be evaluated using the project team's previous work on the pavement Good/Fair/Poor measures. More specifically, the ground-truth data from the pilot study will be used to evaluate the reasonableness of the G/P/F categories.

Because much work has already been done in the development of the individual indices in question by state, national and international highway agencies, it is possible that one or more of those indices could be used either partially or fully in this effort, and hence this will be the next step in the task.

Appendix A of this work plan contains the results of the literature review completed in support of the effort. As anticipated, the pavement condition data collected by the State DOTs varies from one state to another, and hence so do the indices used by these states to represent the functional condition of pavements. According to the information provided in Appendix A, the indices used by nine of the State DOTs can be used directly in conjunction with the HPMS data – this is important since the individual indices as well as the composite FCI must be entirely driven by data contained in the HPMS database.

Based on the information contained in Appendix A, the project team intends on evaluating the individual indices from the following agencies, which range from simple to more sophisticated approaches and which appear to be most promising:

- Florida DOT
- Illinois DOT
- Indiana DOT
- Minnesota DOT
- Mississippi DOT

- Ohio DOT
- Transportation Association of Canada
- Virginia DOT

In support of the evaluation, and as was the case with the G/P/F categories, the project team will use the ground-truth data collected as part of the pavement Good/Fair/Poor measures pilot study.

In addition to the two sets of activities discussed so far, the project team will also:

- Evaluate and consider the lessons learned from the project team's previous work on the pavement Good/Fair/Poor measures.
- Conduct internal brainstorming meetings to identify other potential indices not covered by the two sets of referenced activities, including the potential development of new indices. For example, the recommended set of individual indices could be a combination of G/P/F categories and numeric indices.
- Pursue input from the FHWA and the FHWA TWG established to support the effort.

As part of this task, the project team will further evaluate the viability of separating cracking into load and non-load related cracking, so as to address pavement structural capacity issues, which a number of agencies are already doing. While a number of issues presently exist with the quality of the cracking data in the HPMS database, it should not be a problem to separate cracking and the benefits that could be gained by doing so in terms of the usefulness of the composite FCI are significant.

The outcome from this task will be a list of the recommended individual indices (IRI, cracking, rutting and faulting) for use in the development of the composite FCI. The goal is to have one recommended index per HPMS pavement condition data element, with cracking separated into load and non-load related cracking.

Task 3. Development of Next Generation Pavement Performance Measure

The objective of this task is to develop the composite FCI based on the individual performance condition indices. Like Task 2, it is possible that two composite FCIs could be proposed – one for use now and the other five-years later.

The objective of this task is to investigate how best to combine (if combined at all), the individual indices resulting from the previous task into a composite FCI. The first step towards accomplishing this objective is to establish the relative importance of each HPMS pavement data element in terms of the composite FCI and determine how best to incorporate this relative importance within the composite FCI. Accordingly, as part of this activity, the project team will consider and evaluate the following options:

1. Define the composite FCI in terms of the individual indices developed under Task 2 as they are, without combining them, whether in terms of numeric values or G/P/F

categories, as illustrated below for AC pavements. In other words, each individual index stands on its own.

IRI Category	Rutting Category	Load Cracking Category	Non-Load Cracking Category
3	2	1	2
1	2	3	2
3	1	1	1
2	3	3	3

2. Define the composite FCI based upon the individual pavement performance measure G/F/P categories. For example, "Good" could be assigned a value of 3, "Fair" a values of "2" and "Poor" a value of 1. Similarly, "cracking, rutting and faulting" could be assigned a weight of 3, and IRI a weight of 1. Using these values, the composite FCI value could be numerically computed, as illustrated below for AC pavements:

$$\text{Composite FCI Value} = \frac{(1*\text{IRI category value})+(3*\text{rutting category value})+(3*\text{cracking category value})}{7}$$

The resulting values from the above relation are rounded off to nearest integer and the composite FCI G/FG/P category assigned; 3 for good, 2 for fair and 1 for poor. Example results are provided below for illustration purposes:

IRI Category Value	Rutting Category Value	Cracking Category Value	Composite FCI Value	Composite FCI Category
1	2	3	2	Fair
3	1	1	1	Poor
1	3	3	3	Good

3. Evaluate the composite FCI in use by a number of agencies, which are driven by the pavement condition data consistent with those in the HPMS database. More specifically, based on the results of the literature review presented in Appendix A, the composite FCI used by the same agencies considered under Task 2. They include:

   + Florida DOT

   + Illinois DOT

+ Indiana DOT
+ Minnesota DOT
+ Mississippi DOT
+ Ohio DOT
+ Transportation Association of Canada
+ Virginia DOT

4. Define the composite FCI based on some of the individual indices with the remaining indices serving as flags. For example, the IRI and cracking indices could be used to determine the composite FCI value, while rutting could serve as a safety flag.

5. Define the composite FCI as a combination of two or more of the above options.

The primary basis for evaluating the composite FCI under each of the six options will be the HPMS pavement data (i.e., pilot ground-truth data) from the project team's previous work on the pavement Good/Fair/Poor measures. Using these data, a preliminary assessment regarding the reasonableness of the various composite FCIs considered will be conducted and, as needed, adjustments and refinements to the index will be made. Further calibration and validation of the recommended composite FCI will be done under Task 4.

In addition to the recommended composite FCI, the project team will also pursue development of Good/Fair/Poor criteria under this task based on the composite FCI values. The lessons learned from the project team's previous work on the pavement Good/Fair/Poor measures will again be a primary driver in this effort. Other drivers include the findings from the literature review as well as the input from FHWA and the FHWA TWG.

The outcomes from this task will be the recommended composite FCI and the Good/Fair/Poor criteria. An interim report summarizing the effort carried out under Tasks 1 through 3 as well the associated findings, conclusions and recommendations will also be prepared under this task. This interim report will be provided to the FHWA and to the FHWA TWG and it will be discussed at a face-to-face meeting in Washington, D.C.

Task 4. Calibration and Validation

In order to implement the next generation composite FCI, it is vital that a calibration and validation process be undertaken and such process will be carried out under this task. Towards this end, the project team proposes to carry out a ground-truth exercise. The specific activities associated with this exercise are as follows:

> The objective of this task is to calibrate and validate the recommended composite FCI, which will be accomplished through a ground-truth exercise.

- Select manageable and convenient location for carrying out the ground-truth exercise. The original I-90 pilot study corridor will most likely be the location used given the availability of data, familiarity with the location, State DOT cooperation, etc. Because the corridor is over 800 miles long, targeted (based on condition, pavement type, etc.) segments within the corridor not to exceed 10-miles will be selected so that a more meaningful ground-truth exercise can be carried out. The definition and selection of these shorter segments will be carried out as part of the activity that follows.

- Develop a ground-truth evaluation plan that addresses:

    - Data collection, processing and QC/QA needs; e.g., is all data available or will new data collection and/or processing be required.

    - Analyses to be carried out on the data gathered at the selected location; e.g., computation of individual indices and composite FCI.

    - Formation of the ground-truth panel.

    - Schedule of ground-truth activities.

- In consultation with the FHWA and the FHWA TWG, select the ground-truth panel. It is anticipated that the panel will consist of eight people; 2 project team members, 4 TWG members and 2 FHWA members.

- Perform the ground-truth exercise in accordance to the evaluation plan developed under the second activity of this task. As part of this effort, the panel will travel to and evaluate the selected pavement sections.

- Compile and analyze data from ground-truth exercise and based on the results, calibrate the composite FCI based on established Good/Fair/Poor criteria.

The outcome of this task will be a calibrated and validated composite FCI, which is the ultimate objective of the work plan.

Task 5. Preparation of Report and Implementation Recommendations

> The objective of this task is to clearly document the development of the composite FCI and to recommend the next steps.

Under this task, the project team will prepare a final report documenting the results of the effort. This report will include the results of Tasks 1 through 4, and it will provide concise recommendations for the next generation pavement condition measure, lessons learned, and next steps (e.g., roll out the measure to a broader state audience to get buy-in, calculate the measure for all states using current HPMS data, coordinate with AASHTO's subsequent efforts, etc.).

A draft of the report will be delivered to FHWA and to the FHWA TWG for review and comment. Once comments have been received, the report will be prepared as final.

SCHEDULE

The work plan presented in this document will be reviewed by the FHWA and the FHWA TWG and it will be discussed during a 90-minute FHWA TWG webinar, which will be held during the second half of October 2012. The work plan will be revised as needed based on the FHWA and FHWA TWG input, and finalized by the end of October or early November 2012. Execution of the final work plan will commence immediately afterwards, with an anticipated start date of November 15, 2012.

The proposed work plan schedule is as follows:

- Task 1. Definition of data requirements – November 15 to December 31, 2012 (1.5 months).

- Task 2. Development of individual performance indices – November 1 to December 31, 2012 (2 months, concurrent with Task 1).

- Task 3. Development of next generation pavement performance measure – January 1 to February 15, 2013 (1.5 months).

- Presentation of tasks 1 through 3 results to FHWA and FHWA TWG and revisions to task 3 interim report – February 15 to 28, 2013 (one-day face-to-face meeting in Washington, D.C. and revisions to Task 3 interim report).

- Task 4. Calibration and validation of new pavement performance measure – March 1 to April 30, 2013 (2 months).

- Task 5. Preparation of report and implementation recommendations – May 1 to June 15, 2013 (1.5 months).

APPENDIX A: LITERATURE REVIEW

INTRODUCTION

The literature review presented herein was performed in support of the development of the next generation pavement performance measure that provides an accurate and repeatable assessment of the functional condition of the roadway. This measure is to combine ride, cracking, and rutting or faulting into a composite functional condition index (FCI) and it is to be based upon the use of the Federal Highway Administration (FHWA) Highway Performance Monitoring System (HPMS) data.

Potential approaches to development of the FCI were researched, which included both development of individual performance indicators and combinations of individual indexes into functional composite indices. The findings of the literature review are summarized in this document.

Because the next generation FCI is to be based upon HPMS data, this literature review also contains a summary of the HPMS data elements and associated requirements.

LITERATURE FINDINGS

New Zealand (Brown 2005)

In the development of a Long-Term Pavement Performance (LTPP) study in New Zealand, emphasis was placed on equipment needs, calibration, validation and data collection methodologies so that the data collected from year to year could be attributed to actual changes in pavement performance and not variance in data collection. The paper by Brown focuses on the collection and measurement of rutting, roughness and texture of roadways. As part of the development of the next generation pavement performance measure, data collection protocols will be recommended. A summary of the protocols recommended by Brown follows.

Measurements of longitudinal profiles:

- Changes in roughness from one year to the next can be very small (often less than 0.05 IRI mm/m) and it can be several years before a noticeable change occurs. Equipment resolution and repeatability must exceed these low limits to ensure that observed changes in the data reflect changes in the pavement and not just equipment variability.

- The skill and experience of the surveyors. On smooth surfaces variations between skilled and unskilled surveyors is negligible; however, as roughness and texture increase so does the variability and accuracy of the measurements.

- Transverse and longitudinal alignment. Relatively small changes (100 to 200 mm) in both the transverse and longitudinal location can have a significant influence on the reported IRI. It is important to select equipment and develop procedures which ensure the same or identical measurement location.

- Pavement cross-fall and corners. Steeply sloped surfaces and both vertical and horizontal curvature have been found to influence both the magnitude and repeatability of the reported IRI. Minimizing the effects of these features can be achieved through multiple surveys and by surveying the profile in forward and reverse directions.

- Outlier or erroneous measurements. Collecting multiple profiles can be used to identify when outlier or erroneous data have been collected. Surveying with two or more profilers can also assist in determining measurement accuracy.

- Equipment faults. With over 140 calibration sections taking approximately six months to survey, it is essential to have in place procedures which will detect any long term drift and/or equipment faults. Deploying two or more profilers and establishing and using reference sites where equipment performance can be checked provides assurance that data quality is not compromised.

