Improving FHWA's Ability to Assess Highway Infrastructure Health

Pilot Study Report Addendum

Rutting Bias Investigation

April 2013

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16. Abstract

This addendum documents the investigation of the rutting bias between field data and the Highway Performance Monitoring System (HPMS)/State Department of Transportation (DOT) pavement management system (PMS) data observed in the pilot study conducted as part of the "Improving FHWA's Ability to Assess Highway Infrastructure Health" project. The objectives of this study were to: 1) investigate the discrepancy between rutting observed from field data collection versus that retrieved from HPMS/State data to determine the cause of the bias, and 2) develop data requirements and an algorithm that can be applied to rutting to produce consistent, high-quality data. A conclusive reason for the South Dakota rutting bias found during the pilot study was identified, but one for the Minnesota data could not be identified. It is possible that the rutting bias for the Minnesota data is the result of several variables, including different gage width, different sensor types, different years of data collection, different drivers, and different vehicle types.

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 are recommended.

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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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

Table of Contents

List of Tables

List of Figures

List of Acronyms

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ANOVA	analysis of variance
DCT	Discrete Cosine Transform
DLL	Dynamic Link Library
DOT	Department of Transportation
FHWA	Federal Highway Administration
HPMS	Highway Performance Monitoring System
ICC	International Cybernetics Corporation
IRI	International Roughness Index
IWP	inside wheel path
KDOT	Kansas Department of Transportation
LCMS	Laser Crack Measurement System
LTPP	Long-Term Pavement Performance
LRMS	Laser Rut Measurement System
MRD	maximum rut depth
MSE	Mean Square Error
NIMS	National Information Management System
ODOT	Oklahoma Department of Transportation
OWP	outside wheel path
PMIS	Pavement Management Information System
PMS	pavement management system
PPDB	Pavement Performance Database
S&G	straightedge and dial gauge
SSEn	sum of the square residuals
TxDOT	Texas Department of Transportation
TPL	transverse profile logger
TRL	Transport Research Laboratories

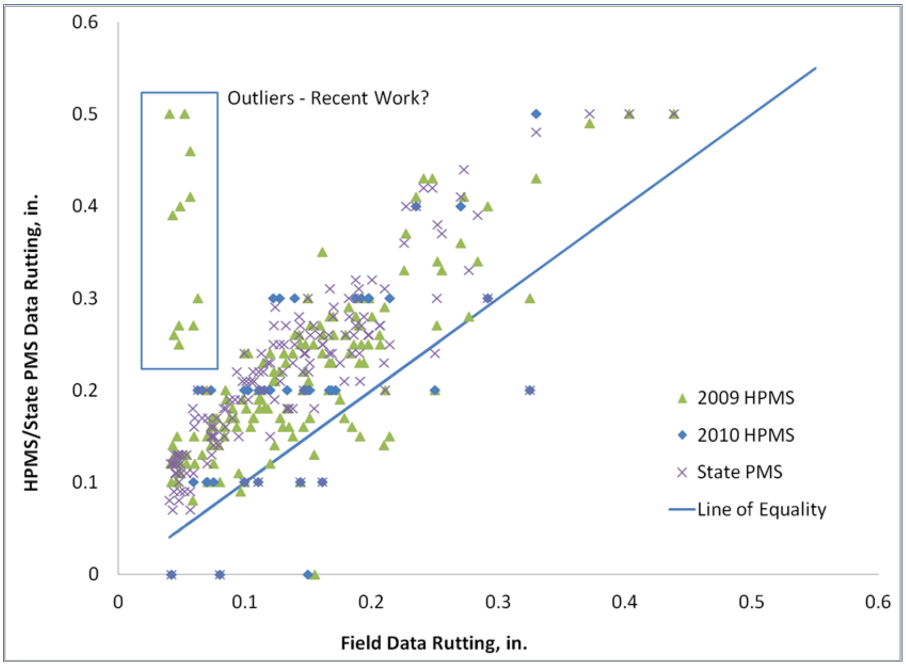
1.0 Introduction

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) test approaches for categorizing bridge and pavement condition as good/fair/poor that potentially could be used 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. The following document is an addendum to the pilot study report and it describes an evaluation of rutting data undertaken to assess why there was a bias in the results obtained during the original pilot study.

For purposes of the pilot study, rutting data were obtained from three data sources – Highway Performance Monitoring System (HPMS), State Department of Transportation (DOT) Pavement Management System (PMS), and field data collection (i.e., collected by the project team as part of pilot study). These data were aggregated to the same data reporting segment limits as used in the HPMS data set. Figure 1-1 presents a comparison of rutting data from the HPMS, field and State DOT PMS data sets. As shown, there are some segments for which the rut depth values obtained from the field data are significantly lower than those obtained from the HPMS or State DOT PMS data. These outliers correspond to the areas where significantly lower field International Roughness Index (IRI) values (as compared to HPMS and State DOT PMS data) were observed in the asphalt concrete (AC) surfaced pavement segments, and they may be associated with maintenance or rehabilitation. The correlations between the three rutting data sets are presented in Table 1-1.

The rutting data compare well between the three data sets, especially when the outliers are removed. However, it may be observed from Figure 1-1 that there is a bias between the field data and the HPMS and State DOT PMS data – the field data are consistently lower (0.05 to 0.1-in.) than the other two data sets. This bias may be related to a change in the data collection methodology between the field data and the HPMS and State PMS DOT data sets.

Figure 1-1 Comparison of Rutting Data from HPMS, State, and Field Data



Source: AMEC Environment & Infrastructure, Inc.

Table 1-1 Correlations Between Rutting Data Sets

	2009 HPMS Rut		2010 HPMS Rut		State Rut	
	Outliers	No Outliers	Outliers	No Outliers	Outliers	No Outliers
2011 Field Rut	.57	.66	.66	.65	.87	.86
2009 HPMS Rut			.73	.74	.58	.69
2010 HPMS Rut	.73	.74			.85	.84

As a result of the bias, the pilot study concluded that a medium-level of confidence exists for rut depth data and that additional investigation is required to resolve the bias issue between the HPMS or State DOT PMS data and the field data collected as part of the pilot study. Accordingly, the objectives of the study documented in this addendum were to:

- Investigate the discrepancy between rutting observed from field data collection versus that retrieved from State PMS/HPMS data to determine the cause of the bias, and
- Develop data requirements and an algorithm that can be applied to rutting to produce consistent, high-quality data.

The activities carried out towards the accomplishment of the above objectives as well as the associated findings, conclusions and recommendations are detailed over the ensuing sections of this addendum. The next section addresses the rutting bias investigation, the following section addresses rutting data requirements and data processing algorithm, and the last section provides the major conclusions and recommendations from the study.

2.0 Rutting Bias Investigation

To assess the bias in the rutting data, the project team pursued the following two items:

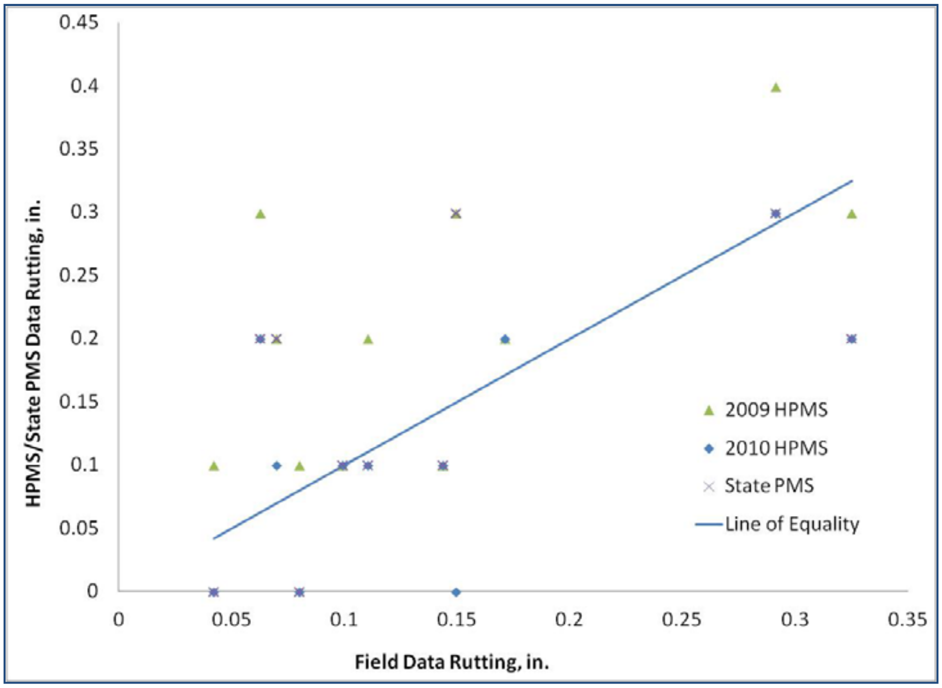
1. Rutting algorithms used by the States when reporting PMS and HPMS data and the rutting algorithm used for the pilot study field data collection.
2. Raw rutting data for South Dakota and Minnesota (no raw data were available from Wisconsin) collected by the States for PMS and HPMS reporting as well as raw data from the data collection vendor that performed the field data collection portion of the pilot study for the study team.

The rutting algorithms were pursued directly through the equipment vendors – Pathways for the State PMS/HPMS data and Mandli Communications for pilot study field data. Specifically, the project team discussed the data processing procedures used by the Pathways and Mandli equipment directly with the vendors. Both vendors use an INO sensor on their equipment. South Dakota and Minnesota both own Pathways data collection vehicles. The State-owned vehicles that would have been used to collect the data in 2010 were equipped with INO Laser Rut Measurement System (LRMS) sensors. These sensors collect approximately 1,200 points per transverse profile. They use a virtual 6-ft. straightedge to estimate the rut depth with a 1.97-in. gage width. Gage width refers to the width of the imaginary ruler used to measure the depth from the straightedge or wireline spanning the lane to the pavement surface.

The Mandli equipment used for the pilot study field data collection was equipped with INO Laser Crack Measurement System (LCMS) sensors. These sensors collect approximately 4,000 points per transverse profile. Like Pathways, the rut depth calculation involves the use of a virtual 6-ft. straightedge, but a 1.57-in. gage width is used instead of 1.97-in. Accordingly, the two main differences between the Pathways and Mandli systems are the 0.39-in. difference in gage width and the approximately 2,800 difference in the number of data points per transverse profile.

Concurrent with the above, a discussion with the South Dakota DOT yielded that their PMS does not use the data from the Pathways INO LRMS sensors for determination of rut depths. In fact, their PMS uses data from the longitudinal profiles to calculate rut depth based on the height sensor output from the two wheelpaths and the center of the lane. Figure 2-1 illustrates the comparison between the rut depths for South Dakota from the State PMS, HPMS, and field data collected. Further, to maintain consistency with historical data, South Dakota applies a factor of 1.21 to the rut depth calculated from the longitudinal profile.

