EXPLORING AASHTO PP69-10 RUT PARAMETERS WITH 3D 1MM PAVEMENT SURFACE MODEL

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ABSTRACT

Rut measurement is critical to modern pavement modeling and management. Over the years, pavement rut has been measured with manual or limited-point automated devices. However, such lagging technologies and outdated protocols have led to the “rut depth” only convention, which compromises the application of rut data. Recently, the new 3D 1mm pavement surface model produced with the PaveVision3D Ultra system is capable of providing pavement engineers full-lane-width high resolution transverse profiles for analysis. Multiple rut characteristics such as rut area and deformation can be consistently derived based on the new AASHTO protocol PP69-10. To provide insight into PP69-10 rut parameters, bulks of transverse profile data collected from Arkansas National Highway Systems (NHS) are analyzed in this study. The value range of the deformation parameter is modeled. The relationship of rut depth measured with traditional method and the new PP69-10 method is established. The correlations among different PP69-10 rut attributes are examined. Results presented in this study will be helpful to highway agencies in shifting the state of the practice of rut measurement.
INTRODUCTION

Rut is a seriously concerned pavement distress and poses various risks to highway agencies and public such as premature failure and safety hazards (1, 2). Pavement engineers have been collecting rut data to develop pavement models, examine deterioration mechanism, and prioritize maintenance and rehabilitation projects (3). In the past and current practices, manual or limited-point automated devices are predominately employed for data acquisition (4). However, the data availability is compromised and data utilization is limited due to the lagging technology and outdated protocols. Both sound pavement modeling and consistent pavement management demand changes in rut measurement (5).

Recently, a new generation of pavement surface data collection system: PaveVision3D Ultra is able to yield 3D 1mm virtual pavement surface at highway speed (6). Meanwhile, the AASHTO protocols PP69-10 and PP70-10 have been issued to regulate rut data collection and characterization (7, 8). In PP69-10, novel methods are proposed to derive multiple rut attributes (7). With these progresses, the current rut measurement needs to be readdressed. Although it is apparent that such positive changes will benefit the entire research field and industry, the challenges are to demonstrate the effectiveness of the new rut data sets and convince the pavement engineers as well as the management to shift the practice to using new technology. To resolve these concerns, this study primarily focuses on the following three aspects: (1) identify the reasonable value range of the some new rut parameters; (2) establish the connection between the rut depth measures derived from traditional method and PP69-10 method; and (3) develop the interrelationship among multiple PP69-10 rut attributes.

This paper is organized as follows: first, a literature review with regard to the current practice and emerging changes in rut measurement is exhibited. Second, the new PaveVision3D Ultra system for pavement transverse profiling and PP69-10 data derivation are introduced. Third, a geometric model is established for estimating the value range of the deformation parameter. Fourth, the rut depth measures derived with traditional straightedge based method and PP69-10 search based method are compared. Finally, the interrelationship among the different PP69-10 rut measures is developed. The feasibility of using rut depth to estimate other critical rut parameters is discussed.

LITERATURE REVIEW

Rut Data Collection

A variety of manual and automated rut survey methodologies have been developed to monitor rut condition. Table 1 lists most of the commonly used devices for rut data collection over the years (9, 10). Automated systems are the most concerned nowadays. The basic mechanism of the automated transverse profilers is to measure the relative height (elevation) of a finite number of points on pavements surface. Various types of sensors with different physical principles can serve this purpose, as summarized in Table 1. For point laser, ultrasonic, and acoustic systems, the number of sensors determines the
number of elevation points that can be collected, which is called data resolution. Regardless of vehicle wandering, the position of the collected elevation points along the transverse direction depends on the mounting location of the sensors. These systems can only collect relatively low resolution data: the maximum number of elevation points ever developed and used in the field is 37 with ultrasonic sensor. However, a 3.7m-wide-bar must be mounted in this case, which is too wide and unsafe on in-service roadways. By contrast, the optical scanning laser systems are capable of obtaining significantly more elevation points. In 2004, a laser system was claimed to have a resolution of 1,280 points per transverse profile \((10)\). Generally, the laser technology based systems achieve a better accuracy and repeatability.