- Data review and processing. On site processing of all data will reveal erroneous data and facilitate visual inspections to confirm changes or find plausible reasons for the change. Where data is suspect or where repeatability limits are exceeded additional runs can be made.

Validation of IRI equipment measurement is based on the 100-m IRI at reference sites and accepted if the Coefficient of Variance (CV) is less than 0.05, while field acceptance is based on the standard deviation of three measurements per site with acceptance values of 0.01 for asphalt and fine graded (6-mm) chip seal and 0.15 for coarse graded locked (20-mm and 12-mm) chip seal. The field repeatability values based on the standard deviation of the three measurements were 0.02 for asphalt surfaces, 0.05 to 0.10 for single grade chip seal and 0.10 to 0.15 for locked grade 3 and 5 chip seal.

Measurements of transverse profiles:

- The device should measure a continuous profile. Many papers have been written which demonstrate the limitations of devices which take spot measurements of the transverse profile.

- The instrument accuracy should have a vertical resolution equal to or better than 0.2 mm. With expected changes in rut depth of 1 to 2 mm per year a resolution ten times this was considered appropriate.

- The profiler should be relatively easy to use, requiring only a single operator and be capable of measuring up to 3.8m without extending into oncoming traffic in adjacent lanes. As ruts develop they grow both vertically and transversely and so the measuring width and height must be flexible rather than a fixed width or set of fixed points over a nominal width.

- The profiler should work equally well on a flat asphalt surface with little or no texture and on a coarse surface (large chip seals) with a lot of texture.

- The instrument should display the profile in real time, calculate the rut depth and display the position of the straight edge once the profile measurements are completed.

- The analysis software should allow for manipulation of or positioning of the straight edge when calculating the rut depth. Measured profiles do not always fall into the characteristic or idealistic shapes and often the positioning of the straight edge needs adjustment to locate the true rut.

Measurements of surface texture:

- Measurement location. Both transverse and longitudinal positioning of the profiler is very important as the texture (in New Zealand at least) is quite positional sensitive especially on flushed surfaces.

- Ease of operation. The mobility of the instrument and its operation.

- Visual display. A visual display of the measured profile is important so the operator can ensure data integrity and quality immediately.

University of Mississippi (George 2000)

Mississippi developed a composite condition index referred to as Pavement Condition Rating (PCR) stored in the state PMS database that is based on physical distresses, rutting, faulting, and roughness data. This index is based on a scale of 0 to 100 and is determined by a rater assessing the serviceability of a pavement considering quality of ride, surface defects, pavement deformation, cracking distress and maintenance patches. Each distress is assigned a deduct value signifying severity and extent of the distress observed based on deduct curves/equations. The combined index consisting of roughness and distress ratings is expressed as:

$$PCR = 100\left(\frac{12 - IRI}{12}\right)^{a} * \left(\frac{DP_{max} - DP}{DP_{max}}\right)^{b}$$

Figure 1. Equation. Mississippi Pavement Condition Rating

Where:

IRI	=	road roughness, m/km
DP_{max}	=	probable maximum deduct points with 205, 230, 185 and 145, respectively for flexible, composite, jointed, and continuously reinforced concrete pavements
DP	=	total deduct points for a pavement section
a	=	0.9567 for flexible, jointed concrete, and continuously reinforced concrete pavements; and 1.11 for composite pavements
b	=	1.4857 for flexible, jointed concrete, and continuously reinforced concrete pavements; and 1.5429 for composite pavements

FHWA-Kansas, Michigan, Minnesota, Texas and Washington (Wu et.al. 2010)

A FHWA research study titled "Performance Evaluation of Various Rehabilitation and Preservation Treatments" investigated the degree to which pavement preservation treatments extended the service life of pavements based on data from six target states. The states provided data from their PMS for 185 projects collectively and the data was summarized for the following items:

- Timing of application – the stage of life (in years) the preventive and/or rehabilitative action was taken.
- Annual average daily traffic and percentage of trucks on the pavement section associated with each treatment.
- Distress types and values used to trigger each treatment.
- Extended pavement service life or structural life associated with each treatment.
- Cost/lane-mile associated with each treatment.

As part of the data collection process, the states also reported how the pavement condition rating (PCR) was calculated. A summary for how the six target states calculated PCR is provided below.

Kansas DOT reported PCR in terms of IRI.

Michigan DOT calculates a Distress Index (DI) as a weighted score of the Distress Points (DPs) assigned based on the type, extent and severity of distresses collected (transverse, longitudinal, and alligator cracking; block cracking; patches; and raveling) and is calculated by:

$$DI = \frac{\sum DP}{L}$$

Figure 2. Equation. Michigan Distress Index

Where L is the number of 0.1-mile pavement sections. The threshold values for DI were reported as low ($DI \leq 20$), medium ($20 < DI < 40$), and high ($DI \geq 40$) with a DI of 50 corresponding to an RSL of 0.

Minnesota DOT calculates three condition indices – Present Serviceability Rating (PSR), Surface Rating (SR) and Pavement Quality Index (PQI) – based on collected roughness, rutting, cracking, and faulting data. PSR, the ride or smoothness index, is calculated as:

$$PSR = 5.6972 - 2.104 * IRI$$

Figure 3. Equation. Minnesota Present Serviceability Rating

The SR, the crack and surface distress index, is calculated by converting the amount of distress to a percentage, multiplying the percentage by an individual weighting factor and summing all individual weighted distresses as the Total Weighted Distress (TWD). The TWD is converted to SR based on Table 1.

The PQI, overall pavement condition index, combines PSR and SR and ranges from 0.0 (failed) to 4.5 (no defects) and is calculated by**:**

$$\mathbf{PQI = \sqrt{PSR * SR}}$$

Figure 4. Equation. Minnesota Pavement Quality Index

Table 1. Calculating SR from Total Weighted Distress (Wu et al., 2010)

Total Weighted Percent	SR	Total Weighted Percent	SR
0	4.0	19-20	1.7
1	3.8	21	1.6
2	3.6	22-23	1.5
3	3.4	24	1.4
4	3.2	25-26	1.3
5	3.0	27	1.2
6	2.9	28-29	1.1
7	2.8	30-33	1.0
8	2.7	34-40	0.9
9	2.6	41-47	0.8
10	2.5	48-54	0.7
11	2.4	55-61	0.6
12	2.3	62-68	0.5
13	2.2	69-75	0.4
14	2.1	76-82	0.3
15	2.0	83-89	0.2
16-17	1.9	90-96	0.1
18	1.8	97-100	0.0

Texas DOT combines distress ratings, ride quality measurements (measured IRI converted to Serviceability Index), average daily traffic and speed limit into a Condition Score (CS) according to the process detailed in the flowchart in Figure 6.

A utility value between 0 and 1 is calculated for each distress following the equation (Wu et al., 2010):

$$\boldsymbol{U_i = 1 - \alpha e^{\left(\frac{\rho}{L_i}\right)^{\beta}}}$$

Figure 5. Equation. Texas Utility Value

Where:

- U = utility value
- L = level of distress (for distress type) or ride quality lost (for ride quality)
- i = distress type (e.g., deep rutting or punchouts)
- e = base of the natural logarithms ($e = 2.71828\ldots$)
- α = a horizontal factor controlling the maximum amount of utility that can be lost
- ρ = a prolongation factor controlling "how long" the curve "last" above a certain value
- β = a slope factor controlling how steeply utility is lost in the middle of the curve.

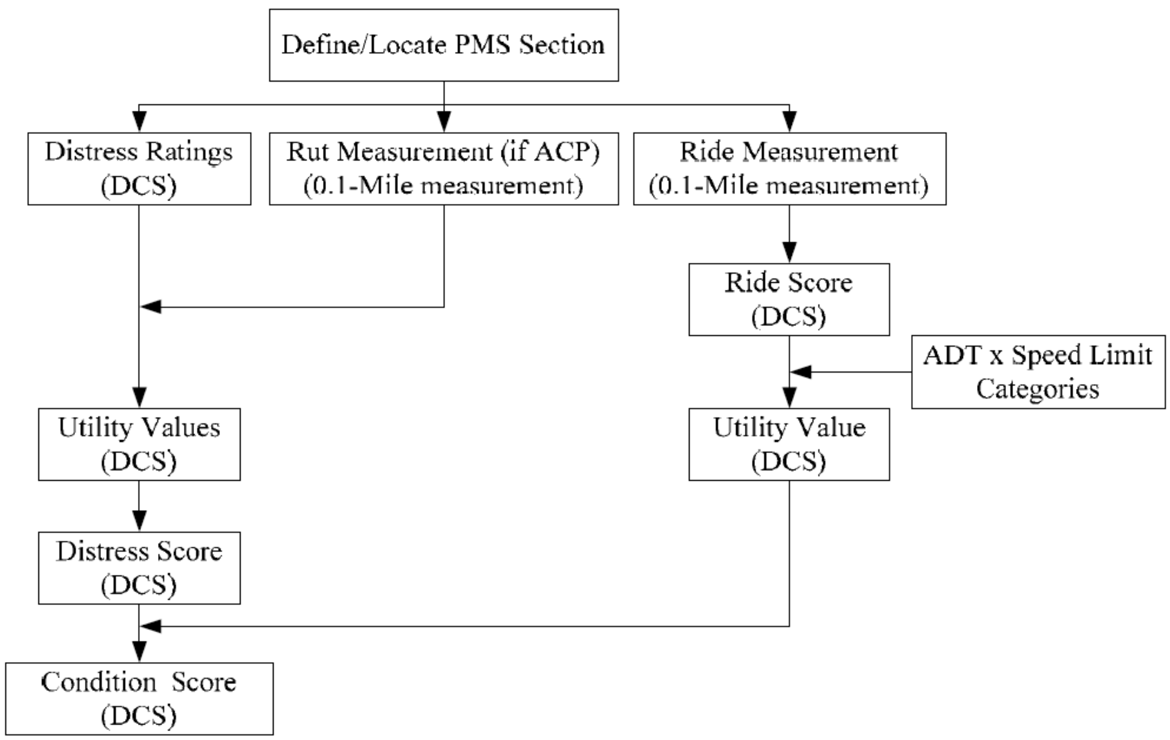

Figure 6. Flowchart. TXDOT Process Used to Calculate PMIS Condition Score (Wu et al., 2010)

The pavement DS is calculated using the utility values of the distresses present based on pavement type as shown in Table 2.

The CS combines the Distress Utility and the Ride Utility:

$$CS = 100 * U_{DS} * U_{RS}$$

Figure 7. Equation. Texas Condition Score

Where:

- CS = Condition Score
- DS = Distress Score
- U_{RS} = Ride utility score from 0 to 1

Washington State DOT uses the Pavement Structural Condition (PSC) to quantify the condition of the pavement based on the severity of distresses present for flexible and rigid pavements and uses the following scale:

- Excellent $75 < PSC \leq 100$
- Good $50 < PSC \leq 75$
- Fair $25 < PSC \leq 50$
- Poor $0 < PSC \leq 25$

Table 2. TXDOT Pavement Types, Distress Types and Rating Methods (Wu et al., 2010)

Pavement Type	Distress Score Equation
Asphalt Concrete Pavement (ACP)	$DS=100*[U_{SRut}*U_{DRut}*U_{Patch}*U_{Fail}*U_{Blk}*U_{Alg}*U_{Lng}*U_{Trn}]$ DS= Distress Score U = Utility Value SRut= Shallow Rutting DRut = Deep Rutting Patch = patching Fail = Failures Blk = Block Cracking Alg = Alligator Cracking Lng = Longitudinal Cracking TRN = Transverse Cracking
Continuously Reinforced Concrete Pavement (CRCP)	$DS=100*[U_{Spall}*U_{punch}*U_{ACPat}*U_{PCPat}]$ DS= Distress Score U = Utility Value Spall = Spalled Cracks Punch=Punchouts ACPat = Asphalt Patches PCPat = Concrete Patches
Jointed Concrete Pavement (JCP)	$DS=100*[U_{Flj}*U_{Fail}U_{SS}*U_{Lng}* U_{PCPat}]$ DS= Distress Score U = Utility Value Flj = Failed Joints and Cracks Fail = Failures SS = Shattered (Failed) Slabs Lng = Slabs with Longitudinal Cracking PCPat = Concrete Patches

An "equivalent cracking (EC)" value is calculated for each distress based on extent and severity level. The PSC is calculated by the following equations:

$$Flexible\ pavements: PSC = 100 - 15.8(EC)^{0.5}$$

Figure 8. Equation. Washington Flexible Pavement Structural Condition

$$Rigid\ pavements: PSC = 100 - 18.6(EC)^{0.43}$$

Figure 9. Equation. Washington Rigid Pavement Structural Condition

FHWA-Delaware, Maryland and Virginia (Giuffre 2010)

The research study performed for the FHWA by William L. Giuffre titled *Evaluation of Highway Performance Measures for a Multi-State Corridor – A Pilot Study* analyzed bridge and pavement data across a multi-state corridor and evaluated the quality of existing performance measures. The research considered HPMS and PMS databases from Virginia, Maryland and Delaware for pavements. Both Delaware and Virginia compute a composite index combining several distresses to measure the overall pavement condition.