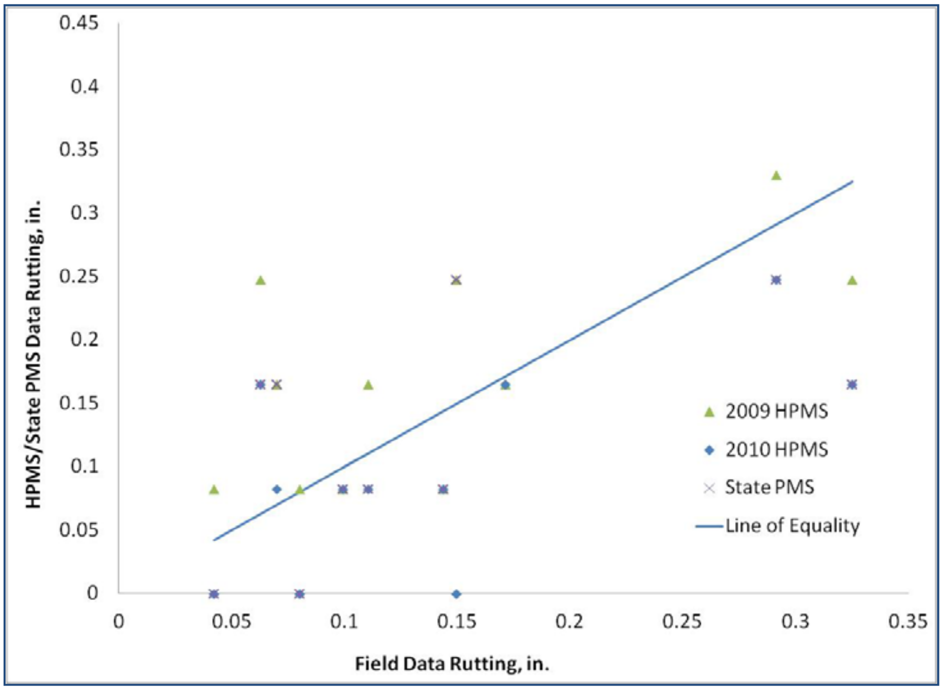
Figure 2-1 Comparison of Rut Depths from South Dakota



Source: AMEC Environment & Infrastructure, Inc.

Figure 2-2 illustrates the comparison between the rut depths with the factor removed from the State PMS and HPMS data. This figure shows that the bias observed in the data is removed when the factor is removed.

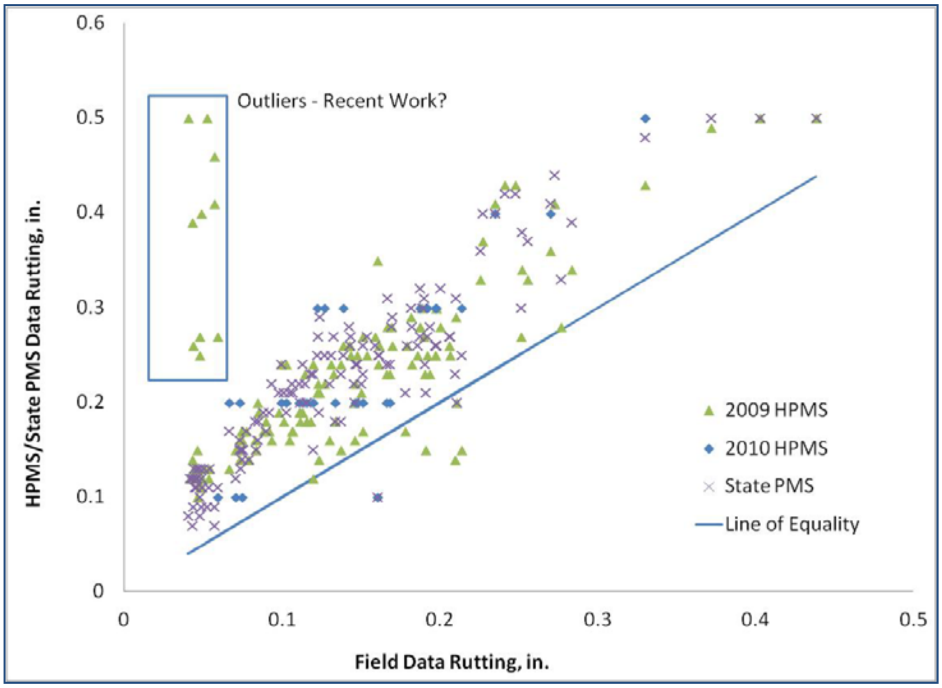
Figure 2-2 Rut Depths from South Dakota with Factor Removed



Source: AMEC Environment & Infrastructure, Inc.

A review of the Minnesota DOT data, as shown in Figure 2-3, illustrates that the bias observed in the full data set (all States) was evident in Minnesota's data as well. Accordingly, additional review of the Minnesota DOT data was pursued in order to fully understand the bias in the rutting data. Minnesota DOT and Mandli raw transverse profile data was obtained as well as the means for viewing the transverse profile.

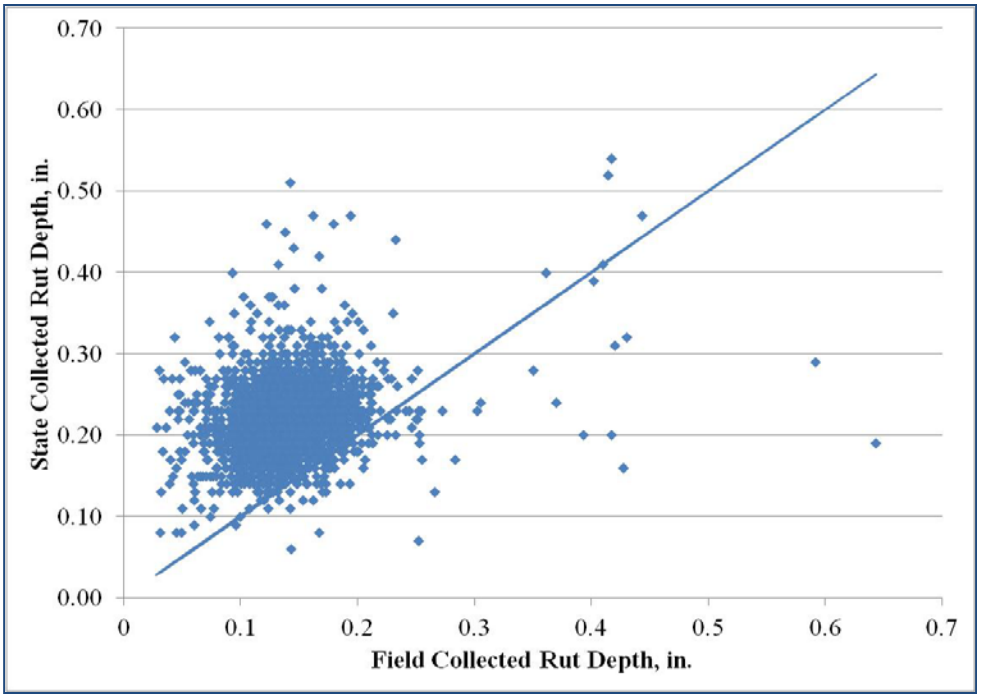
Figure 2-3 Comparison of Rut Depths from Minnesota



Source: AMEC Environment & Infrastructure, Inc.

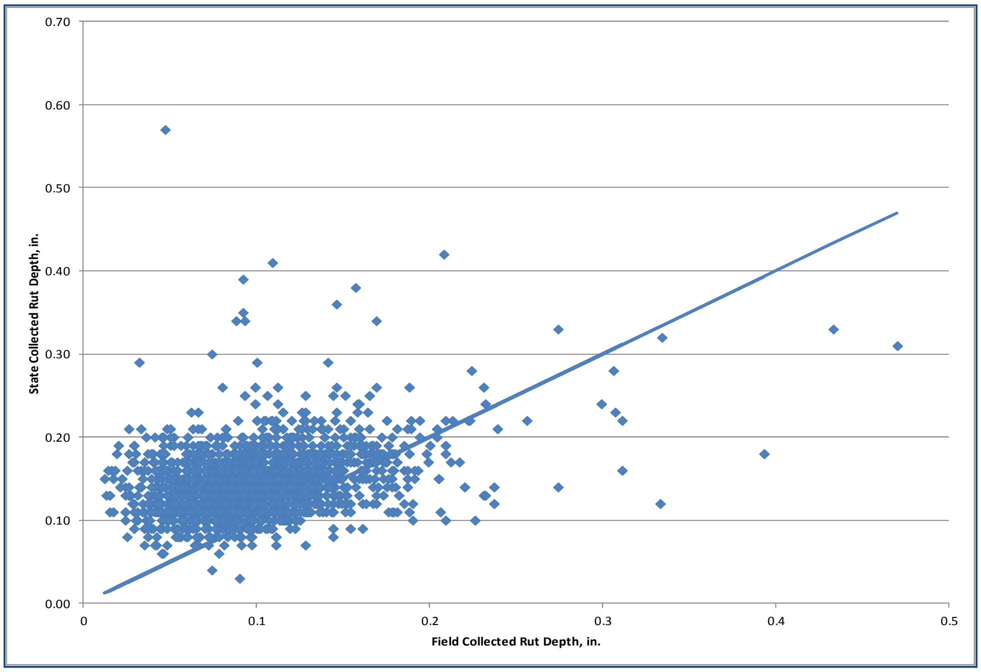
While it was not possible to perform a direct comparison between the transverse profiles from the INO LRMS sensors used by the Minnesota DOT and the INO LCMS sensors used for the field data collection, there were 2,077 computed rut depth values over an approximate 10-mile distance from the two sensors collected at the same location as measured to the nearest 0.0001-mile. These values were identified and reviewed. A graph of this comparison is provided in Figure 2-4 for the left wheelpath and Figure 2-5 for the right wheelpath.

Figure 2-4 Comparison of State and Field Collected Rut Depths for the Left Wheelpath



Source: AMEC Environment & Infrastructure, Inc.

Figure 2-5 Comparison of State and Field Collected Rut Depths for the Right Wheelpath



Source: AMEC Environment & Infrastructure, Inc.

As illustrated in Figure 2-4 and Figure 2-5, the comparison between the two rut depth value data sets shows a lack of correlation between these values. The rut depths for the two devices appear to average to a reasonably similar value as presented in the original pilot study report, while the individual values do not match well. Furthermore, no apparent explanation can be discerned from the available information.

Earlier in this section it was noted that the two equipment manufacturers for the devices used to collect the State PMS and field data used a different gage width to evaluate the rut depth. The State PMS device was set to use a gage width of 1.97-in. and the field data collection was based on a gage width of 1.57-in. The impact of gage width on rut depth is discussed in greater detail in the next section of this document. For the purposes of the rutting bias investigation, it is believed that the impact of the difference in gage width is minimal. As will be shown later, the average change in rut depth based on this change in gage width is expected to be less than 0.01-in. Given that the average difference observed between the direct comparison of a sample of the rut depth values was on the order of 0.05-in., the difference expected for the change in gage width is insufficient to explain the difference between the two devices.

Given the above discussion, a conclusive reason for the rutting bias found during the pilot study cannot be identified. It is possible that the rutting bias is the result of a number of variables, including different gage width, different sensor types, different years of data collection, different drivers, and different vehicle types.