Table 1. Common Devices for Rut Data Collection

<table>
<thead>
<tr>
<th>Type</th>
<th>Device</th>
<th>Brief Introduction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Systems</td>
<td>Straightedge and Gauge</td>
<td>Place the 1.8 m straightedge across the wheel-path, and then use the gauge to measure the maximum vertical or perpendicular distance between pavement surface and the straightedge.</td>
<td>ASTM standard and LTPP have different definitions for measuring rut depth.</td>
</tr>
<tr>
<td></td>
<td>Stringline and Gauge</td>
<td>Use the 3.7 m stringline to stretch across the pavement lane. The stringline only touches the peaks of pavement. Then measure each wheel-path like straightedge method.</td>
<td>Adopted by LTPP program.</td>
</tr>
<tr>
<td></td>
<td>Walking Profiler</td>
<td>A device looks and operates like a lawnmower. Measure elevation points of the transverse profile every 241 mm.</td>
<td>Developed by Australian Road Research Board.</td>
</tr>
<tr>
<td></td>
<td>Dipstick Profiler</td>
<td>Two feet of the Dipstick are spaced 305 mm. Measure the transverse profile by stand one foot and rotate the other.</td>
<td>Adopted by LTPP program.</td>
</tr>
<tr>
<td>Automated Systems</td>
<td>3-Point Rut Bar (South Dakota Profiler)</td>
<td>3 acoustic sensors mounted along the rut bar of the van to detect the distances from the bumper to pavement surface. One sensor in the middle of the bumper and the other two over each wheel-path.</td>
<td>Can only cover partial lane per restriction of width, which in consequence may underestimate rut.</td>
</tr>
<tr>
<td></td>
<td>5-Point Rut Bar</td>
<td>Similar to 3-Point rut bars, 5 acoustic sensors usually spaced 813 mm between two outside ones and 406 mm between the inside ones.</td>
<td>It has the same deficiency but more accurate than the 3-point rut bar. Number of sensor can further increase to improve accuracy.</td>
</tr>
<tr>
<td></td>
<td>Rut Bars with Many Sensors</td>
<td>Up to 37 ultrasonic sensors to collect transverse profile data.</td>
<td>The 37-sensor version system is able to cover full lane, but exceeds the width limit by some States’ law.</td>
</tr>
<tr>
<td></td>
<td>Scanning Laser Rut Bar</td>
<td>Laser mounted on the rut bar scans along the bar to collect a continuous transverse profile.</td>
<td>The laser-based rut bar is the predominant method in current automated rut data collection.</td>
</tr>
<tr>
<td></td>
<td>Optical Systems</td>
<td>A camera and a strobe mounted on the van. The camera takes picture of the shadow projected from a preset line. The line is the digitized to transverse profile.</td>
<td>Illumination has been updated to laser now. Ever adopted by LTPP program.</td>
</tr>
</tbody>
</table>

A questionnaire survey conducted in 2004 investigated the state of practice of rut measurement \((10)\). 46 out of 56 responding State or Province agencies in both US and Canada used automated rut bar systems to collect rut data, 32 of which adopted the 3-point or 5-point rut bars while the rest used similar systems with more sensors. A more
recent telephone interview was carried out by Texas DOT in 2007 (11). According to the responses from 24 State agencies, 13 used a 37 sensor ultrasonic rut bar; 5 used a scanning laser profiler with collected points from 960 to 1,280; and 5 used a point laser rut bar. One agency applied manual measurement.

Standard or protocol is critical to technical measurement. However, in the past, the specifications for rut data collection systems are inexplicit and inconsistent. Recently, the AASHTO Designation: PP70-10 Standard Practice for Collecting the Transverse Pavement Profile (PP70-10 for short) was released to provide a practicing standard for transverse profile data collection (8). The minimum technical requirements of transverse profiles for analysis such as transverse measurement width, longitudinal and transverse resolution etc. are specified in PP70-10. Any system meeting the requirements are supposed to yield identical transverse profiles for further analysis.