Delaware uses the Overall Pavement Condition (OPC), which combines the average and standard deviation of five individual indexes for asphalt patching, surface defects, fatigue cracking, block cracking and transverse cracking that are calculated based on severity and extent of the distress. The OPC is calculated as:

OPC = average – (1.25*stdev)

Figure 10. Equation. Delaware Overall Pavement Condition

Virginia uses the Critical Condition Index (CCI), combining a load distress index (LDR) which describes distress related to wheel loads, and a non-load distress index (NDR) which describes weathering related distresses. The CCI is computed as the lower of the LDR and NDR. The LDR and NDR are based on deduct values (based on the curves from PAVER) for severity and extent of the distresses and more detrimental distresses are weighted more heavily than others. The CCI does not include IRI as an input.

Maryland did not use a composite index.

With the importance of developing consistent performance measures to be used across the nation, this study compared the algorithms for the composite indexes across states by computing the OPC using Virginia data and the Delaware algorithm. The distresses provided by Virginia were mapped to the distresses used in calculating OPC, with the assumption that Surface Defects is equal to IRI*Rut Depth being the most problematic. The extent and severity of the distresses were also calculated for the Virginia data and the OPC calculated. The OPC calculated based on the Virginia data was compared to the CCI as shown in Figure 12 and has a correlation coefficient of 0.714. Giuffre concludes that based on this relationship and the fact that neither OPC nor CCI correlated well with IRI in Virginia (-0.49 and -0.45, for OPC versus IRI and CCI versus IRI, respectively), composite indices provide a better measure of pavement condition than IRI.

Illinois Center for Transportation (Heckel and Ouyang, 2007)

The Illinois Department of Transportation (IDOT) has used models to calculate Condition Rating Survey (CRS) and predict future CRS since 1994 and 1995. Existing models were updated and new models were created for pavement types without models using multiple linear regression. The regression model took the following form:

$$CRS = Intercept - x*IRI - y*Rutting - z*Faulting - a*A - b*B - c*C\ldots$$

Figure 11. Equation. Illinois Condition Rating Survey

Where:

Intercept	=	starting point for the calculation
x, y, and z	=	coefficients for the sensor data (as applicable)
IRI, Rutting, and Faulting	=	values of the sensor data
a, b, c	=	coefficients for the distresses
A, B, C	=	severity values of distresses recorded by the raters

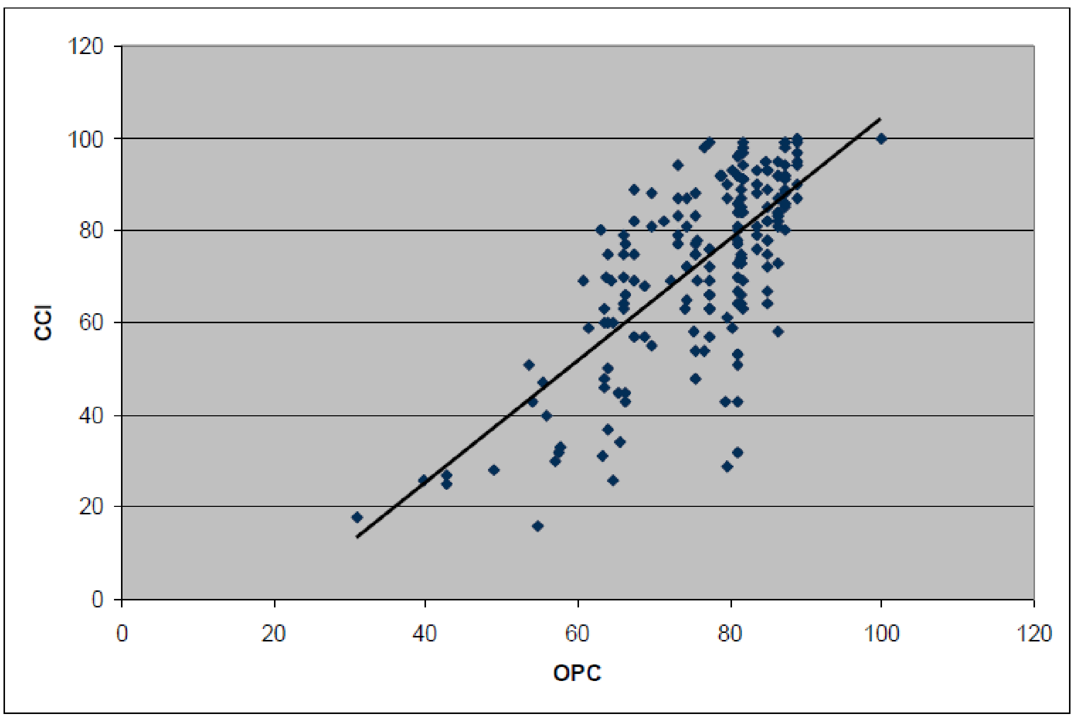

Figure 12. Graph. OPC versus CCI in Virginia (Giuffre 2010)

The maximum value for CRS is 9.0. The regression models were optimized by the percent of sections where the predicted CRS is within ±0.5 of the actual CRS and evaluating the regression coefficient along with graphs of the predicted versus actual CRS. Table 3 contains the model coefficients for interstate asphalt surface pavements and Table 4 contains the distress definitions and severities used in the model. Figure 13 depicts the comparison of the actual and predicted CRS for interstate AC/CRCP pavements**.**

Table 3. Interstate Asphalt Surface CRS Calculation Model Coefficients (Heckel and Ouyang, 2007)

Distress	**ACP**	**AC/JPCC**	**AC/CRCP**
Intercept	9.0	9.0	9.0
IRI	-0.007	-0.005	-0.006
Rut	-2.589	-1.829	-1.605
M	-0.544	-0.326	-0.356
O	-0.091	-0.142	-0.115
P	-0.301	-0.214	-0.235
Q	-0.118	-0.189	-0.139
S	-0.234	-0.350	-0.387
U		-0.112	-0.171
V			-0.064
W		-0.383	
X		-0.326	-0.351

Table 4. Distress Definitions and Severities (Heckel and Ouyang, 2007)

Letter Code	**Definition**	**Range**
IRI	International Roughness Index (from vans)	Any
Faulting	Faulting Height (from vans)	Any
L	Alligator Cracking	1 - 4
M	Block Cracking	1 - 4
N	Rutting	1 - 3
O	Transverse Cracking/Joint Reflection Cracks	1 - 5
P	Overlaid Patch Reflective Cracks	1 - 5
Q	Longitudinal/Center of Lane Cracking	1 - 5
R	Reflective Widening Crack	1 - 5
S	Centerline Deterioration	1 - 4
T	Edge Cracking	1 - 4
U	Permanent Patch Deterioration	1 - 4
V	Shoving, Bumps, Sags, Corrugation	1 - 3
W	Weathering, Raveling, Segregation, Oxidation	1 - 4
X	Reflective D-Cracking	2 - 3

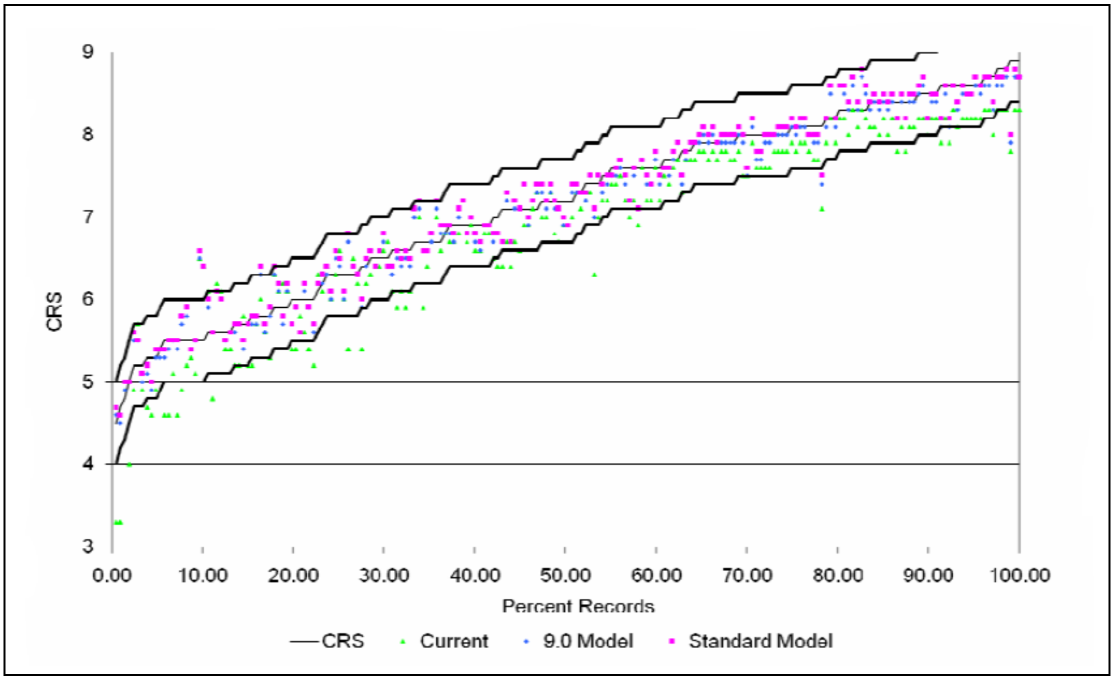

Figure 13. Graph. Interstate AC/CRCP percent within ± 0.5 CRS (Heckel and Ouyang, 2007)

COST (Litka et al. 2008)

The European Cooperation in the field of Scientific and Technical Research (COST) Action 354 "Performance Indicators for Road Pavements" objective was to define a uniform European performance indicator for road pavements. COST identified individual performance indicators such as longitudinal evenness, transverse evenness, macro-texture, skid resistance, and bearing capacity. Transfer functions were developed based on the technical parameter used to estimate the performance indicator such as IRI for longitudinal evenness.

The developed Combined Performance Indicator (CPI) for pavements included: safety index, comfort index, structural index and environmental index. The approach used to develop CPI for pavements included:

- Selection of single/pre-combined performance indices as input variable for each CPI
- Development of a combination procedure
- Validation of the formula including proposals for the weights of the various input variables
- Sensitivity analysis
- Practical application guide

CPI was based on the advanced maximum criteria, which considers the maximum weighted PI and values of other weighted PIs based on an influence factor, p. Two alternatives for CPI were developed, with the preference being the first alternative:

$$CPI_I = \min\left[5; I_1 + \frac{p}{100} * \overline{(I_2, I_3, \ldots, I_n)}\right]$$

Figure 14. Equation. COST Combined Performance Indicator Alternative 1

$$CPI_I = \min\left[5; I_1 + \frac{p}{100} * I_2\right]$$

Figure 15. Equation. COST Combined Performance Indicator Alternative 2

Where

$I_1 \geq I_2 \geq I_3 \geq \ldots \geq I_n$

$I_1 = W_1 * PI_1$; $I_2 = W_2 * PI_2$;….; $I_n = W_n * PI_n$

p = influence factor controlling weighted performance indices (suggested 10-20%)

(Note: the scale used for PI is from 0 to 5 with 0 being very good and 5 being very poor.)