3.0 Rutting Data Requirements and Algorithm

The objective of this activity was to establish rutting data collection requirements and an algorithm for use as a rutting condition indicator. In order to evaluate rutting in asphalt pavements, it is important to have consistent, high-quality data as well as an appropriate algorithm. Accordingly, as part of this effort, data collection requirements were considered as well as the rut depth calculation algorithm.

3.1 DATA REQUIREMENTS

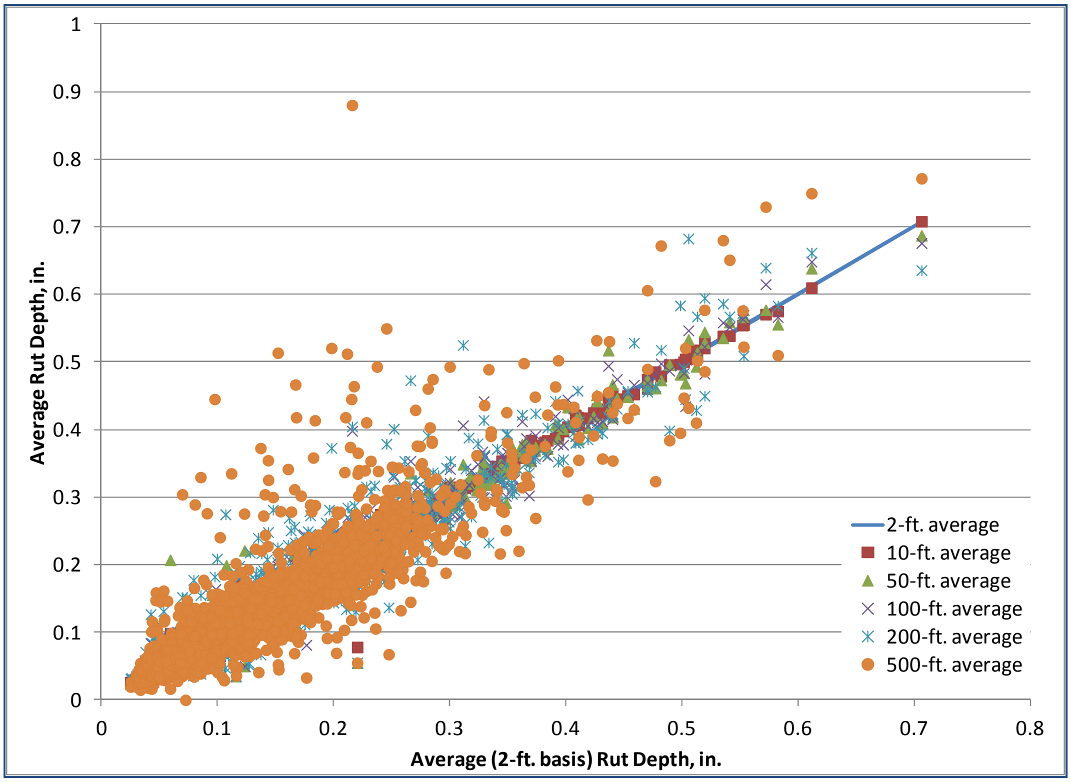
The data collection requirements considered as part of this study included longitudinal spacing of the transverse profiles, number of points in the transverse profiles, and moving average. The findings associated with these three elements are provided next.

Longitudinal Spacing

An analysis was conducted to investigate the impact of longitudinal spacing on the accumulated rut depth reported at 0.1-mile intervals. The field data for the project were collected at a longitudinal spacing of 2-ft. The rut depths collected at the 2-ft. spacing were aggregated to a 0.1-mile interval. In addition, these values were sampled at different spacing intervals and aggregated to 0.1-mile intervals to investigate the impact of larger spacing on the average values. The rut depths were sampled to represent data collection at intervals of 10-ft., 50-ft., 100-ft., 200-ft., and 500-ft. These sampled values were then aggregated to the 0.1-mile average rut depth.

Figure 3-1 illustrates the impact of this type of sampling on the rut depth in comparison to the values collected at 2-ft. intervals.

Figure 3-1 Comparison of Average Rut Depth Sampled at 2-ft. Intervals and at Larger Intervals

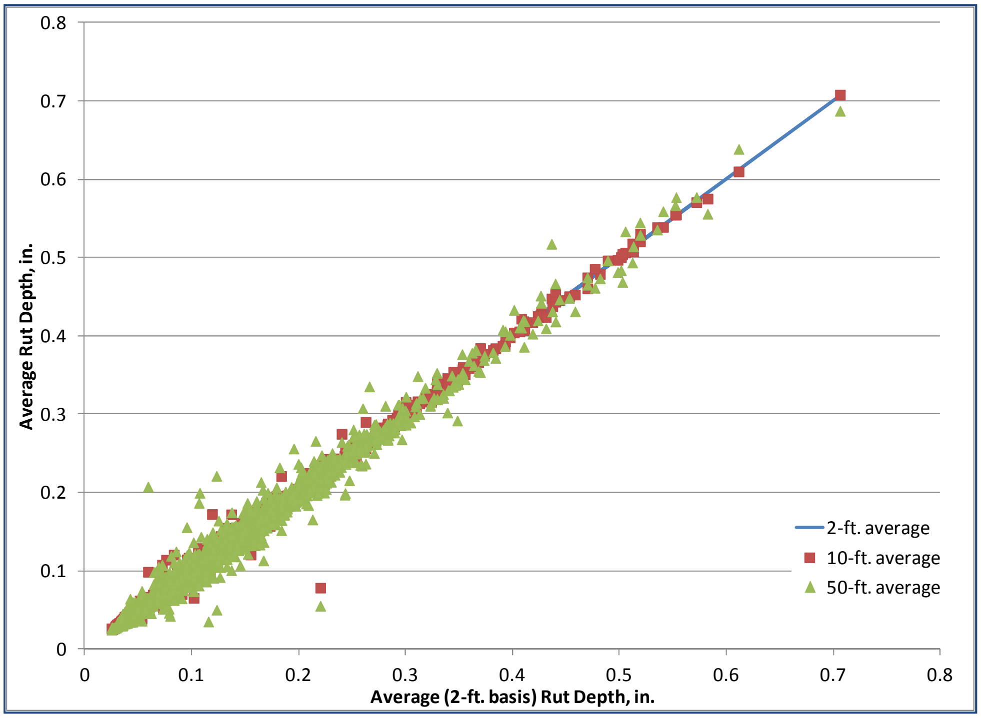


Source: AMEC Environment & Infrastructure, Inc.

Figure 3-2 provides the same data except that the average rut depth from the 100-ft., 200-ft., and 500-ft. sampling intervals were eliminated from the graph. The data sampled at 10-ft. and 50-ft. intervals show considerably less scatter than the data sampled at the longer intervals.

As an additional review of the impact of sampling interval, the data collected at 2-ft. intervals were used to estimate the number of samples required to produce a similar estimate for each interval. This analysis was completed for the segment of the I-90 corridor from milepost 102.1 to milepost 138.8 in Minnesota. The estimated required number of samples ranges from 1 to 68 (sampling from 528-ft. to 8-ft.), and the average within this range is 2 (sampling at 264-ft. intervals).

Figure 3-2 Comparison of Average Rut Depth Sampled at 2-ft., 10-ft. and 50-ft. Intervals



Source: AMEC Environment & Infrastructure, Inc.

The statistical analysis points to a longer data collection interval, but the information provided in Figure 3-1 and Figure 3-2 suggests a shorter interval is required to develop accurate estimates. The transverse profile is a continuous variable suggesting that the transverse profile does not change dramatically within a short distance. However, it may also generally be expected that the larger rut depths will not necessarily exist over long distances.

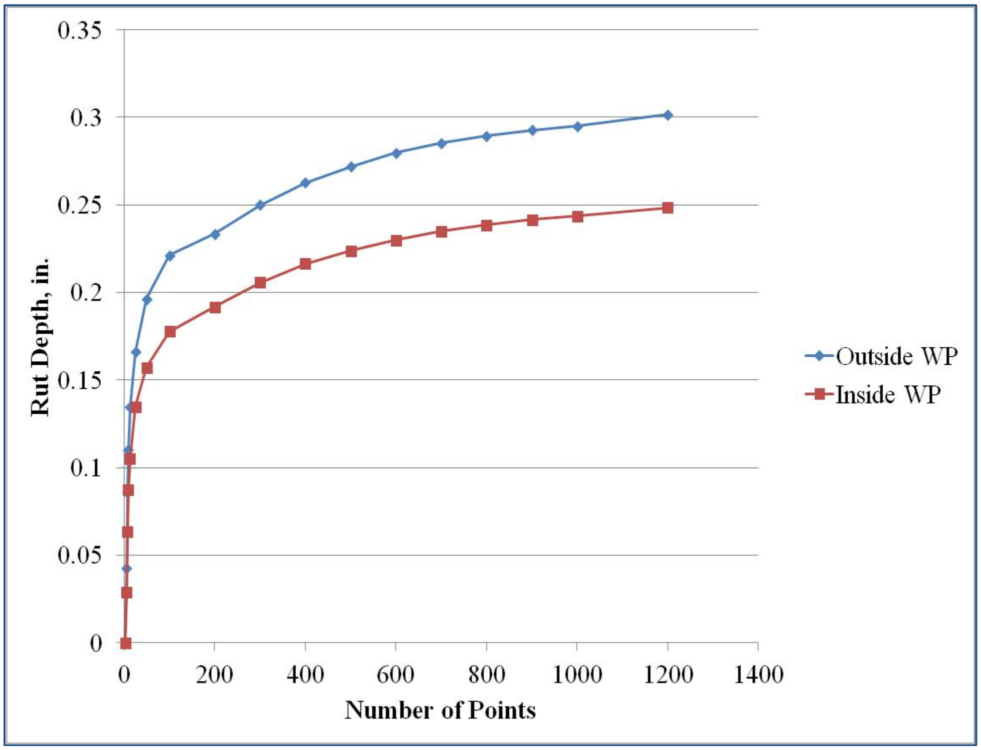
Therefore, one objective of the data collection effort is to capture these areas of large rutting. Accordingly, the recommended interval should be no more than a 50-ft. interval, recognizing that the smaller the interval the more likely the data collection will capture the maximum rutting occurring on the pavement surface.

Number of Points in the Transverse Profile

The next data item considered was the number of points within the transverse profile. The profiles were evaluated using increasing numbers of points selected across the transverse profile. The number of points considered ranged from 3 to 1,200. Figure 3-3 shows the impact of changing the number of points within this range.

The graph shown in Figure 3-3 illustrates the drastic change in the average rut depth with the change becoming less significant towards the end of the graph. However, in this case, it is important to consider the overall change between successive rut depths. The change in average rut depth between the average at 400 points and the average at 1,200 points is less than 0.05 inch. The data reviewed suggest that a minimum of 400 points within a transverse profile are required to reasonably estimate the rut depth.