Rut Characterization

According to Antunes et al. (12), transverse profile is the intersection between the road surface and a reference plane perpendicular to the road surface and to the lane direction. A true transverse profile can only be obtained by taking a trench of the pavement surface layer, which is too costly and unrealistic in practice. As an alternative, pavement engineers measure multiple surface elevation points to estimate the transverse profile. It is evident that the more points a system can collect the higher resolution the data possess. For those systems which cannot collect a sufficient number of points, interpolation is a necessary step to simulate a continuous transverse profile.

Various standards, protocols, or publications are relied on to convert the transverse profiles to rut parameters (13, 14). For the purpose of comparison, some of the commonly seen rut parameters and their traditional measurement methods are summarized in Table 2 (9). Due to the vague definition and weak applicability, although several parameters have been defined in various standards, only rut depth has been extensively applied in agencies’ practices (11, 12, and 13).
### Table 2. Commonly Seen Technical Parameters for Rut Evaluation

<table>
<thead>
<tr>
<th>Technical Parameters</th>
<th>Definition and Data Processing Methodology</th>
<th>Degree of Wide Use/Application of Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rut Depth (Two Methods)</td>
<td><strong>Straightedge method:</strong> the concept is similar to that of the manual surveys in Table 1. Only the 1.8 m straightedge is a fictive one. <strong>Stringline method:</strong> the concept is similar to that of the manual surveys in Table 1. Only the 3.7 m stringline is a fictive one.</td>
<td>The most widely used parameter, required by almost every standard.</td>
</tr>
<tr>
<td>Rut Width (Two Methods)</td>
<td><strong>Straightedge method:</strong> the rut width is the horizontal distance or straight-line length between two points on which the straightedge rests where the rut depth was obtained. <strong>Stringline method:</strong> the rut width is the horizontal distance or straight-line length between two peaks where the stringline touches the pavement surface around the location of the maximum rut depth is occurred.</td>
<td>Used along with rut depth but is not always collected.</td>
</tr>
<tr>
<td>Rut Cross-Sectional Area (Three Methods)</td>
<td><strong>Positive area:</strong> the area between a straight-line which connects two end points of the transverse profile and the pavement surface above the line. <strong>Negative area:</strong> the area between a straight-line which connects two end points of the transverse profile and the pavement surface below the line. <strong>Fill area:</strong> uses a stringline to stretch across the profile and measure the area between the stringline and pavement surface.</td>
<td>Not very common in most of the protocols, but is proposed by LTPP.</td>
</tr>
</tbody>
</table>

Recently, a breakthrough in rut characterization is the release of AASHTO Designation: *PP69-10 Standard Practice for Determining Pavement Deformation Parameters and Cross Slope from Collected Transverse Profiles* (PP69-10 for short) (7). In brief, PP69-10 has the following important features (7):

- Multiple technical parameters including rut depth, cross-sectional area, etc. are explicitly defined in the protocol and can be extracted from a transverse profile.
- In PP 69-10, the derivation of rut attributes is a computer-based and fully automated process. The entire process solely is feasible through computer programs. No human interventions are required. Variation in data report is minimized and repeatability is assured.
- The transverse profile data used for PP69-10 analysis must meet the technical requirement specified in PP70-10. The homogeneity of raw data is assured.

Detailed procedures such as determination of wheel-path location, search algorithm, longitudinal reporting sample interval, and data consistency are explicitly outlined in PP69-10, which rarely have been specified in previous protocols (7). In companion with PP70-10, PP69-10 has the potential to become a real practicing standard for the evaluation of pavement rut.
Data Collection System

In the recent years, the advance of laser imaging and sensor technology changed the landscape of transverse profiling (6, 15). The PaveVision3D Ultra (3D Ultra for short) system engineered by WayLink System Co. is capable of automatically acquiring both 2D and 3D laser imaging data from actual pavement surface at 60 miles per hour and reconstructs the 3D virtual pavement surface at 1mm resolution. This system breaks the constraints of historical line-of-sight technique and yields fundamentally novel data sets. Figure 1a is the 3D Ultra hardware system and Figure 1b shows the software exhibiting collected images and relevant analysis.