Ohio Northern University (Reza et al., 2005)

The Ohio Department of Transportation (ODOT) investigated incorporating a measure of roughness (IRI) into their PMS, which currently used only Pavement Condition Rating (PCR) to evaluate pavements. ODOT developed four preliminary alternatives for a combined pavement index, Pavement Quality Index (PQI), which considers both distresses (PCR) and roughness (IRI), based on three pavement families developed based on pavement type (flexible, jointed concrete and composite pavement). Initially, the preliminary alternatives considered were all forms of IRI deducts from the current PCR measurement. The four preliminary alternatives were:

1. Changing rate of deduct

$$PQI = \begin{cases} PCR - D_{IRI} & if\ PCR > 55 \\ PCR & if\ PCR \leq 55 \end{cases}$$

Figure 16. Equation. Ohio Pavement Quality Index

$$D_{IRI} = \frac{IRI * (PCR - 55)}{IRI_T}$$

Figure 17. Equation. Ohio IRI Deduction

$$IRI_T = \frac{IRI_{max} - IRI_{T55}}{45}(PCR - 55) + IRI_{T55}$$

Figure 18. Equation. Ohio IRI Trigger Value

Where,

D_{IRI}	=	deduction as a result of IRI
IRI_T	=	trigger value of IRI
IRI_{T55}	=	trigger value of IRI for PCR = 55
IRI_{max}	=	maximum allowable IRI

2. Modified Mississippi Equation

$$PQI = 100\left(\frac{760 - IRI}{760}\right)^a \left(\frac{PCR}{100}\right)^b$$

Figure 19. Equation. Modified Mississippi PQI

Where,

IRI	=	measured IRI, in/mi
PCR	=	ODOT's PCR
a, *b*	=	constants (0.74655 and 1.0, respectively).

3. Pendulum Concept

$$PQI = 100 - Deduct$$

$$Deduct = \sqrt{\left(\frac{45 * IRI}{IRI_{max}}\right)^2 + (100 - PCR)^2}$$

Figure 20. Equation. PQI - Pendulum Concept

4. Flat rate of IRI deduct

$$PQI = PCR - \frac{45 * IRI}{760}$$

Figure 21. Equation. PQI – Flat Rate of IRI Deduct

After discussion and analysis of the preliminary alternatives, ODOT decided to consider developing an index based on functional class instead of pavement type. The three functional classes considered were priority system (interstates, freeways and multi-lane portions of the NHS), urban systems (state and federal routes in cities with speed limit usually < 40 mph), and general systems (remaining two-lane routes outside cities). Since the validity of IRI at low speeds is questionable, only PCR was considered for urban systems due to the low speeds. The failure PCR value for priority and general systems was 65 and 60, respectively. ODOT has recently implemented a reward program for contractors producing pavements with IRI < 60 in/mi; therefore, there should not be any deduct value in the PQI for pavements with IRI < 60 in/mi. Considering a maximum allowable IRI of 250 in/mi, ODOT developed secondary alternatives:

1. Changing rate of deduct (fixed maximum and minimum IRI equation)

$$PQI = \begin{cases} PCR & \text{if } IRI \leq 60 \\ PCR - \left(\frac{35}{IRI_{max} - IRI_{min}}\right)(IRI - 60) & \text{if } IRI > 60 \end{cases}$$

Figure 22. Equation. PQI – Changing Rate of IRI Deduct

Where,

IRI_{max} = maximum allowable IRI = 250 in/mi

IRI_{min} = IRI value below which there is no deduct = 60 in/mi

2. Six-parameter polynomial function

$$PQI = a + b(IRI) + c(PCR) + d(IRI)^2 + e(PCR)^2 + f(IRI)(PCR)$$

Figure 23. Equation.PQI – Six-parameter Polynomial Function

Where,

a = -0.80493356

b = 0.1846962421

c = 1.0188704

d = -0.0001272238453

e = -0.00010621239

f = -0.0029702110

3. Four-parameter power function

This model utilizes the IRI reward system, which can result in having a PQI higher than the PCR. The coefficients for the model for the priority and general systems are listed in Table 5.

$$PQI = a(IRI)^b + c(PCR)^d$$

Figure 24. Equation. PQI – Four-parameter Power Function

Table 5. Coefficients of four-parameter power function (Reza et al., 2005)

Coefficient	Priority System	General System
a	-0.02083295112	-0.04488140828
b	1.345036760	1.177571693
c	1.96065	1.96065
d	0.8538	0.8538

Each of the alternatives provided advantages and disadvantages. The advantages of the fixed minimum and maximum IRI are its simplicity and the ability to ensure no deductions for IRI less than 60 in/mi. However, this method is a piecewise function and has a linear failure curve, which does not provide flexibility for future adjustments on the curvature. The advantages of the six-parameter polynomial model is the flexibility for adjusting the curvature of the failure curve; however, the complexity of this model using six parameters requires increased sections for calibration. The four-parameter power equation provides flexibility for future adjustments on the curvature and also can reflect the reward concept for IRI.

With consideration of the advantages and disadvantages of the alternative models, along with ODOT needs and ease for implementation into the PMS, the authors developed a single equation incorporating essential parts of the maximum and minimum IRI model that also provides greater flexibility by utilizing a nonlinear failure curve (Reza et al., 2005). This model considers a linear PCR with a power IRI deduction and is given by (Reza et al., 2005):

$$PQI = PCR - a(IRI)^b$$

Figure 25. Equation. PQI – Linear PCR and Power IRI Deduction

Where,

a = 0.0000371642597 and b = 2.49128114 for priority systems
a = 0.00004914652885 and b = 2.423026247 for general systems

The relationship is depicted in Figure 26 and Figure 27 for PQI = 65 and PQI = 60, respectively, as well as PQI =75 and PQI = 90, which are the threshold values for overlay and maintenance triggers used by ODOT.

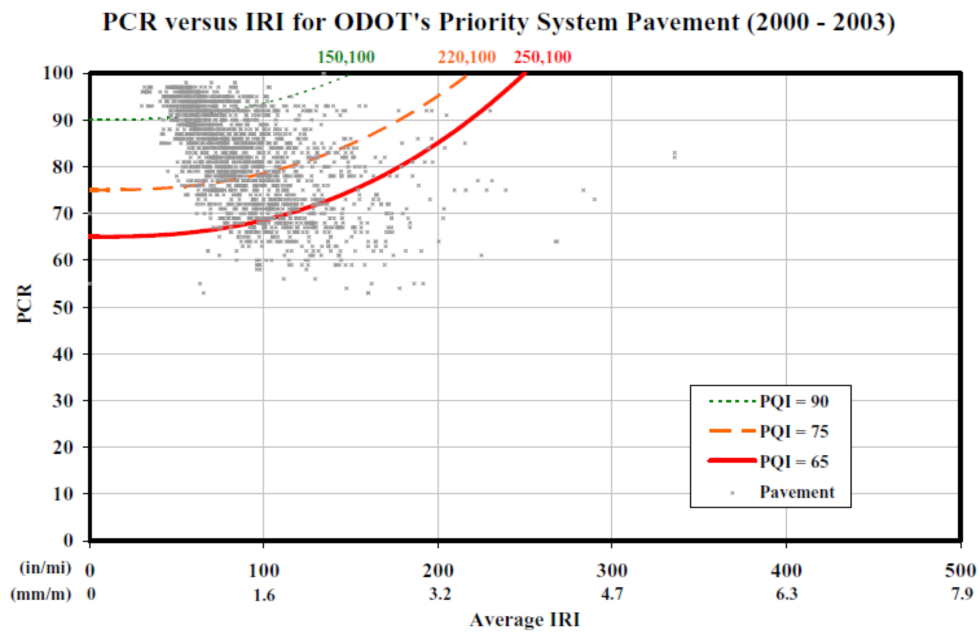

Figure 26. Graph. Linear PCR with Power IRI function for priority System (Reza et al., 2005)

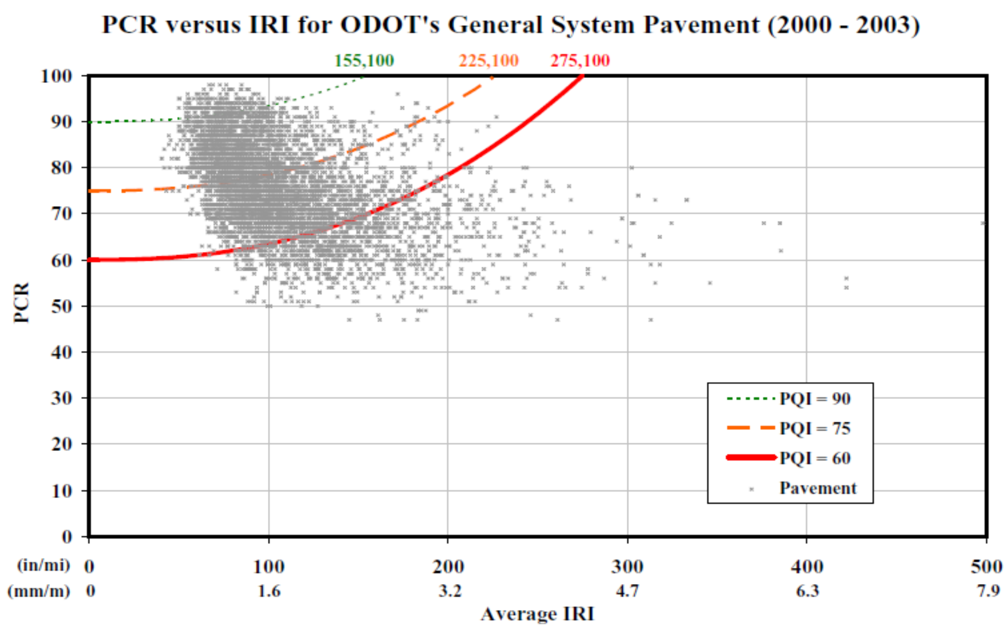

Figure 27. Graph. Linear PCR with Power IRI function for General System (Reza et al., 2005)

Transportation Association of Canada (Haas et al., 2012)

Although all provinces and territories in Canada evaluate their road networks using some form of performance measure, there is not uniformity amongst the jurisdictions on the type of performance measure used, making it difficult to compare roadways in different jurisdictions. A recent study published by the Transportation Association of Canada's (TAC's) Chief Engineers' Council titled "Performance Measures for Highway Road Networks" identified key performance measures needed to effectively manage road network infrastructure and recommended best practices for use in comparing road networks in different jurisdictions, assisting agencies in planning, evaluating, investing, day-to-day operations and other asset management decisions.

The report recommended performance measures based on a tiered methodology for system preservation and safety. Table 6 provides the recommended tiers of performance measures for the system preservation. It is highly recommended that Tier 1 performance measures are collected and Tier 2 performance measures are desirable but not mandatory (Haas et al., 2012).

Data from four Canadian provinces (Alberta, British Columbia, Ontario and Nova Scotia) was used to establish the system preservation performance measures and threshold values. As stated in Table 6, the International Roughness Index (IRI) and Distress Index (DI) are recommended as the system preservation Tier 1 performance measures. The threshold values for IRI were determined taking into consideration threshold values for Canadian Provinces and International agencies. The threshold values established for IRI were:

- Very Good 0.00 – 1.00 m/km
- Good 1.00 – 1.75 m/km
- Fair 1.75 – 2.80 m/km
- Poor > 2.80 m/km

The threshold values were verified using the PMS data from the four provinces, having an average IRI of 1.62 m/km, which falls in the good category.