Figure 3-3 Average Rut Depth based on Varying Number of Points within the Transverse Profile



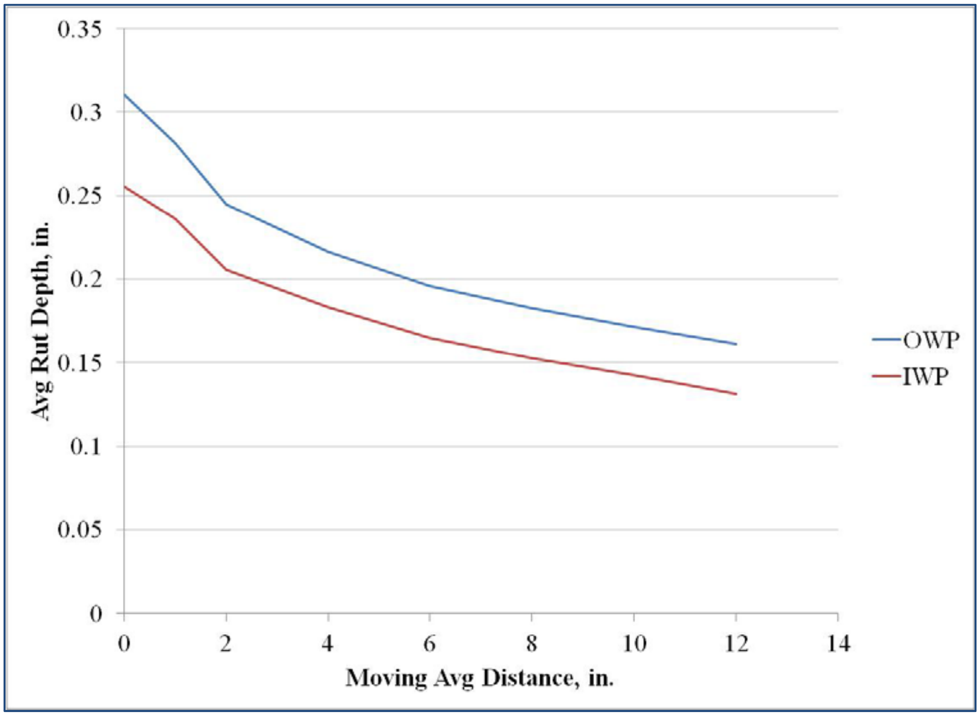
Source: AMEC Environment & Infrastructure, Inc.

Moving Average

White noise is commonly observed in signal processing and is caused by the electrical system. White noise may be observed within the collected transverse profile. The noise is generally small with an expected average of 0 meaning that the average values over a short distance may provide the "true" signal. As part of the investigation, the impact of using a moving average as part of the signal processing to develop the transverse profile used for the rut depth calculation was reviewed.

The data were processed and the rut depth calculated using a moving average ranging in width from 0 to 12 inches in length. Figure 3-4 illustrates the impact of the moving average of varying lengths on the average rut depth. Based on the change in slopes around the moving average width of 2 inches, this value is the processing length which appears to reduce the moving average while maintaining the "true" signal.

Figure 3-4 Impact of Moving Average on the Average Rut Depth



Source: AMEC Environment & Infrastructure, Inc.

Algorithm

To establish a recommended rutting algorithm, a literature review was first conducted to determine current rutting algorithms and existing software available for computing rut depths. Based on the findings from the literature review, the two most promising algorithms were evaluated using the field pilot study data. The different aspects of the rut depth calculation reviewed included straightedge length and gage width. The findings from these two sets of activities are presented next.

3.2 RUT DEPTH PROCEDURE

There are several procedures used to measure rut depth including manually measuring with straightedge and dial gauge (S&G), ultrasonics, point lasers, scanning lasers and optical. This section provides a summary of the major findings from the literature review, which is contained in appendix A.

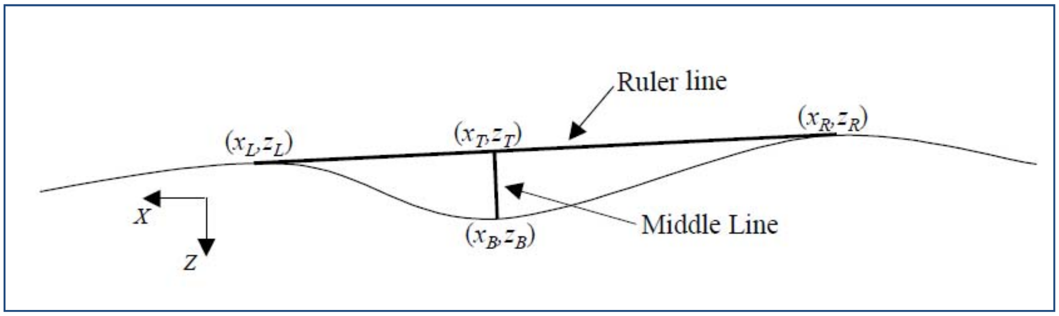
There are three main methods used to calculate rut depth: straightedge model, wireline model and the pseudo-rut model. The straightedge model connects the two highest points on either side of the rut with 3.9-ft. virtual straightedges. The wireline model is similar to the straightedge model by assuming a wire is stretched across the high points of the profile. Unlike the straightedge model, the wireline model can change slopes as the wire contacts other high points. However, in most cases, this model produces the same results as the straightedge model (Hoffman and Sargand, 2011). The pseudo-rut model calculates the rut depth based on the difference between the highest and lowest points. As this does not necessarily translate to the actual rut depth, this method can produce poor results and is not reliable (Hoffman and Sargand, 2011).

The length of the straightedge or wireline used has a major impact on the depth of the rut. According to Simpson, the use of a 4-ft. straightedge is not recommended for calculating rut depth as it is considered unreliable (Simpson, 1999). The current ASTM E1703 Standard Test Method for Measuring Rut-Depth of Pavement Surfaces Using a Straightedge requires a minimum straightedge length of 6-ft. and recommends using a straightedge with length of at least 6-ft. up to 12-ft. (ASTM, 2010).

Many states began automating the process of collecting network level rut depths using either the three-point or five-point laser system. Research conducted by a number of researchers (Simpson, 2001; Bennett, 1996; and Flintsch and McGhee, 2009) all agree that the number of sensors and transverse sampling affects the precision and accuracy of calculated rut depths. Simpson concluded that the three-point and five-point rut depth measurements were not reliable or accurate compared to the wireline rut depths (Simpson, 2001). The research also showed that fewer sensors and larger transverse sampling leads to underestimated rut depth estimates (Simpson, 2001; Bennett, 1996; Flintsch and McGhee, 2009).

Derived from the straightedge model and in accordance with ASTM 1703, the rut depth is calculated from data collected by the LRMS as depicted in Figure 3-5.

Figure 3-5 Rut Depth Calculation used by the LRMS



Source: Grondin et al., 2002.

Tsai et al. assessed the measurement of rut depth using 3D continuous laser profiling technology. The research evaluated the rut depth measurement using the LCMS which uses two laser profiling units and collects 2,080 3D laser points on each transverse profile at a frequency of 5,600 Hz (Tsai et al., 2011). The 6-ft. straightedge method is used to calculate the rut depth by connecting the two high points from the smoothed profile. Comparison of laboratory testing to ground truth showed the difference of rut depth as measured by the LCMS to the ground truth varied from 0.0031-in. to 0.03-in. with a standard deviation of 0.0028-in. to 0.013-in. indicating high accuracy and good repeatability (Tsai et al., 2011).

An independent assessment of the accuracy and precision of the TxDOT 3D laser rut measurement system and state-of-the-practice commercially available automated rut measurement systems compared the maximum rut depth (MRD) and transverse profiles to the ground truth. Each of the five participants reported the MRD values calculated by applying an algorithm to the measured transverse profiles. The algorithms used by each of the vendors were not provided to the researchers. The transverse profiles and MRD values provided by the vendors were compared to ground truth values using five statistical parameters. The researchers concluded that all five systems were capable of capturing surface profiles with the necessary accuracy and that no single piece of equipment performed better overall in terms of MRD measurement (Serigos et al., 2012).

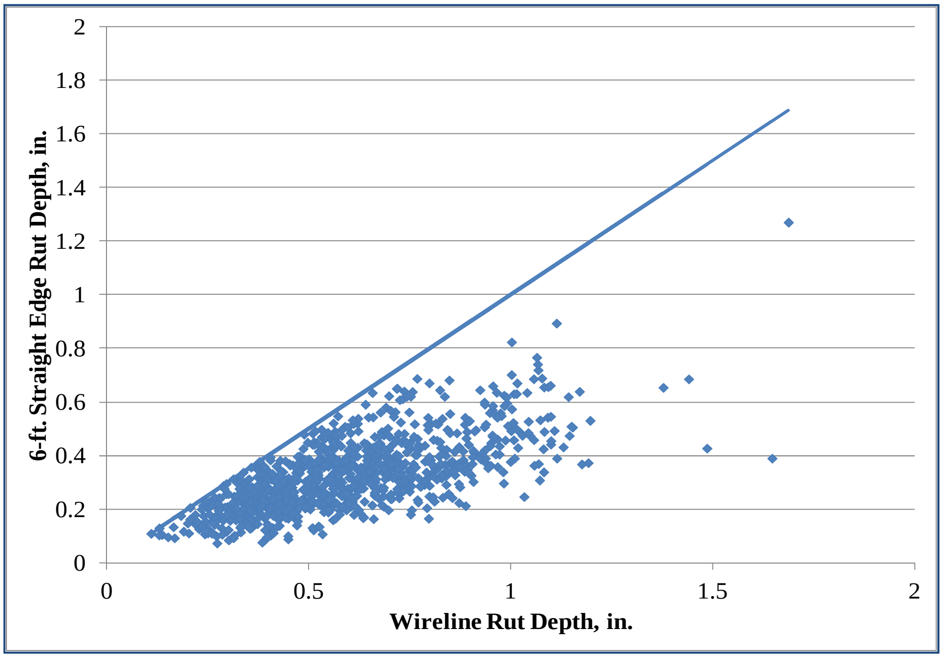
Many agencies use the software provided by the manufacturer of the equipment to collect transverse profiles, such as Kansas DOT (KDOT) using the International Cybernetics Corporation (ICC) software and Oklahoma DOT (ODOT) using the Dynatest software. The software packages usually filter and smooth the collected transverse profiles for profile analysis and rut depth calculation. The LRMS utilizes a standard Win32DLL (Dynamic Link Library) and C-language functions which can be integrated into the end users' software application (Grondin et al., 2002).

3.3 RUT DEPTH CALCULATIONS

The literature review showed that there are a number of methods possible for estimating the rut depth from a transverse profile. The list of options was narrowed down to the two most promising algorithms for further investigation – 6-ft. straightedge and lane-width wireline. The three-point and five-point systems, as shown in the literature review, have been identified as having a high degree of variability associated with them. Some agencies have opted for a 4-ft. straightedge; however, as some of the literature review studies noted, this straightedge is of insufficient length to fully capture the observed rut.