3D Ultra system simultaneously collects both 2D and 3D images at 1mm resolution. For both images, the fixed transverse width is 4,096mm (161 in.). This coverage is sufficient for roadways as a traveled lane is usually no more than 3.6m (12 ft). On the longitudinal direction, one image covers a length of 2,048mm (80 in.) pavement section, which accordingly contains 2,048 successive transverse profiles at 1mm resolution. For 3D images, the resolution reaches 0.3mm in the vertical direction.

The calculation algorithms of the PP69-10 attributes are coded using C++ programming language and integrated into the embedded software Automated Distress Analyzer 3D (ADA3D). Laboratory and field tests manifest that the 3D Ultra exceeds all technical requirements specified in PP70-10 and produces data for computing all attributes in PP69-10.

a. Hardware System on a Digital Highway Data Vehicle (DHDV)
b. Software System with Analysis on Display

Figure 1. Illustration of PaveVision3D Ultra System

Calculation of PP69-10 Rut Attributes

Seven parameters are calculated in this study according to PP69-10: Total Percent Deformation (TDF), Left Percent Deformation (LDF), Right Percent Deformation (RDF), Left Rut Depth (LRD), Right Rut Depth (RRD), Left Rut Cross-Sectional Area (LRA), and Right Rut Cross-Sectional Area (RRA). The detailed processes are outlined as follows:

Deformation Parameters

Deformation parameter is a completely new definition proposed in PP69-10. The calculation of the percent deformation defined in PP69-10 (Eq.1) consists of four steps (7): first, the length of the pavement transverse profile between the two edge points is computed. The profile length is approximated by summing the section length between each two adjacent points. Second, the straight-line distance of the pavement is measured. Third, the straight-line length is subtracted from the profile length. After dividing the result by the straight-line length and multiplying by 100, the percent deformation is obtained. As per this procedure and illustrated in Figure 2a, three parameters TDF, LDF, and RDF are defined (Eq.1-3) and their values are 0.358, 0.411, and 0.252, respectively.
a. Illustration of Derivation of Deformation Parameters

\[
\text{Total Percent Deformation (TDF)} = \frac{(\text{Profile Length of } AB - \text{Straightline Length of } AB)}{\text{Straightline Length of } AB} \times 100
\]  

\[
\text{Left Percent Deformation (LDF)} = \frac{(\text{Profile Length of } AC - \text{Straightline Length of } AC)}{\text{Straightline Length of } AC} \times 100
\]  

\[
\text{Right Percent Deformation (RDF)} = \frac{(\text{Profile Length of } BC - \text{Straightline Length of } BC)}{\text{Straightline Length of } BC} \times 100
\]  

b. Illustration of Derivation of Rut Depth and Cross-Sectional Area

Figure 2. Calculation of PP69-10 Rut Attributes

Rut Depth and Cross-Sectional Area

Being different from the traditional rut depth quantification methodology, a fundamentally novel approach is proposed in PP69-10 to extract rut related parameters.
As shown in Figure 2b, the calculation of rut depth and rut cross-sectional area are given in Eq.4-7.

\[
\text{Left Rut Depth (LRD)} = |\text{Spot } 2| .................................................... (4)
\]

\[
\text{Right Rut Depth (RRD)} = |\text{Spot } 4| .................................................... (5)
\]

\[
\text{Left Rut Area (LRA)} = \text{Area between Straightline } AB \text{ and Profile } AB  \text{........... (6)}
\]

\[
\text{Right Rut Area (RRA)} = \text{Area between Straightline } CD \text{ and Profile } CD \text{......... (7)}
\]