The recommendations for data collection requirements include:

- Use Class 1 profilers that meet ASTM Specification E950/E950M.
- Follow equipment calibration specifications such as the LTPP Equipment Calibration Procedure (FHWA 2008).
- Reference GPS coordinates using inertial/differential equipment and Distance Measuring Instrument, which improves accuracy and repeatability.
- Summarize IRI data at reasonable intervals (10-100 m intervals), avoid summarizing IRI data to the section level (i.e., one IRI for 10 kilometer section for example).
- Provinces should use blind sites or calibration sites to ensure high quality data is being collected by consultants or agency staff.
- Collect IRI data on pavements every year and if not feasible, every two years.

Table 6. Performance Measures – System Preservation for Rural Highways (Haas et al., 2012)

<table>
<tr><th>Performance Measure</th><th>Description</th><th>Measurement Type</th><th>Pavement Component</th><th>Pavement Types</th><th>Value of Measure[2]</th></tr>
<tr><td>IRI</td><td>Measurement of the ride quality of a road or highway</td><td>Inertial Profiler (Class I to V)</td><td>Functional Performance</td><td>AC
PCC
CO (AC/PCC)
SRFT/Chip Seal
Not Suitable for Gravel Roads</td><td rowspan="2">Tier 1</td></tr>
<tr><td>DI[1]</td><td>Measure of the extent and severity of individual pavement distress</td><td>Manual, Semi-Automated or Automated Methods</td><td>Functional and Structural Performance</td><td>AC
PCC
CO (AC/PCC)
SRFT/Chip Seal
Gravel Roads</td></tr>
<tr><td>SAI</td><td>Measure of the insitu structural capacity of a pavement and subgrade soils</td><td>Falling Weight Deflectometer (LWD, FWD, HWD)</td><td>Structural Performance</td><td>AC
PCC
CO (AC/PCC)
SRFT/Chip Seal
Gravel Roads</td><td rowspan="3">Tier 2</td></tr>
<tr><td>Remaining Service Life (RSL)</td><td>Estimated measurement of RSL of a pavement to structural failure</td><td>Falling Weight Deflectometer (FWD/HWD)</td><td>Structural Performance</td><td>AC
PCC
CO (AC/PCC)
SRFT/Chip Seal
Gravel Roads</td></tr>
<tr><td>Surface Friction</td><td>Measurement of the surface friction of the pavement</td><td>Locked wheel skid tested (ASTM E274)</td><td>Functional Performance</td><td>AC
PCC
CO (AC/PCC)
SRFT/Chip Seal</td></tr>
</table>

[1]The distress index must be normalized from the agency's standard to a common Pavement Distress Index using Key distress types.
[2]Values of Measure: Tier 1: Important, highly recommended that agency collects this data; Tier 2: Desirable, data is desirable but not mandatory.

Implementing the DI as a system preservation performance measure requires a number of steps to ensure that it is comparable across provinces since distress methodologies or protocols, scale of the index and the technology used to collect distresses varies across the provinces. Using four categories (Very Good, Good, Fair and Poor) and a scale of 0-100 for the DI, threshold limits were established based on review of DI thresholds for Canadian provinces and are:

- Very Good 80 to 100
- Good 65 to 80
- Fair 35 to 65
- Poor 0 to 35

Not all provinces collect the same distress types within their Pavement Management System (PMS). As a result, the critical or predominant distresses collected by all provinces were identified to be included in the DI:

- Alligator Cracking
- Longitudinal Cracking
- Transverse Cracking
- Rutting

The DI threshold values were verified using distress data from the four provincial PMS. The recommendations for distress data collection requirements include:

- Use high resolution downward cameras to collect images for subsequent distress identification in the office.
  - This is more accurate and objective
  - Improves accuracy and repeatability
- Reference GPS coordinates using inertial/differential equipment and DMI, which improved accuracy and repeatability.
- Survey 100% of lane rather than using samples.
- Reduce number of collected distresses to be in line with industry standards.
- Ensure distress raters are certified to conduct distress surveys and evaluations.
- Provinces should use blind site or calibration sites to ensure high quality data is being collected by consultants or agency staff.

These two performance measures were combined into an overall measure termed Pavement Index (PI). In order to use the same scale as the DI of 0 to 100, the IRI was converted to a Ride

Index (RI) using the following equation and resulting in the converted threshold values in Table 7:

$$RI = 100 * e^{(-0.26*IRI)}$$

Figure 28. Equation. TAC Ride Index

Table 7. Conversion of IRI Threshold Value to a 0-100 RI Threshold Scale (Haas et al., 2012)

Category	IRI Threshold Value (m/km)	RI Threshold
Poor	> 2.8	< 48
Fair	1.75-2.8	48 to 63
Good	1.0-1.75	63 to 77
Very Good	< 1.0	77 to 100

After considering five options using linear weighted combinations and exponentially weighted combinations and correlating the results to the PMS data, the PI is calculated by the following equation and threshold limits shown in Table 8:

$$PI = RI^{0.6} * DI^{0.4}$$

Figure 29. Equation. TAC Pavement Index

Table 8. PI Thresholds (Haas et al., 2012)

	IRI	RI	DI	$PI=RI^{0.6}*DI^{0.4}$
Very				
	1	77	80	78.19
Good				
	1.75	63	65	63.79
Fair				
	2.8	48	35	42.30
Poor				

Texas Transportation Institute (Papagiannakis et al., 2009)

A synthesis conducted by the Texas Transportation Institute summarizes the pavement scores used by states including scales, descriptions, computations, distresses collected, rating methods, sampling methods, survey frequency and legislative or internal goals Table 9 contains the rating computations by state as collected during the synthesis. A handful of these states have been discussed earlier in this document.

Table 9. Synthesis Results–Rating Computation (Papagiannakis et al., 2009)

State	Rating Computation
Alabama	Combined deducts for age, traffic (AADT) and distress
Arizona	AASHTO PSI expression
California	The combinations of individual distresses observed on a pavement are evaluated for severity and broadly classified into overall levels of structural distress
Colorado	For major highways: Individual indices by distress using: Index = 100-(Meas.-min)/(max-min)*100 RSL=min of indices For secondary roads: Function of year of last rehabilitation
Delaware	OPC = (Threshold Value) + [(Remaining Service Life*(Reduction Rate)]
DC	Visual inspection by raters
Florida	Cracks, ride, and ruts – the three indices are equally important, and the lowest one represents the overall pavement condition.
Georgia	Deduct values for project average extent/severity by distress Deducts are added and subtracted from 100 to give PACES
Idaho	RI= function of IRI CI=unclear Index used is the lowest of RI and CI
Illinois	For ACP, CRS = regression model of IRI, rutting, and severity ratings (0-5) of predominant distresses For CRCP, CRS=regression model of IRI, and severity rating (0-5) of predominant distresses
Indiana	Flexible and Rigid: Combine PCR with IRI and Rut into Pavement Quality Index (PQI)
Iowa	PCI=100-Deduct values, Deduct=f(distress type, severity, and extent)
Kansas	Flexible/Rigid: PL depends on pavement type and the combination of distresses present, whereby a level is assigned to each distress type as a weighed sum of their severities
Kentucky	IRI is converted to 0-5 scale Rut depth is reported in units of 1/16 inch
Louisiana	Deduct values
Maine	Flexible: Deduct values Rigid: N/A
Massachusetts	Lowest of Rut Index, Ride Index, and Condition (Distress) Index

State	Rating Computation
Minnesota	$PQI = \sqrt{(RQI)(SR)}$ $SR = e^{(1.386-(0.045)(TWD))}$ RQI is based on IRI and rating panel correlation
Michigan	A Distress Index of 50 or greater equates to a RSL of zero. DI values of 0 to 50 have corresponding RSL values greater than zero. A RQI of 70 of greater equates to a RSL equal to zero. RQI values of 0 to 70 have corresponding RSL values greater than zero.
Mississippi	Flexible/Rigid Deduct values for distress combined with IRI $PCR = 100\left(\frac{12-IRI}{12}\right)^a * \left(\frac{DP_{max}-DP}{DP_{max}}\right)^b$
Missouri	PSR is 50/50 IRI and distress
Montana	Flexible: Ride Index (IRI converted to RI 0-100), Rut, Alligator Cracking Index and Miscellaneous Cracking Index Rigid: N/A
Nebraska	Flexible: Crack, rut depth and IRI Rigid: Fault depth and damaged joints
Nevada	Add all points from Ride IRI, Rut Depth, Fatigue and Block cracking, Non-wheel path transverse block cracking, patching, bleeding, raveling, friction number
New Hampshire	Flexible: Deduct values similar to Vermont's Rigid: Unclear
New Jersey	Flexible/Rigid: DV_NL=distr weight*severity*%occurrence $NDI = \frac{(500-\sum DV)}{100}$ DV_L=350*severity coeff.*%occurrence $LDI = \frac{(500-(\sum DV_L + DV\_rut))}{100}$ Flex: $SDI = \frac{NDI*LDI}{5}$ Rigid: SDI=NDI (scale 0 to 5)
New York	Pavement Surface Rating, dominant distress, IRI and rut Info combined into PCI
North Carolina	Deduct values
Ohio	PCR=100-Deduct, Deduct=(Weight for distress)*(Wt. for severity)*(Wt. for Extent)

State	Rating Computation
Oregon	For each tenth-mile, raveling index, patching index, fatigue index, and no load index are combined into one tenth-mile index value. This tenth-mile index value is compared to the tenth-mile rut index value. The lower of the index values is determined to be the "tenth-mile overall condition" index value. Next, to determine the overall pavement management section condition index, the "tenth-mile overall condition" indices are averaged. The GFP rating method involves driving the highways with 2-person rating teams at 50 mph or posted speed, whichever is lower, conducting a visual survey and scoring pavement sections with a subjective value from very good to very poor.
Pennsylvania	Ride Index (45 percent), Structural index (30 percent) Surface distress index (20 percent), and Safety index (5 percent).
South Carolina	PSI: Pavement Serviceability Index (based on roughness) PDI: Pavement Distress Index (based on distresses) PQI: Pavement Quality Index composite function of PSI and PDI
South Dakota	CMP=Mean-1.25*SD where: CMP=Composite index (≥ lowest individual index and ≥ 0.00) Mean=Mean of all contributing individual indices SD=Standard deviation of the above mean
Tennessee	PSI: Pavement Serviceability Index (based on roughness) PDI: Pavement Distress Index (based on distresses) PQI: Pavement Quality Index composite function of PSI and PDI $PQI=PDI^{0.7}*PSI^{0.3}$
Vermont	Flexible: Deduct values Rigid: Not developed yet
Virginia	CCI=min of Load related Distress rating (LDR) and Non-Load related Distress Rating (NDR) (IRI is ignored)
Washington	Flexible: EC=equivalent cracking computation Rigid: Deduct value computation (currently individual indices are proposed for each rigid pavement distress surveyed)
West Virginia	Flexible: Minimum of PSI, SCI, ECI, and RDI Rigid: Minimum of PSI, JCI and CSI
Wisconsin	PDI=Weighted average of 11 elements of distress for ACP and 12 elements of distress for PCCP
Wyoming	PSI AASHTO expression

HPMS DATA

States are required annually to report the required data for all roadways as outlined in the *HPMS Field Manual 2012*. HPMS data is used by the Federal government as the source of the extent, condition, performance, use and operating characteristics of the nation's highways and length, lane-miles, and travel reported are used in the apportionment of Federal-aid highway funds. The *Conditions and Performance (C&P) Report to Congress* is supported by HPMS data as the basis for analyses. HPMS data consists of three different types of data: Full Extent data items, Sample Panel data items and Summary data items. Full Extent data items are reported for all public roads and include length, lane-miles and travel, while Sample Panel data items are reported for a selected sample of roadways and provide more detailed data, and Summary data items provide aggregated data. Table 10 lists the HPMS data items and the extent to which each is collected.