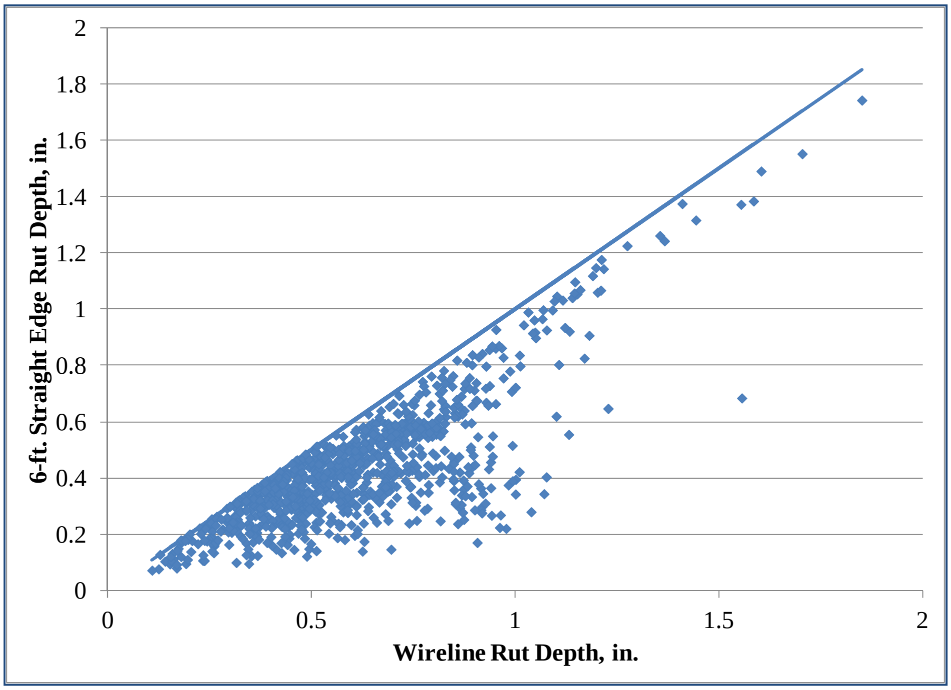
Figure 3-6 and Figure 3-7 provide a comparison of the rut depth based on a 6-ft. straightedge and a wireline method. In both figures the rut depth is larger based on the wireline method than the 6-ft. straightedge. These figures suggest that the wireline method of evaluation provides a more complete method of estimation of the rut depth on asphalt pavements.

Figure 3-6 Comparison of 6-ft. Straightedge and Wireline Rut Depths in the Left Wheelpath



Source: AMEC Environment & Infrastructure, Inc.

Figure 3-7 Comparison of 6-ft. Straightedge and Wireline Rut Depths in the Right Wheelpath



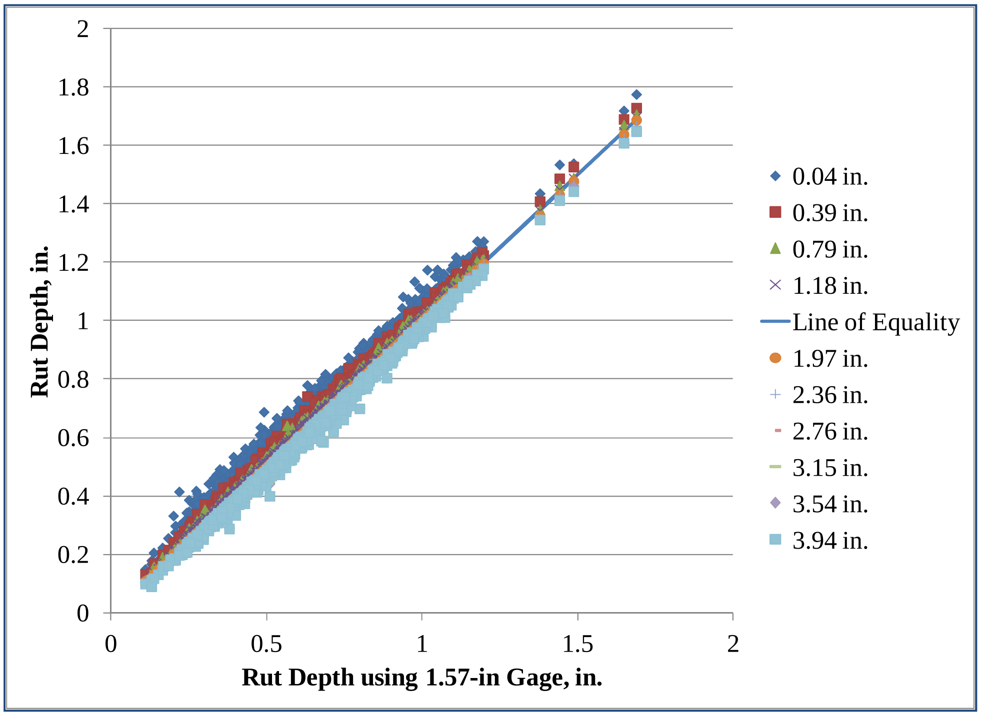
Source: AMEC Environment & Infrastructure, Inc.

3.4 GAGE WIDTH

The gage width is the figurative width of the ruler used to measure the rut depth from the straightedge. With a very narrow gage width, the ruler would fall within narrow gaps that would not impact vehicular traffic. If the ruler is too wide, then the ruler would not measure to the bottom of ruts that do impact vehicular traffic. In this study, the gage width was varied from 0.039 to 3.9-in. to review the impact this value had on the measured rut depth. This evaluation was completed using the transverse profile data from both the field data collection and the State PMS data from Minnesota.

Figure 3-8 illustrates a comparison of the individual values from the field collected data. In this case, the rut depths were estimated based on varying gage widths with the 1.57-in. gage width identified as the basis for comparison. Little can be said about the differences in rut depth estimated using the differing gage widths based on this graph. Generally, it appears that the rut depths from the larger gage widths are smaller than those from narrower gages. An analysis of variance (ANOVA) was completed based on these data to identify the impact of gage width. The ANOVA illustrated a statistically significant difference between the data sets.

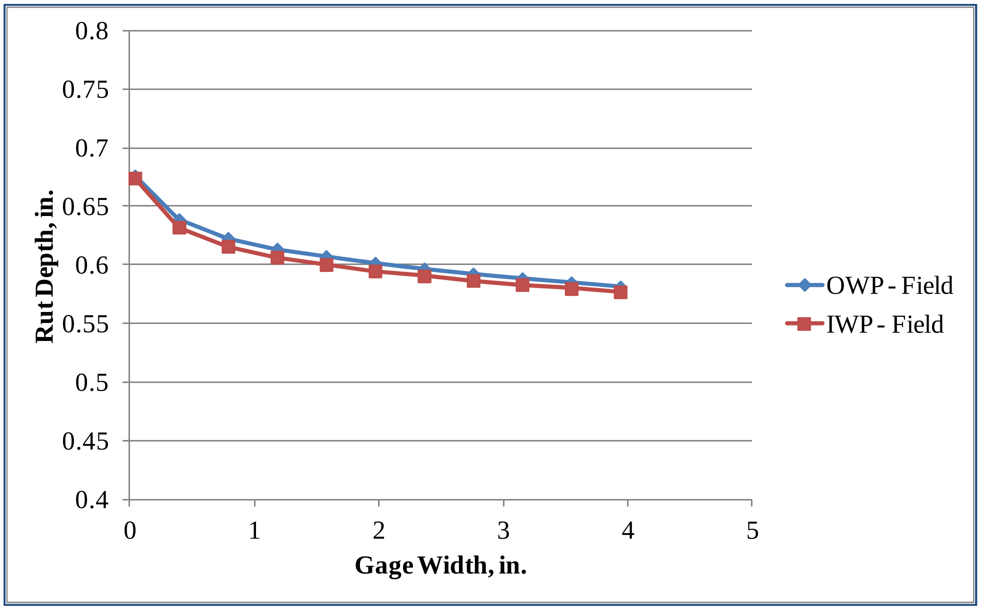
Figure 3-8 Rut Depths for Left Wheelpath Estimated from Field-Collected Data Using Varying Gage Width



Source: AMEC Environment & Infrastructure, Inc.

Figure 3-9 provides an illustrative picture of the impact of gage width on the estimated rut depth for the transverse profile data provided by field data collection. Figure 3-9 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 1.57-in. Beyond this width, the decreases are less significant. This change suggests that at the smaller gage widths, the rut depth is impacted by the white noise and/or cracks in the pavement surface that may be observed in the transverse profile. Based on this review, the optimal gage width is on the order of 1.2 to 1.57-in.

Figure 3-9 Average Rut Depth from Varying Gage Widths



Source: AMEC Environment & Infrastructure, Inc.

4.0 Conclusions and Recommendations

The objectives of this study were to:

1. Investigate the discrepancy between rutting observed from field data collection versus that retrieved from State PMS/HPMS data to determine the cause of the bias, and
2. Develop data requirements and an algorithm that can be applied to rutting to produce consistent, high-quality data.

Based on this investigation, a conclusive reason for the rutting bias between the South Dakota DOT PMS data and the field data was identified. The South Dakota DOT does not use the data from the Pathways INO LRMS sensors for determination of rut depths, the DOT used the rut measurement from the three profile sensors and applied a factor of 1.2 to their State PMS data which, when removed, reduced the bias.

However, a conclusive reason for the rutting bias between the Minnesota DOT PMS data and the field data found during the pilot study could not be identified. It is possible that the rutting bias is the result of a number of variables, including different gage widths, different sensor types, different years of data collection, different drivers, and different vehicle types. With regards to the rutting data requirements and algorithm, the following recommendations are made based upon the literature review and study analysis findings:

- A maximum longitudinal spacing of 50-ft. should be used for the collection of transverse profile data. A spacing of 10-ft. provides a more optimal approach for estimating the average rut depth.
- A minimum of 400 data points should be used to characterize the transverse profile.
- For transverse profiles containing 1,000 points or more, a moving average of 2 inches may be used to reduce the white noise in the signal obtained during data collection.
- A lane width wireline should be used to calculate the rut depth from the transverse profile.
- The gage width should be set to a value of between 1.2 and 1.57-in. for calculating rut depth.

These requirements are similar to those in the American Association of State Highway and Transportation Officials (AASHTO) procedure defined in PP70. The AASHTO procedure requires that for network level evaluation, profiles should not be spaced more than 10-ft. apart and a moving average of 2 inches be used for processing the profile. However, the AASHTO calculation is based on reviewing the data by lane-half rather than looking at a full lane-width wireline. The AASHTO protocol does not address the required number of points for the profile.

Appendix A. Literature Review

This appendix provides a summary of the information gleaned through a literature review on the topic of pavement rut measurement.

There are several procedures used to measure rut depth including manually measuring with S&G, ultrasonics, point lasers, scanning lasers and optical. Various algorithms are used to determine the rut depth. This literature review conducted as part of this study provides a summary of the various rutting algorithms available.

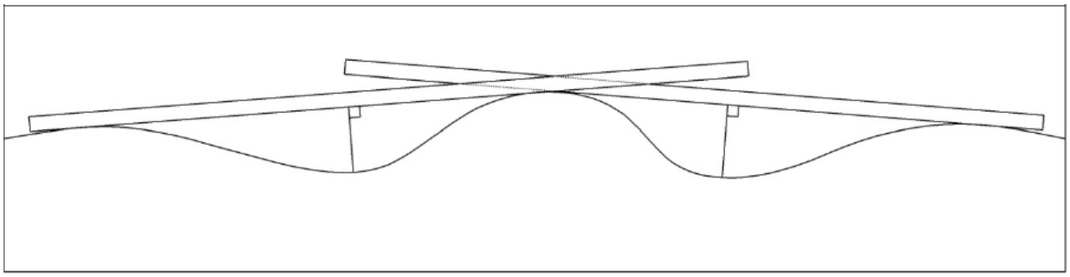
Manually measuring rut depth using a straightedge and dial gauge is time consuming and leads to only small sections of the roadway being evaluated, which can cause sections of roadway with severe rutting to be overlooked. Manually measuring rut depth also poses a safety concern since it involves lane-closure as opposed to most automated methods ability to operate at regular driving speeds. Because of this, many agencies use automated procedures to measure rut depths at the network level. By automating the process, larger sections of roadway can be processed in a shorter amount of time since the vehicles can travel at or close to highway speeds.

AASHTO PP 69-10, "Determining Pavement Deformation Parameters and Cross Slope from Collected Transverse Profiles," addresses deriving pavement deformation parameters, such as rut depth from transverse profiles collected in accordance with AASHTO PP 70-10, "Collecting Transverse Pavement Profile." According to the AASHTO standard, once the raw transverse profile data has been processed and smoothed, using a moving average filter, the rut depth is calculated by leveling the profile and rotating the profile about the inside lane edge until zeroed and then determining the depth of the rut (AASHTO PP 69, 2010).

There are three main methods used to calculate rut depth: straightedge model, wireline model and the pseudo-rut model. As depicted in Figure A-1, the straightedge model connects the two highest points on either side of the rut with 6.56-ft. virtual straightedges.

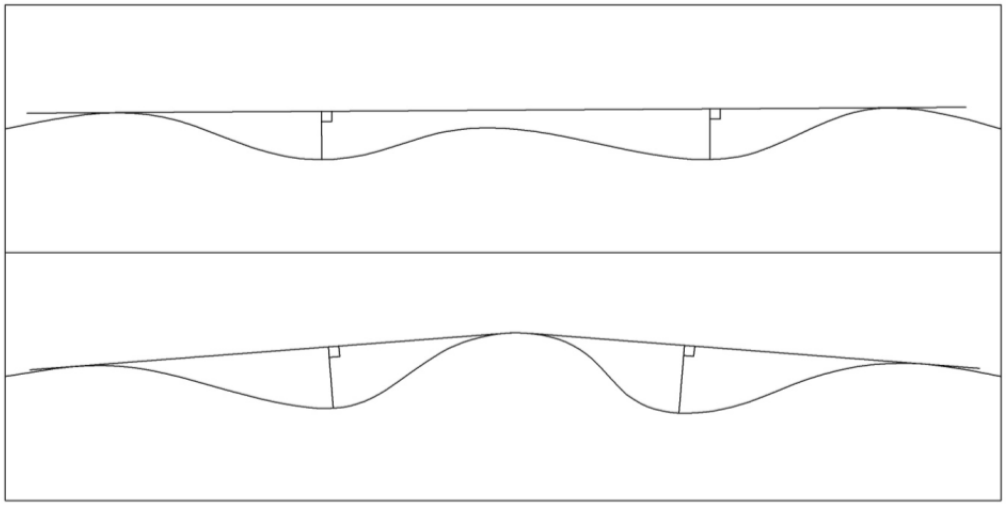
The wireline model is similar to the straightedge model as depicted in Figure A-2. This model assumes a wire is stretched across the high points of the profile. Unlike the straightedge model, the wireline model can change slopes as the wire contacts other high points. However, in most cases, this model produces the same results as the straightedge model (Hoffman and Sargand, 2011). The pseudo-rut model calculates the rut depth based on the difference between the highest and lowest points. As this does not necessarily translate to the actual rut depth, this method can produce poor results and is not reliable (Hoffman and Sargand, 2011).

Figure A-1 Virtual 6.56-ft. Straightedge Model



Source: Hoffman and Sargand, 2011.

Figure A-2 Virtual Wire Model for Measuring Rut Depth



Source: Hoffman and Sargand, 2011.

The length of the straightedge or wireline used has a major impact on the depth of the rut. According to Simpson, the use of a 4-ft. straightedge is not recommended for the use of calculating rut depth as it is has lack of repeatability and is considered unreliable (Simpson, 1999). The current ASTM E1703 Standard Test Method for Measuring Rut-Depth of Pavement Surfaces Using a Straightedge requires a minimum straightedge length of 6-ft. and recommends using a straightedge with length of at least 6-ft. up to 12-ft. (ASTM, 2010).

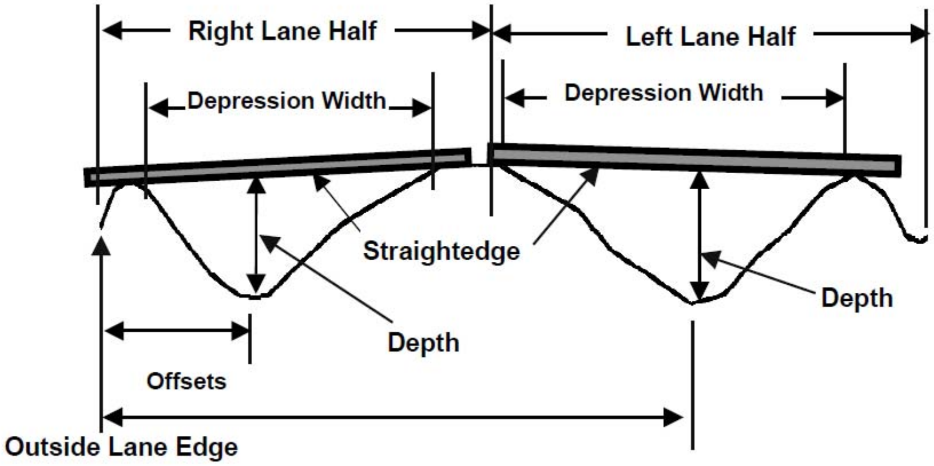
The Long-Term Pavement Performance (LTPP) program collects and stores transverse profiles and several indices in the Pavement Performance Database (PPDB). The LTPP program measure rut depth based on a 6-ft. straightedge and lane-width wireline reference, similar to the procedures previously described. The straightedge method measures the maximum rut displacement from the bottom of the straightedge to the top of the pavement surface by positioning the straightedge at various locations in each half of the lane (Elkins et al., 2011). Figure A-3 depicts the surface profile indices computed at each location for half the lane. Figure A-4 depicts the lane-width wireline rut indices stored in the LTPP database.

Many states began automating the process of collecting network level rut depths using either the three-point or five-point laser system. Both of these systems consist of lasers arranged on a rut bar across the front of the vehicle. The three-point system has a laser mounted over each wheelpath and one laser mounted over the center while the five-point system also has two additional lasers located on each edge.

Source: Elkins et al., 2011.

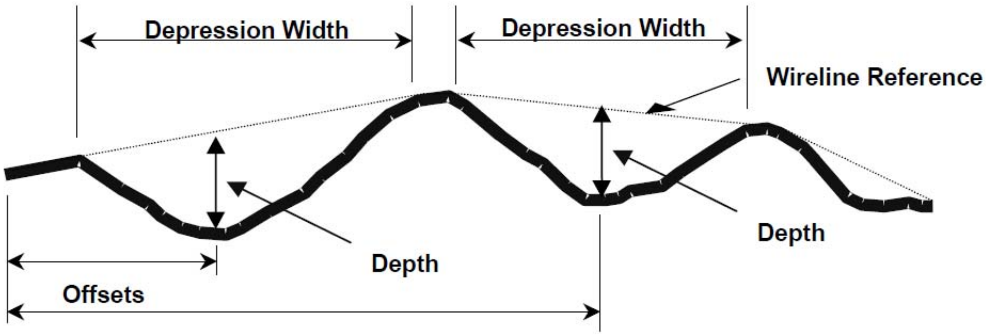
Figure A-5 and Figure A-6 depict the measurements collected by the three-point and five-point laser systems, respectively.

Figure A-3 Illustration of LTPP Transverse Pavement Distortion Indices based on 6-ft. Straightedge Reference



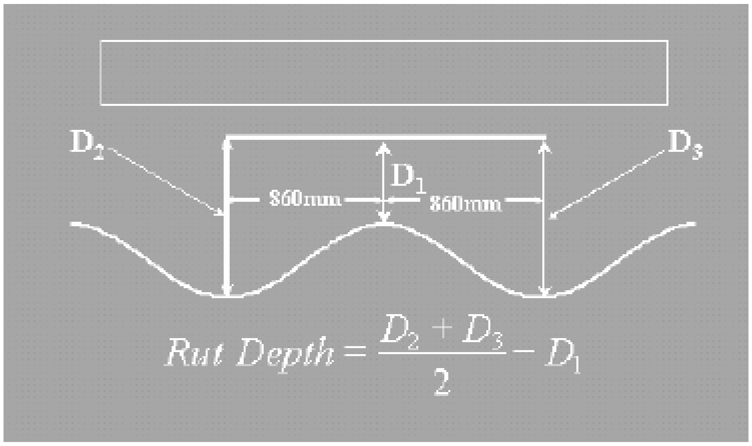
Source: Elkins et al., 2011.

Figure A-4 Illustration of LTPP Transverse Pavement Distortion Indices based on Lane-Width Wireline Reference



Source: Elkins et al., 2011.

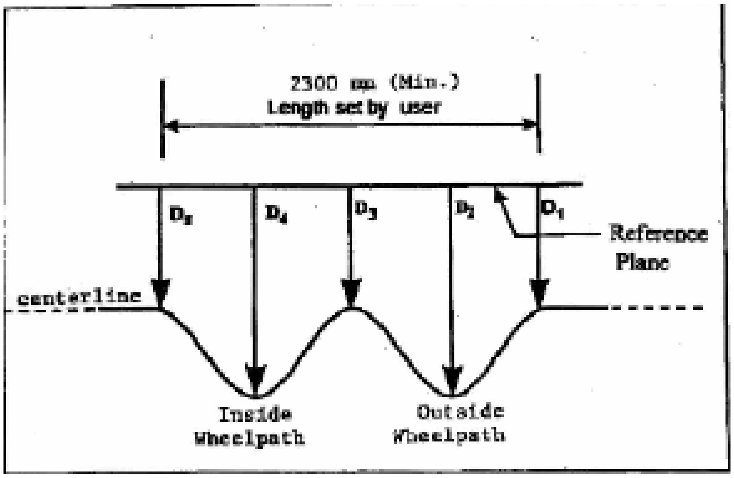
Figure A-5 Example of Three-Point Laser System



$$\text{Rut Depth} = \frac{D_2 + D_3}{2} - D_1$$

Source: Vedula et al., 2002.

Figure A-6 Example of Five-Point Laser System



Source: Vedula et al., 2002.