Table 10. HPMS Data Items (HPMS Field Manual, 2012)

Data Item Type	Item Number	Data Item	Extent	
Inventory	1	F_system	FE + R	
	2	Urban_Code	FE + R	
	3	Facility_Type	FE + R	
	4	Structure_Type	FE	
	5	Access_Control	FE*	SP*
	6	Ownership	FE	
	7	Through_Lanes	FE + R	
	8	HOV_Type	FE	
	9	HOV_Lanes	FE	
	10	Peak_Lanes		SP
	11	Counter_Peak_Lanes		SP
	12	Turn_Lanes_R		SP
	13	Turn_Lanes_L		SP
	14	Speed_Limit		SP
	15	Toll_Charged	FE	
	16	Toll_Type	FE	
Route	17	Route_Number	FE*	
	18	Route_Signing	FE*	
	19	Route_Qualifier	FE*	
	20	Alternative_Route_Name	FE	
Traffic	21	AADT	FE + R	
	22	AADT_Single_Unit	FE*	SP*
	23	Pct_Peak_Single		SP
	24	AADT_Combination	FE*	SP*
	25	Pct_Peak_Combination		SP
	26	K_Factor		SP
	27	Dir_Factor		SP
	28	Future_AADT		SP
	29	Signal_Type		SP
	30	Pct_Green_Time		SP
	31	Number_Signals		SP

Data Item Type	Item Number	Data Item	Extent	
	32	Stop_Signs		SP
	33	At_Grade_Other		SP
Geometric	34	Lane_Width		SP
	35	Median_Type		SP
	36	Median_Width		SP
	37	Shoulder_Type		SP
	38	Shoulder_Width_R		SP
	39	Shoulder_Width_L		SP
	40	Peak_Parking		SP
	41	Widening_Obstacle		SP
	42	Widening_Potential		SP
	43	Curves A, Curves B,…Curves F		SP*
	44	Terrain_Type		SP
	45	Grades A, Grades B,…Grades F		SP*
	46	Pct_Pass_Sight		SP
Pavement	47	IRI	FE*	SP*
	48	PSR		SP*
	49	Surface_Type		SP
	50	Rutting		SP
	51	Faulting		SP
	52	Cracking_Percent		SP
	53	Cracking_Length		SP
	54	Year_Last_Improv		SP
	55	Year_Last_Construction		SP
	56	Last_Overlay_Thickness		SP
	57	Thickness_Rigid		SP
	58	Thickness_Flexible		SP
	59	Base_Type		SP
	60	Base_Thickness		SP
	61	Climate_Zone**		SP
	62	Soil_Type**		SP
Inventory	63	County_Code	FE	
Special Networks	64	NHS	FE	
	65	STRAHNET_Type	FE	
	66	Truck	FE	
	67	Future_Facility	FE	
Inventory	68	Maintenance_Operations	FE	
FE = Full Extent for all functional systems (Including State and non-State roadways) FE* = Full Extent for some functional systems, see Data Item descriptions for more details SP = All Sample Panel Sections (as defined by HPMS) SP* = Some Sample Panel Sections, see Data Item descriptions for more details FE + R = Full Extent including ramps located within grade-separated interchanges ** = States have the option to override initial codes assigned by FHWA				

HPMS data will be used in the development of the next generation individual and composite indices. Data elements to be considered from the HPMS database include but are not limited to, roughness, rutting, faulting, percent cracking and cracking length.

The *HPMS Field Manual* outlines the pavement data collection procedures:

- IRI is used as the standard roughness index for HPMS and is measured in accordance to AASHTO R 43-07, AASHTO Standard Practice for Determination of International Roughness Index for Quantifying Roughness of Pavements. IRI is reported in units of in/mi.

- Rutting is measured according to AASHTO R 48-10, AASHTO Standard Practice for Determining Rut Depth in Pavements, and the LTPP Distress Identification Manual. The average rut depth is reported to the nearest tenth of an inch.

- Faulting is measured according to AASHTO R 36-04, AASHTO Stand Practice for Evaluating Faulting of Concrete Pavements, and the LTPP Distress Identification Manual. The average joint faulting is reported to the nearest tenth of an inch.

- Cracking length is measured in accordance with AASHTO PP 67-10, AASHTO Provisional Protocol for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Images Utilizing Automated Methods, and the LTPP Distress Identification Manual. The total cracking length is reported in ft/mi.

- Cracking Percent is measured in accordance with AASHTO PP 67-10, AASHTO Provisional Protocol for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Images Utilizing Automated Methods, and the LTPP Distress Identification Manual. The cracking percent is reported to the nearest 5 percent for fatigue type cracking in AC and 5 percent for percent cracked slabs for jointed PCC and CRCP pavements.

As show in Table 12, the indices used by nine of the State DOTs can be used directly in conjunction with the HPMS data. Additional information will need to be pursued for the indices of another 17 State DOTs, while those indices from 16 State DOTs/agencies cannot be used as a result of the data requirements, which are not contained in or are consistent with the HPMS database.

Table 11 contains additional standards, specifications and documented procedures for the collection of pavement data.

SUMMARY

A summary of the indices discussed as part of the literature review are contained in Table 12. Since the distress data collected by states varies, so do the composite indices developed by the states to represent the functional pavement condition. This information will be used as a starting point to develop the next generation pavement performance measure that combines ride, cracking and rutting or faulting into a combined functional pavement condition index. Table 12 also contains whether the computation of the index is compatible with HPMS data.

As shown in Table 12, the indices used by nine of the State DOTs can be used directly in conjunction with the HPMS data. Additional information will need to be pursued for the indices of another 17 State DOTs, while those indices from 16 State DOTs/agencies cannot be used as a result of the data requirements, which are not contained in or are consistent with the HPMS database.

Table 6. Additional Standard, Specifications and Documented Procedures for Pavement Data Collection (HPMS Field Manual, 2012)

Distress	Standard, Specification or Documented Procedure
IRI	ASTM Standard E 950 (Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference)
	NCHRP 20-24(37B) Comparative Performance Measurement: Pavement Smoothness
	Sayers, M.W., On the Calculation of International Roughness Index from Longitudinal Road Profile, Transportation Research Record 1501, Transportation Research Board, Washington, DC, 1995.
	ASTM StandardE1926 Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements
	AASHTO MP11-08 (2008) (Inertial Profiler)
Rutting	AASHTO PP 69-10 (Determining Pavement Deformation Parameters and Cross-Slope from Collected Transverse Profiles)
	AASHTO PP 70-10 (Collecting the transverse Pavement Profile)
Cracking Percent/Cracking Length	AASHTO R 55-10 (Quantifying Cracks in Asphalt Pavement Surface)
	AASHTO PP 68-10 (Collecting Images of Pavement Surfaces for Distress Detection)

Table 7. Summary Composite Indices

Agency	Composite Index	HPMS Compatible
Alabama	Combined deducts for age, traffic (AADT) and distress	Possibly-dependant on distresses included
Arizona	AASHTO PSI expression	Possibly-dependant on use of IRI in model
California	The combinations of individual distresses observed on a pavement are evaluated for severity and broadly classified into overall levels of structural distress	No- severity not contained in HPMS

Agency	**Composite Index**	**HPMS Compatible**
Colorado	For major HW: Individual indices by distress using: Index = 100-(Meas.-min)/(max-min)*100 RSL=min of indices For secondary roads: function of year of last rehab	Possibly-dependant on distresses included
COST	$CPI_I = \min\,[5; I_1 + \frac{p}{100} * \overline{(I_2, I_3, \ldots, I_n)}]$ $CPI_I = \min\,[5; I_1 + \frac{p}{100} * I_2]$	No-not all distress needed contained in HPMS
Delaware	OPC = average – (1.25*stdev)	No-not all distress needed contained in HPMS
DC	Visual inspection by raters	Possibly-dependant on distresses included
Florida	Cracks, ride, and ruts-the three indices are equally important, and the lowest one represents the overall pavement condition.	Yes
Georgia	Deduct values for project average extent/severity by distress Deducts are added and subtracted from 100 to give PACES	No-extent and severity not contained in HPMS
Idaho	RI= function of IRI CI=unclear Index used is the lowest of RI and CI	Possibly-dependent on CI
Illinois	CRS = Intercept – x*IRI – y*Rutting – z*Faulting – a*A – b*B – c*C…	Yes
Indiana	Flexible and Rigid: Combine PCR with IRI and Rut into Pavement Quality Index (PQI)	Yes
Iowa	PCI=100-Deduct values, Deduct=f(distress type, severity, and extent)	No-extent and severity not contained in HPMS
Kansas	Flexible/Rigid: PL depends on pavement type and the combination of distresses present, whereby a level is assigned to each distress type as a weighed sum of their severities	No-severity not contained in HPMS
Kentucky	IRI is converted to 0-5 scale Rut depth is reported in units of 1/16 inch	Yes

Agency	Composite Index	HPMS Compatible
Louisiana	Deduct values	Possibly-dependant on distresses included
Maine	Flexible: Deduct values Rigid: N/A	Possibly-dependant on distresses included
Massachusetts	Lowest of Rut Index, Ride Index, and Condition (Distress) Index	Possibly-dependant on distresses included
Michigan	$DI = \frac{\sum DP}{L}$	No-extent and severity not contained in HPMS
Minnesota	$PQI = \sqrt{PSR * SR}$	Yes
Mississippi	$PCR = 100\left(\frac{12 - IRI}{12}\right)^a * \left(\frac{DP_{max} - DP}{DP_{max}}\right)^b$	Yes
Missouri	PSR is 50/50 IRI and distress	Yes
Montana	Flexible: Ride Index (IRI converted to RI 0-100), Rut, Alligator Cracking Index and Miscellaneous Cracking Index Rigid: N/A	Yes
Nebraska	Flexible: Crack, rut depth and IRI Rigid: Fault depth and damaged joints	Possibly for flexible; No for rigid-damaged joint data not contained in HPMS
Nevada	Add all points from Ride IRI, Rut Depth, Fatigue and Block cracking, Non-wheel path transverse block cracking, patching, bleeding, raveling, friction number	No-not all distress needed contained in HPMS
New Hampshire	Flexible: Deduct values similar to Vermont’s Rigid: Unclear	Possibly-dependant on distresses included

Agency	Composite Index	HPMS Compatible
New Jersey	Flexible/Rigid: DV_NL=distr weight*severity*%occurrence $NDI = \frac{(500 - \sum DV)}{100}$ DV_L=350*severity coeff.*%occurrence $LDI = \frac{(500 - (\sum DV_L + DV\_rut))}{100}$ Flex: $SDI = \frac{NDI*LDI}{5}$ Rigid: SDI=NDI (scale 0 to 5)	No-severity not contained in HPMS
New York	Pavement Surface Rating, dominant distress, IRI and rut Info combined into PCI	Possibly-dependant on distresses included
North Carolina	Deduct values	Possibly-dependant on distresses included
Ohio	$PQI = PCR - a(IRI)^b$	Yes
Oregon	For each tenth-mile, raveling index, patching index, fatigue index, and no load index are combined into one tenth-mile index value. This tenth-mile index value is compared to the tenth-mile rut index value. The lower of the index values is determined to be the "tenth-mile overall condition" index value. Next, to determine the overall pavement management section condition index, the "tenth-mile overall condition" indices are averaged. The GFP rating method involves driving the highways with 2-person rating teams at 50 mph or posted speed, whichever is lower, conducting a visual survey and scoring pavement sections with a subjective value from very good to very poor.	No-not all distress needed contained in HPMS
Pennsylvania	Ride Index (45 percent), Structural index (30 percent) Surface distress index (20 percent), and Safety index (5 percent).	No-structural performance not included in HPMS
South Carolina	PSI: Pavement Serviceability Index (based on roughness) PDI: Pavement Distress Index (based on distresses) PQI: Pavement Quality Index composite function of PSI and PDI	Possibly-dependant on distresses included
South Dakota	CMP=Mean-1.25*SD where: CMP=Composite index (≥ lowest individual index and ≥ 0.00) Mean=Mean of all contributing individual indices SD=Standard deviation of the above mean	Possibly-dependant on distresses included

Agency	Composite Index	HPMS Compatible
TAC	$PI = RI^{0.6} * DI^{0.4}$	No-extent and severity not contained in HPMS
Texas	$CS = 100 * U_{DS} * U_{RS}$	No-not all distress needed contained in HPMS
Vermont	Flexible: Deduct values Rigid: Not developed yet	Possibly-dependant on distresses included
Virginia	CCI=min of Load related Distress rating (LDR) and Non-Load related Distress Rating (NDR)	Possibly-dependant on distresses included
Washington	$Flexible\ pavements: PSC = 100 - 15.8(EC)^{0.5}$ $Rigid\ pavements: PSC = 100 - 18.6(EC)^{0.43}$	No-extent and severity not contained in HPMS
West Virginia	Flexible: Minimum of PSI, SCI, ECI, and RDI Rigid: Minimum of PSI, JCI and CSI	No-structural performance not included in HPMS
Wisconsin	PDI=Weighted average of 11 elements of distress for ACP and 12 elements of distress for PCCP	No-not all distress needed contained in HPMS
Wyoming	PSI AASHTO expression	Possibly-dependant on use of IRI in model

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Appendix C. Minutes of Second TWG Meeting

TECHNICAL MEMORANDUM

Date: November 26, 2012

To: Nastaran Saadatmand **FHWA Contract No.:** DTFH61-07-D-00030-T-10002
From: Gonzalo Rada **AMEC Project No.:** 6420101002.15
CC: Steve Gaj, Jonathan Groeger, Amy Simpson, Beth Visintine

Subject: FHWA Highway Infrastructure Health Assessment Study – Task 15 "Next Generation Pavement Performance Measure" Technical Working Group: TWG Meeting #2 Minutes

The second TWG meeting - a webinar - was held on November 15, 2012, between 2:00 pm and 4:00 pm EST.

The participants of the webinar included all of the TWG members:

- Edgardo Block, Connecticut DOT
- Judy Corley-Lay, North Carolina DOT
- Colin Franco, Rhode Island DOT
- Ralph Haas, University of Waterloo
- Rick Miller, Kansas DOT
- Brian Schleppi, Ohio DOT
- Roger Smith, Texas A&M University/TTI
- Katie Zimmerman, Applied Pavement Technology (APTech)
- Nadarajah Sivaneswaran, FHWA
- Thomas Van, FHWA

In addition to the TWG members, the following FHWA and project team members participated in the webinar:

- Steve Gaj, FHWA
- Gonzalo Rada, AMEC
- Amy Simpson, AMEC
- Beth Visintine, AMEC

The agenda for the webinar as well as highlights for each agenda item are provided next.

1. **Introduction**

   Gonzalo provided a brief overview from the first TWG webinar. Steve again thanked everyone for their participation and stressed the importance of comments provided.

   The objective for the next generation performance measure was provided by Gonzalo. The audience, as requested from the first TWG webinar, was defined as FHWA but noted that other highway agencies may also have interest in it. The purpose of the next generation pavement performance measure, as requested by the TWG, was given as enabling the FHWA to more accurately and consistently assess condition of portions or entire national highway pavement system.

2. Work Plan – Definition of Data Requirements (Task 1)

An overview of the work plan was presented by Gonzalo. The overview included the following five tasks:

1. Definition of data requirements
2. Development of individual performance indices
3. Development of next generation performance measure
4. Calibration and validation of new pavement performance measure
5. Preparation of report/implementation recommendations

The focus of this portion of the webinar was on data collection, data processing, data QC/QA and data storage, and the key issues were highlighted by Gonzalo. It was noted that the data collection requirements pose a significant challenge due to the impact to State DOTs and that it would take a five year transition period or greater. To illustrate the data requirements issue, Amy provided an overview of the rutting investigation study done as part of the task order and the suggested data collection and data processing requirements with respect to rutting. The presentation delivered by Gonzalo and Amy is provided under Attachment A of these minutes.

After the presentations by Gonzalo and Amy, discussion was opened up for the TWG. Highlights of the input provided by the TWG members are presented below:

+ Value used to quantify the average rut depth should take into consideration the length of the segment. For short segments, the average value may be sufficient; however, for longer segments a measure or variability, such as standard deviation or percentiles should be considered to give a better representation of the segment.
+ States are fiscally in bad shape. States have just finished implementing the HPMS reassessment and are not going to be enthusiastic about new changes, such as requiring 400 points in transverse profiles. This would require new equipment to be purchased by many states. If the next generation performance measure is intended solely for FHWA, States are having to endure a lot of change without seeing the benefit.
+ Need to assess the need for more detailed consistent data. For what the data is being used for, is the benefit justified?
+ Although there may be around 20 States using sophisticated technology, there are still roughly 20 States using windshield surveys. For rutting data, many States are currently using 5 sensors, which is quite far from the 400 points suggested. Might be able to close the gap, but need to show the States the benefit.
+ MAP-21 requires moving to performance measures. The goal would be to have States collect data uniformly so that the performance measures are uniform. This will need to be a long term commitment and an incremental process.
+ Difference between what FHWA wants to use the data collected for (performance measure) and what States use the collected data for (treatment selection, etc.).
+ Cracking is still 5-10 years out technology wise, but there needs to be a focused initiative now.
+ Need to show implications of how the differences in data collection can make a difference.

3. Work Plan – Individual Indices and Composite FCI (Tasks 2 and 3)

Gonzalo presented an overview of the five options for developing performance indices; the presentation is provided as part of Attachment A to these minutes. The five options for developing the composite functional condition index (FCI) are:

1. Good/Fair/Poor (G/F/P) Categories
2. Individual Agency Indices
3. Development of Next Generation Pavement Performance Measure
4. Composite FCI based on some individual indices with remaining indices serving as flags
5. Composite FCI based on combination of two or more first four options

Roger then made a presentation on condition indices that consider psychometrics; the presentation is provided as Attachment B to these minutes. The presentation covered measurement scales, cues and anchors required to discern between levels, and common errors in indices. Developing a condition index is a complex process and if not done properly, it is not going to be useable.

After the presentations by Gonzalo and Roger, discussion was opened up for the TWG. Highlights of the input provided by the TWG members are presented below:

+ Possible drawbacks to a composite index such as that outlined in option 2 is that the same score can reflect two (or more) pavements with very different conditions.
+ The intended use of the proposed indices/composite index is important. If it is to simply be used as a reporting tool for Congress, a composite index may be sufficient, but individual indices can also provide useful information as a single index can mask certain issues.
+ Different distresses used to indicate different concerns, such as safety (rutting), ride (IRI), or to manage programs and treatments (cracking). Different states have different concerns when it comes to distresses experienced.

Action Item: *Gonzalo to follow up with Nastaran and Steve regarding how important it is to have a composite index in terms of reporting health?*

Action Item: *Gonzalo to send Rutting Bias Investigation Report and MS PowerPoint presentations from Webinar #2 to the TWG members.*

4. Work Plan – Calibration/Validation, Report and Schedule (Tasks 4 and 5 plus Schedule)

This portion of the webinar focused on the schedule for Tasks 1 through 5. Highlights of the input provided by the TWG members are presented below:

+ The schedule is way too aggressive. The current time frame is more appropriate to develop a plan for developing an index, but not actually developing a national composite index.
+ Schedule is set as a result of the contract with FHWA, which was developed prior to MAP-21. AASHTO is moving forward with recommendations of performance measures with respect to MAP-21.

Action Item: *Gonzalo to discuss with Nastaran and Steve the aggressive schedule and path forward.*

Action Item: *Gonzalo to get clarification from Nastaran and Steve on the intended purpose of the index. The intended audience is FHWA, but what will its use be (i.e., reporting to Congress?, etc.).*

5. Next Steps (webinar minutes, revised work plan, face-to-face meeting in DC, etc.)

Gonzalo stated that the next step will be to have discussions with Steve, Nastaran and Thomas to address the input provided by the TWG during the second webinar as well as the action items and to formulate a more realistic schedule.

In order to keep the communication moving forward, a possible face-to-face meeting during the TRB Annual Meeting was discussed. Although it is a busy time for many, there is potential. However, as people are making travel arrangements and schedules are filling up quickly, a plan needs to be made quickly.

FHWA and the project team again thanked the TWG members for their willingness to help on this important undertaking as well as for their valuable input during the webinar. The webinar concluded at 4:00 pm EST.

Overall, the second webinar provided excellent feedback for carrying out the remainder of the index development work.

Please let us know if you have questions, require clarification or would like to discuss the above.

Thank you!

Appendix D. Minutes of Third TWG Meeting

TECHNICAL MEMORANDUM

Date: March 5, 2013

To: Nastaran Saadatmand **FHWA Contract No.:** DTFH61-07-D-00030-T-10002
From: Gonzalo Rada **AMEC Project No.:** 6420101002.415
CC: Steve Gaj, Jonathan Groeger, Amy Simpson, Beth Visintine

Subject: FHWA Highway Infrastructure Health Assessment Study – Task 15 "Next Generation Pavement Performance Measure" Technical Working Group: TWG Meeting #3 Minutes

The third TWG meeting – a webinar- was held on February 21, 2013, starting at 3:00 pm EST.

The participants of the webinar included:

- Edgardo Block, Connecticut DOT
- Judy Corley-Lay, North Carolina DOT
- Brian Schleppi, Ohio DOT
- Roger Smith, Texas A&M University/TTI
- Katie Zimmerman, Applied Pavement Technology (APTech)
- Nadarajah Sivaneswaran, FHWA
- Thomas Van, FHWA

In addition to the TWG members, the following FHWA and project team members participated in the webinar:

- Nastaran Saadatmand, FHWA
- Jonathan Groeger, AMEC
- Joe Guerre, Cambridge Systematics
- Gonzalo Rada, AMEC
- Amy Simpson, AMEC
- Beth Visintine, AMEC

The agenda for the webinar as well as highlights for each agenda item are provided next. The presentation that was used in support of the webinar is contained in Attachment A to these minutes.

1. **Review of November 15, 2012 TWG Webinar Action Items**

   Gonzalo reviewed the status of the November 15, 2012 webinar action items.

   1. Gonzalo to follow up with Nastaran and Steve regarding importance of composite index in reporting health – Having a single composite index is not critical to FHWA, especially in light of the comments provided by the TWG during the November 15, 2012 webinar.
   2. Gonzalo to send Rutting Bias investigation report and presentations to the TWG members – Both the rutting bias investigation report and the November 15, 2012 TWG presentations were distributed to the TWG shortly after the webinar.

3. Gonzalo to discuss with Nastaran and Steve the schedule and path forward – Based on discussions with FHWA, the focus of the effort will shift to the establishment of data requirements that will consistently produce high-quality HPMS data.
4. Gonzalo to obtain clarification of intended purpose of the index – Intended use of the re-focused effort is to produce a set of performance indices that will enable FHWA to more accurately and consistently assess condition of portions or entire national highway pavement system. It is not to report to congress, but to report to FHWA front office.

All of the above action items are complete.

2. Data Requirements for Rutting and Ride Quality (IRI)

An overview of the data requirements (collection, processing, QC/QA, thresholds) was presented by Amy for both rutting and ride quality. The overview focused on:

- Data collection elements
- Data collection equipment specifications
- Equipment calibration and/or check requirements prior to data collection
- Data collection temporal requirements
- Data collection spatial requirements
- Data collection speed requirements

After the presentation by Amy, discussion was opened up for the TWG. Highlights of the input provided by the TWG members are presented below.

<u>Rutting</u>:

+ The purpose of the index and data requirements is for a national perspective, not selecting a treatment. Therefore, using larger base lengths for a national perspective is expected although as the base lengths gets larger, the usefulness of the data diminishes regarding identification of areas of both good and poor condition.
+ Rutting poses a safety issue, which is important at the national level and therefore it cannot be averaged similar to IRI. At what point does it become a meaningful indication for national reporting? In addition to reporting the average, consider using standard deviation as well or another measure to help indicate a safety issue.
+ Good/fair/poor rutting is affected by travel speed and cross slope (and ability of ruts to hold water). Suggest looking into these factors as part of the thresholds.