The rut depth based on the three-point laser system is calculated as (Vedula et al., 2002):

$$Rut\ Depth = \frac{(D_2 + D_3)}{2} - D_1$$

Where,

D1, D2 and D3 are the distances/heights measured as shown in Figure A-45.

The rut depth based on the five-point laser system is calculated as (Vedula et al., 2002):

$$R_o = D_2 - \frac{D_1+D_3}{2}; \text{ and}$$

$$R_i = D_4 - \frac{D_3 + D_5}{2}$$

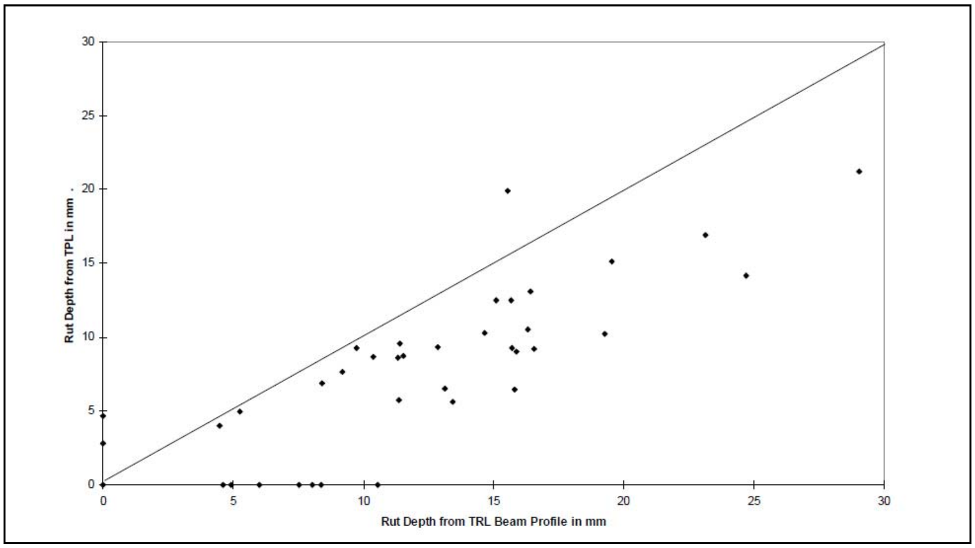
Where,

R_o and R_i are rut depths for the outer and inner wheel paths, respectively.

D1, D2, D3, D4, and D5 are distances/heights measured as shown in Figure A-6.

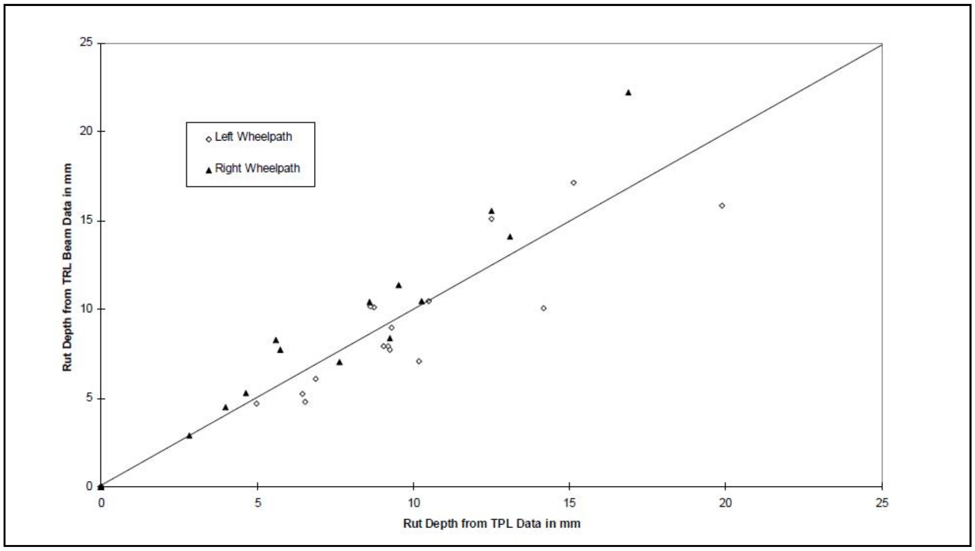
The research conducted by Bennett discusses the effects of the number of sensors on a profilometer and the resulting spacing and sampling rates on rut depth calculation. The profiles were measured by a Transport Research Laboratories (TRL) Beam with a sampling interval of 1-in. and a transverse profile logger (TPL) consisting of 30 ultrasonic transducers with a sampling interval of 3.94-in. (Bennett, 1996). Although the study showed that the transverse profiles compared very well (correlation of 0.99), the rut depths did not as depicted in Figure A-7 (Bennett, 1996). Since the profiles compared well, the discrepancies in the rut depths were thought to be caused by the difference in transverse sampling. Therefore, the author compared the rut depth from the TPL and the TRL Beam using 3.94-in. sampling. This significantly improved the comparison as depicted in Figure A-8 (Bennett, 1996). The TPL tends to underestimate the rut depth compared to the TRL Beam as a result of the larger sampling space and limitations capturing the true high and low points or the transverse profile (Bennett, 1996).

Figure A-7 Rut Depths from 1-in. TRL Beam and 3.94-in. TPL (1-in. = 25.4-mm)



Source: Bennett, 1996.

Figure A-8 Rut Depths from 3.94-in. TRL Beam and 3.94-in. TPL (1-in. = 25.4-mm)



Source: Bennett, 1996.

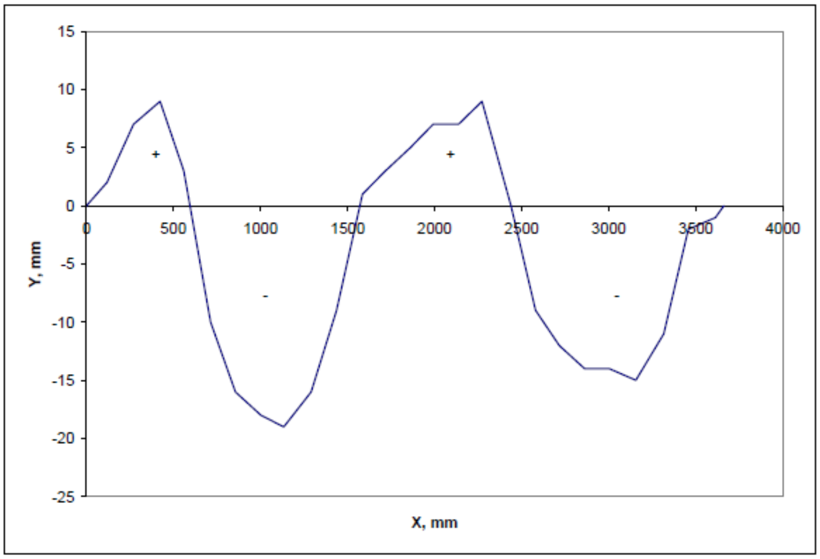
A study conducted by Simpson titled, "Characterization of Transverse Profiles," examined the transverse profile data contained in the LTPP program database and recommended five indices be included in the National Information Management System (NIMS) to quantify and qualify the transverse profile. The recommended indices include the area of the rut below a straight line connecting the end points of the transverse profile, the total area below the straight lines connecting the maximum surface elevations, the maximum depth for each wheelpath between a 6-ft. straightedge placed across the wheelpath and the surface of the pavement, and the width of the rut based on a 6-ft. straightedge (Simpson, 2001).

The trapezoid rule was suggested for determining the positive and negative areas and area of fill for the transverse profile for a pair of coordinates as depicted in Figure A-9 (Simpson, 2001) and is expressed as:

$$Area = \frac{1}{2}(y_{i+1} + y_i)(x_{i+1} - x_i)$$

Where,
y = height
x = lateral distance

Figure A-9 Illustration of Positive and Negative Area Indices (1-in. = 25.4-mm)



Source: Simpson, 2001.

Simpson also examined the rut depths based on the three-point and five-point systems and compared the results to the rut depth based on the lane-width wire model. Here is a summary of the study (Simpson, 2001):

- The transverse location of the rut bar dramatically affects the measurement and, hence, the rut depth computation. Thus, consistent lateral placement of the survey vehicle is essential to repeatable rut depth measurements using the three- or five-point rut bars.

- The paired t-tests illustrate that the three rut depth measurement systems (three-point, five-point, and wireline) do not provide the same values (i.e., there are statistically significant differences among them).
- The three-point rut depths underestimate the wireline rut depths for transverse profiles where the middle of the profile is lower than the outside edges of the lane.
- Although a better correlation (but still considered poor) existed between the five-point rut depths and the wire line rut depths than between the three-point rut depths and the wireline rut depths, they consistently underestimated the wireline rut depths.
- A better correlation was found between the rut depths for those transverse profile shapes with a "hump" in the middle.
- Generally, the larger the wireline rut depths, the bigger the difference that will be observed between the wireline rut depths and the three-point and five-point rut bars.

Based on this summary, Simpson concluded that the three-point and five-point rut depth measurements were not reliable or accurate compared to the wireline rut depths (Simpson, 2001).

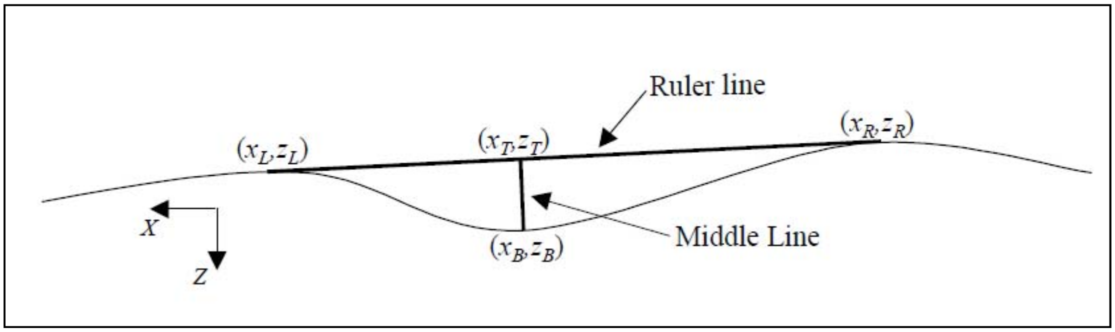
NCHRP Synthesis 401, "Quality Management of Pavement Condition Data Collection," reports similar findings that more accurate measurements result from using a greater number of sensors and that due to lack of full-lane-width coverage, older rut bars could under-report rut depth (Flintsch and McGhee, 2009). Oklahoma DOT experienced this when changing from an older style rut bar to a scanning laser, as the new rut depths were deeper, but closer to the manual measurements (Flintsch and McGhee, 2009).

The LRMS is utilized by the agencies in this research to collect rutting data. Derived from the straightedge model and in accordance with ASTM E1703, the rut depth is calculated from data collected by the LRMS as depicted in Figure A-10 and based on the following algorithm (Grondin et al., 2002):

$$Depth = \sqrt{(X_B - X_T)^2 - (Z_B - Z_T)^2}$$

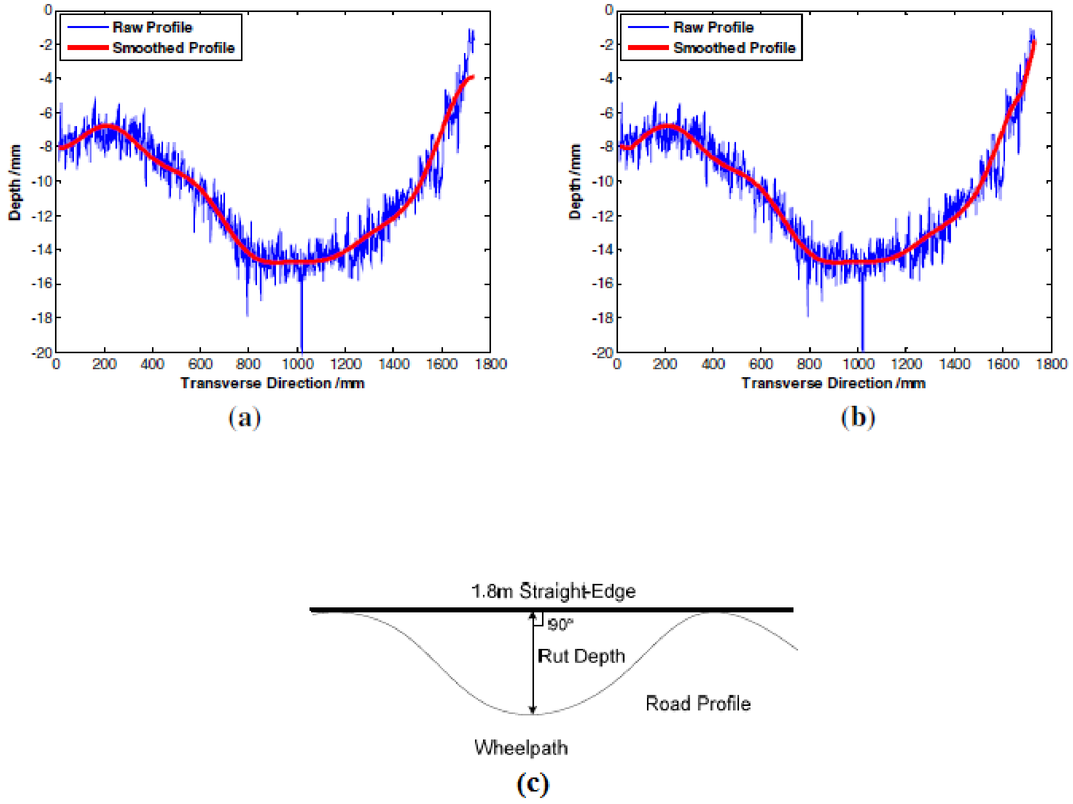
Tsai et al. assessed the measurement of rut depth using 3D continuous laser profiling technology. The research evaluated the rut depth measurement using the LCMS which uses two laser profiling units and collects 2,080 3D laser points on each transverse profile at a frequency of 5,600 Hz (Tsai et al., 2011). The profiles collected are smoothed using Discrete Cosine Transform (DCT) and DCT plus stepwise linear interpolation at the profile ends (Tsai et al., 2011) as shown in Figure A-11 (a) and (b). The 6-ft. straightedge (Figure A-11 (c)) method is used to calculate the rut depth by connecting the two high points from the smoothed profile. Comparison of laboratory testing to ground truth showed the difference of rut depth as measured by the LCMS to the ground truth varied from 0.0031-in. to 0.0.03-in. with a standard deviation of 0.0028-in. to 0.013-in. indicating high accuracy and good repeatability (Tsai et al., 2011).

Figure A-10 Rut Depth Calculation used by the LRMS



Source: Grondin et al., 2002.

Figure A-11 Smoothed Transverse Profiles: (a) DCT only; (b) DCT plus Stepwise Linear Interpolation and (C) 6-ft. Straightedge Method (1-in. = 25.4-mm)



Source: Tsai et al., 2011.

For the last 15 years, the Texas DOT (TxDOT) had used a five-point ultrasonic sensor rut measurement system, but was motivated to develop a new high-speed 3D laser camera system for rut measurements since the five-point system tends to underestimate the rut depth values and the sensors’ high sensitivity to environmental factors (wind, temperature, humidity, etc.). Serigos et al. (2012) conducted an independent assessment of the accuracy and precision of the TxDOT 3D laser rut measurement system and state-of-the-practice commercially available automated rut measurement systems. The assessment consisted of 24 550-ft. sections covering coarse and fine surface textures, narrow and wide lanes, a range of rut depths, plus particular cases or anomalies considered potentially challenging for automated equipment as well as a 10-mile section used for network-level data comparison (Serigos et al., 2012). Manual measurements were performed using a 6-ft. straightedge and rut wedge at 5-ft. intervals and Leica laser transverse profile measurements at 25-ft. intervals to establish the ground truth MRD and transverse profiles, respectively.

In addition to the TxDOT 3D laser system, four other vendors participated in the assessment, each operating an optical system able to measure a continuous transverse profile at highway speeds. The four vendors and the equipment used were:

- Pathway Services Inc. – unknown brand 3D camera laser system
- Dynatest – INO LRMS
- Fugro-Roadware Inc. – INO LRMS
- Applus RTD – LCMS

Each of the five participants reported the MRD values calculated by applying an algorithm to the measured transverse profiles. The algorithms used by each of the vendors were not provided to the researchers. The transverse profiles and MRD values provided by the vendors were compared to the ground truth values. The comparison of transverse profiles consisted of five statistical parameters: bias, precision, Mean Square Error (MSE), Average Sum of the Square Residuals (SSEn) and Correlation Coefficient. The comparison of MRD consisted of five statistical parameters: bias, precision, MSE, slope of the linear regression line, and correlation coefficient. Table A-1, Table A-2 and Table A-3 provide a summary of the comparisons containing the number of sections with the best transverse profile statistics and inside wheel path (IWP) and outside wheel path (OWP) MRD statistics, respectively, as well as the absolute range of each statistic. TxDOT provided MRD values calculated using two different algorithms, the algorithm currently used in the Pavement Management Information System (PMIS), denoted TxDOT PMIS, and an algorithm to account for the procedure used in field measurements, denoted TxDOT ASTM.

Table A-1 Summary of Transverse Profile Comparison

	TxDOT	Pathway	Dynatest	Roadware	Applus	Range
Bias[1]	9 (37.5%)	1 (4.2%)	9 (37.5%)	1 (4.2%)	4 (16.7%)	0.00-1.36
Precision[2]	2 (8.3%)	0 (0%)	7 (29.2%)	4 (16.7%)	11 (45.8%)	0.50-6.27
MSE[3]	2 (8.3%)	0 (0%)	7 (29.2%)	4 (16.7%)	11 (45.8%)	0.50-6.42
SSEn[4]	2 (8.3%)	0 (0%)	7 (29.2%)	4 (16.7%)	11 (45.8%)	0.49-6.26
Correlation[5]	2 (8.3%)	0 (0%)	11 (45.8%)	2 (8.3%)	9 (37.5%)	0.81-1.00

Source: Serigos et al., 2012.

Notes:

1. Number of sections (percentage) at which each participant presents the bias closest to 0.
2. Number of sections (percentage) at which each participant presents the minimum precision.
3. Number of sections (percentage) at which each participant presents the minimum MSE.
4. Number of sections (percentage) at which each participant presents the minimum SSEn.
5. Number of sections (percentage) at which each participant presents the correlation coefficient closest to 1.

Table A-2 Summary of IWP MRD Comparison

	TxDOT PMIS	TxDOT ASTM	Pathway	Dynatest	Roadware	Applus	Range
Bias[1]	1 (4.2%)	13 (54.2%)	3 (12.5%)	0 (0%)	5 (20.8%)	2 (8.3%)	0.05-9.67
Precision[2]	0 (0%)	6 (25%)	2 (8.3%)	14 (58.3%)	0 (0%)	2 (8.3%)	0.36-9.22
MSE[3]	0 (0%)	10 (41.7%)	1 (4.2%)	9 (37.5%)	4 (16.7%)	0 (0%)	0.43-11.65
Slope[4]	0 (0%)	7 (29.2%)	1 (4.2%)	12 (50%)	2 (8.3%)	2 (8.3%)	0.00-1.40
Correlation[5]	0 (0%)	7 (29.2%)	1 (4.2%)	13 (54.2%)	1 (4.2%)	2 (8.3%)	0.02-0.99

Source: Serigos et al., 2012.

Notes:

1. Number of sections (percentage) at which each participant presents the bias closest to 0.
2. Number of sections (percentage) at which each participant presents the minimum precision.
3. Number of sections (percentage) at which each participant presents the minimum MSE.
4. Number of sections (percentage) at which each participant presents the slope value closest to 1.

5. Number of sections (percentage) at which each participant presents the correlation coefficient closest to 1.

Table A-3 Summary of OWP MRD Comparison

	TxDOT PMIS	TxDOT ASTM	Pathway	Dynatest	Roadware	Applus	Range
Bias[1]	0 (0%)	4 (16.7%)	1 (4.2%)	6 (25%)	12 (50%)	1 (4.2%)	0.00-13.01
Precision[2]	0 (0%)	7 (29.2%)	1 (4.2%)	6 (25%)	4 (16.7%)	6 (25%)	0.66-10.56
MSE[3]	1 (4.2%)	4 (16.7%)	1 (4.2%)	8 (33.3%)	8 (33.3%)	2 (8.3%)	0.75-16.76
Slope[4]	0 (0%)	10 (41.7%)	1 (4.2%)	7 (29.2%)	6 (25%)	0 (0%)	0.00-1.11
Correlation[5]	0 (0%)	9 (37.5%)	1 (4.2%)	6 (25%)	5 (20.8%)	3 (12.5%)	0.02-1.00

Source: Serigos et al., 2012.

Notes:

1. Number of sections (percentage) at which each participant presents the bias closest to 0.
2. Number of sections (percentage) at which each participant presents the minimum precision.
3. Number of sections (percentage) at which each participant presents the minimum MSE.
4. Number of sections (percentage) at which each participant presents the slope value closest to 1.
5. Number of sections (percentage) at which each participant presents the correlation coefficient closest to 1.

Based on the comparison as summarized above, the following final conclusions were reached (Serigos et al., 2012):

- Although some pieces of equipment did marginally better than others during the collection of surface profiles, all five systems are clearly capable of capturing surface profiles with the necessary accuracy. However, the researchers strongly recommend that all the equipment systems be enhanced to capture the true profile - the profile of the road relative to a horizontal datum.
- In terms of MRD measurement, no single piece of equipment performed better overall.

Many agencies use the software provided by the manufacturer of the equipment used to collect the transverse profiles, such as KDOT using the ICC software and ODOT using the Dynatest software. The software packages usually filter and smooth the collected transverse profiles in order for profile analysis and rut depth calculation. The LRMS utilizes a standard Win32DLL and C-language functions which can be integrated into the end users' software application (Grondin et al., 2002).

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