<u>Ride</u>:

+ The recommendation for data to be collected in the same season each year is desirable. However, it is not likely that this ideal consistency can be delivered by the States due to equipment issues, collection efficiency, etc. Although there can be a significant difference in IRI between seasons for JPCP, on a national scale how meaningful is this slight improvement in data quality?
+ Ride quality can vary depending on functional class. Suggested to keep threshold values the same regardless of functional class, but to have different target values for different functional classes.

3. **Next Steps (webinar minutes, next webinar, etc.)**

   Gonzalo indicated that the next step will be to hold a webinar to discuss the cracking and faulting data requirements as well as the field validation of the data requirements and threshold values during the first week in March 2013. Gonzalo will send out an e-mail message to schedule the next webinar.

   A draft of the data requirements report will be sent out to the TWG for review and comment towards the end of March or early April 2013, covering all four data elements (rutting, ride quality, cracking and faulting).

   FHWA and the project team again thanked the TWG members for their willingness to help on this important undertaking as well as for their valuable input during the webinar. The webinar concluded at 4:20 pm EST.

Overall, the third webinar was very productive and provided excellent feedback for carrying out the remainder of the work.

Please let us know if you have questions, require clarification or would like to discuss the above.

Thank you!

Appendix E. Minutes of Fourth TWG Meeting

TECHNICAL MEMORANDUM

Date: March 14, 2013

To: Nastaran Saadatmand **FHWA Contract No.:** DTFH61-07-D-00030-T-10002
From: Gonzalo Rada **AMEC Project No.:** 6420101002.15
CC: Steve Gaj, Jonathan Groeger, Amy Simpson, Beth Visintine

Subject: FHWA Highway Infrastructure Health Assessment Study – Task 15 "Next Generation Pavement Performance Measure" Technical Working Group: TWG Meeting #4 Minutes

The fourth TWG meeting – a webinar – was held on March 13, 2013, starting at 10:30 am EDT.

The participants of the webinar included:

- Ralph Haas, University of Waterloo
- Rick Miller, Kansas DOT
- Brian Schleppi, Ohio DOT
- Nadarajah Sivaneswaran, FHWA
- Roger Smith, Texas A&M University/TTI
- Katie Zimmerman, Applied Pavement Technology (APTech)

In addition to the TWG members, the following FHWA and project team members participated in the webinar:

- Nastaran Saadatmand, FHWA
- Jonathan Groeger, AMEC
- Gonzalo Rada, AMEC
- Amy Simpson, AMEC
- Beth Visintine, AMEC

The webinar began with the FHWA and project team (1) greeting the TWG members, (2) thanking them for their participation in this very critical project, and (3) emphasizing how important their input is given that at least one and possibly all of the performance indicators in question may be incorporated into the Rule Making required under MAP-21.

The agenda for the webinar as well as highlights for each agenda item are provided next. The presentation that was used in support of the webinar is contained in Attachment A to these minutes.

1. **Review of February 21, 2013 TWG Webinar Action Items**

   The only action item resulting from the February 21, 2013 webinar was the distribution of the webinar minutes, which has been completed.

2. **Data Requirements for Faulting and Cracking**

   An overview of the data requirements (collection, processing, QC/QA, thresholds) was presented by Amy for both faulting and cracking. The overview focused on:

- Data collection
- Data processing
- Data QC/QA

The discussion was opened up to the TWG three times during the webinar: (1) after the faulting portion, (2) after the cracking data collection portion and (3) after the cracking processing and QC/QA portion. Highlights of the input provided by the TWG members are presented below.

Faulting:

+ One TWG member confirmed most of the ProVal findings as presented by Amy with the exception that ProVal does not perform well at detecting joints for pavements without faulting. This brought up for consideration how to find joints in those cases where there is no curling, warping, or dropoff, etc.
+ It was recommended that mid-panel cracks should be incorporated in the review. These cracks often exhibit more faulting than the joints. However, using the auto-detection function in ProVal, the joint window units are inches and even if the window is widened, it does not perform well at identifying those mid-panel cracks. It was suggested that there is still improvement needed in automated joint detection.

Action Item: Amy to follow-up with Bob Orthmeyer of FHWA on the on the issue of faulting at cracks.

Cracking (Data collection):

+ The presentation prompted discussion regarding the coefficient of variance (COV) for automated cracking data collection, which has not been documented for automated data collection. Automated data collection still presents variability based on the interpretation software, images, placement of vehicle on repeat runs, etc. Nonetheless, several of the participants felt that the COV of the automated data collection should be less than that for manual data collection.
+ It was suggested to keep in perspective what the data being collected are going to be used for (i.e., States PMS or as a performance measure). Although it would be beneficial if the data collected could also be used for State PMS, this is unlikely as different States have different needs.
+ It was highlighted that this project was initiated to determine the health of the interstate highway system using data currently available (i.e., HPMS data). The purpose now is to identify issues and make recommendations to address those issues in the case that the Rule Making requires any of these performance measures. Although this might not help the States in terms of their PMS, the States will need to comply if these performance measures are included in the Rule Making.
+ Several members expressed concern over the amount of QC/QA that would be performed on fully automated data collection if the data were only used for the national reporting or performance measures and not in the States' PMS.
+ Concern over the use of HPMS data was also expressed, as it appears those responsible for the HPMS database are resistant to change because they want to enable development of a comparative data set. Therefore, advancements under AASHTO cracking standards will need to give consideration to the collection of cracking data for the HPMS database.

Cracking (Processing and QC/QA):

- Clarification was provided by Amy on the type of validation system to use, such as the LTPP FWD calibration sites. It was suggested that cracking maps containing detailed information such as location, type, width, etc. be used. Concern was expressed regarding having to travel long distances to calibration sites with expensive equipment.
- The use of repeat runs was recommended in order to determine the COV for automated distress surveys. The repeat runs could be performed in conjunction with the validation runs in order to characterize the expected variability. The repeat runs should consist of a minimum of three, but that may not be adequate. The current profile standard is 10 repeat runs. It was also noted that the COV will be different for different vendors as each uses different processing methods. However, it was also noted that repeat runs become expensive and hinder production rates, so there needs to be a balance between QC/QA and production.
- One member of the TWG may have COV data available soon and, if so, will provide them to the project team.
- Another member of the TWG noted that Linda Pierce developed QC/QA recommendations for automated data collection. The report with the QC/QA recommendations has been submitted to Thomas Van at FHWA for review. It was suggested that Thomas be contacted to obtain a copy of the report in support of this effort.

3. Next Steps (webinar minutes, next webinar, etc.)

The next step in the project will be to finalize the draft of the data requirements report, covering all four data elements (rutting, ride quality, faulting and cracking). It is anticipated that the report will be completed by the end of March 2013 and it will be sent to FHWA and the TWG for review and comment. Field validation of the data requirements and threshold values are scheduled for mid-April 2013, and this activity would include two project team members, two FHWA members and four TWG members. It is anticipated that the last TWG webinar will be held in late April 2013. The project team will finalize the data requirements report by the middle of May 2013, prior to the task order end date of May 31, 2013.

Initially, it was expected that the field validations would be used in support of development and validation of a next generation performance index. Since the scope of the work changed focus to data requirements and processing for rutting, ride, faulting and cracking, the value of field validations was discussed. It was also noted that due to FHWA travel restrictions, only one member from FHWA can participate in the field validations. Siva agreed to participate on behalf of FHWA.

Action Item: *TWG members who are available to participate in field validations during mid-April to notify the project team.*

Action Item: *FHWA and project team to consider alternative activity instead of field validations.*

FHWA and the project team again thanked the TWG members for their willingness to help on this important undertaking as well as for their valuable input during the webinar. The webinar concluded at 11:55 am EDT.

Overall, the fourth webinar was very productive and provided excellent feedback for carrying out the remainder of the work.

Please let us know if you have questions, require clarification or would like to discuss the above.

Thank you!

Appendix F. Minutes of Fifth TWG Meeting

TECHNICAL MEMORANDUM

Date: May 14, 2013

To: Nastaran Saadatmand **FHWA Contract No.:** DTFH61-07-D-00030-T-10002
From: Gonzalo Rada **AMEC Project No.:** 6420101002.15
CC: Steve Gaj, Jonathan Groeger, Amy Simpson, Beth Visintine

Subject: FHWA Highway Infrastructure Health Assessment Study – Task 15 "Next Generation Pavement Performance Measure" Technical Working Group: TWG Meeting #5 Minutes

The fifth TWG meeting – a teleconference – was held on May 13, 2013, starting at 2:00 pm EDT.

The participants of the webinar included:

- Judy Corley-Lay, North Carolina DOT
- Colin Franco, Rhode Island DOT
- Ralph Haas, University of Waterloo
- Rick Miller, Kansas DOT
- Brian Schleppi, Ohio DOT
- Nadarajah Sivaneswaran, FHWA
- Roger Smith, Texas A&M University/TTI
- Katie Zimmerman, Applied Pavement Technology (APTech)

In addition to the TWG members, the following FHWA and project team members participated in the webinar:

- Jonathan Groeger, AMEC
- Gonzalo Rada, AMEC
- Amy Simpson, AMEC
- Beth Visintine, AMEC

The teleconference began with the project team (1) greeting the TWG members and (2) thanking them for their participation in this very critical project.

The agenda for the teleconference as well as highlights for each agenda item are provided next.

1. **Review and discussion of draft report items**

   Comments received from Brian, Katie, Siva, and Roger were discussed with the group. In particular, the reference to the requirement for a length of sensor footprint for collection of longitudinal profile data will be eliminated from the report. The lasers collect thousands of data points per second and the requirement for a length provides an erroneous view of the data. Additionally, a base length will be added to Table 4-2 to provide a clearer understanding of the implications of these data.

   A statement will also be added to the report recognizing other potential approaches to data collection. One of the initial requirements of the project was that the data used would be from the

HPMS database; however, there are other approaches to data collection, particularly with respect to cracking, that may provide a similar or better picture of condition than the approach used by HPMS.

The suggestion was made that the recommendation of 100 percent sampling for the cracking be codified to note that this recommendation is made for those who use fully automated collection and interpretation methods. Manual or semi-manual collection at a 100 percent sampling rate would be too onerous with little added benefit.

Additionally, the report wording will be checked regarding the recommendations for future research on faulting. The recommendation is intended to identify improvements that need to be made in the faulting measurement, in particular with relation to finding cracks and joints that have little to no faulting.

A comment was made related to the threshold values for rutting. The thresholds used need to not only identify where repairs are required, but also where rutting presents a safety risk.

It was requested that metric units be added in brackets to at least the Executive Summary. The project team committed to incorporating metric units to the full report.

2. **Review of Field Validation**

   An overview was provided of the field validation effort. The results from that study are currently under review and no specific results could be provided.

   From the field validation effort there were two specific items that were identified for further consideration: sealed cracks and length of ruts. Currently HPMS does not provide much guidance on the inclusion/exclusion of sealed cracks into the total quantity of cracking. The AASHTO specification provides a minimum length of a rut before an area can be considered "rutted." These two items will be reviewed and addressed in the final report.

3. **Production of final report**

   The final report will be revised to incorporate the comments provided by the TWG members either in writing or during today's conference call. Additionally, the final report will be revised to include a chapter identifying the field validation study. The results from the field validation will be incorporated into each of the four chapters discussing the four data elements reviewed. The final report will not be provided to the TWG for an additional review due to the limited time left in the contract; however, with approval from FHWA, a copy of the report will be provided to them once ready.

FHWA and the project team again thanked the TWG members for their willingness to help on this important undertaking as well as for their valuable input during the teleconference. The teleconference concluded at 2:55 pm EDT. Overall, the fifth webinar was very productive and provided excellent feedback for carrying out the remainder of the work.

Please let us know if you have questions, require clarification or would like to discuss the above.

Thank you!

U.S. Department of Transportation
Federal Highway Administration
Office of Asset Management
1200 New Jersey Avenue, SE
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