According to PP69-10, the five spots are used to determine the rut depth by applying the following procedures: first, the original profile (Figure 2a) is counterclockwise rotated a cross slope to reach a leveled profile (Top/Blue profile in Figure 2b) (It might not be significantly visible as the cross slope is only -0.74 in this example). In this leveled profile, the Spot 3 is set to 0. Then, the profile is rotated about Spot 3 until Spot 1 reaches 0. The rotated profile (Left middle and right bottom/Black profile in Figure 2b) is used to characterize left rut information. At this time, the absolute value of Spot 2 is LRD. Based on the profile where Spot 1 is 0, the profile is further rotated about Spot 1 until Spot 5 reaches 0. This new profile (Right middle and left bottom/Green profile in Figure 2b) is used for right rut characterization. At this time, the absolute value of Spot 4 is the RRD. In this example profile, the LRD and RRD are 11.92 mm and 30.94 mm, respectively.

The black and green profile is also used for left and right rut cross-sectional area calculation, respectively. Scanning from the location of Spot 2 and Spot 4, when three values equal to or greater than 0 are encountered, the first reached point of the three points is identified as a rut edge. This scanning is applied to both sides of the Spot 2 and Spot 4. For each occurrence of rut depth, there are two rut edges (A and B for left rut and C and D for right rut in Figure 2b). The area between the straight-line connecting two rut edges and the profile is defined as the rut cross-sectional area. Note that the rut edge may be located on the other side of the pavement centerline. In calculation, the area is approximated using integral calculus methods (Eq.8). In this example, the LRA and RRA are 11,317.44 mm^2 and 30,245.65 mm^2, respectively.

\[
A = \int_a^b f(x)dx = \Sigma_{i=a}^{b-1} (f(x_{i+1}) + f(x_i))/2 ................................................................. (8)
\]

Where  
- \(A\) is the one-sided rut cross-sectional area;  
- \(a\) and \(b\) are the left and right rut edge of one-sided rut respectively;  
- \(f(x)\) is the elevation at the point \(x\).

Network Data Acquisition

The data used in this study are collected under Arkansas State Highway and Transportation Department (AHTD) Project TRC1103 (6). Two asphalt surfaced National Highway Systems (NHS) sections: US Highway 65 North Bound (US65N) and US Highway 70 East Bound (US70E) in Arkansas are used for analysis. Data collections were conducted on March 7th and March 5th of 2013 for the two roadway sections, respectively. The weather condition of both days was sunny and the pavement surfaces were dry. The section length of US65N is about 110 km (70 miles). The beginning point is near Lake Village (GPS: 33.331598, -91.291864) and the end point is about 10 miles to Pine Bluff (GPS: 34.160522, -91.828583). The section length of US70E is about 95 km.
(60 miles). The beginning point is south of Brinkley (GPS: 35.146316, -90.156416) and
the end point is about 2 miles to the border of West Memphis (GPS: 35.147073, -
90.25943). The US65N is a divided highway and the US70E is undivided. Data are
collected on the outmost lanes.

Since PP70-10 suggests a rigorous longitudinal interval of 500mm, the 1st, 501st, 1001st,
and 1501st transverse profiles of each image are selected for analysis (8). To cover a
longer pavement section without redundant data, every three consecutive images are
randomly sampled in every 100 images. In other words, twelve successive profiles with a
longitudinal interval of about 500mm are selected from about every 200m section. In
total 9,504 transverse profiles are used for analysis, 5,160 for US65N and 4,344 for
US70E, respectively.

ANALYSIS OF DEFORMATION PARAMETERS

As suggested in PP69-10, deformation parameters shall be a preliminary examination of
pavement rut condition. However, some unusually large values are observed in the
deformation attributes in this study. As is a common physical sense, pavement rut cannot
grow infinitely and attribute values should be within reasonable range. As a matter of fact,
pavement engineers are only acquainted with the value range of some intuitive
parameters such as rut depth. It is difficult to judge the range of the deformation
parameter out of air. To identify the range of deformation parameters, a simplified
approach is used to model the percent deformation. As shown in Figure 3, rut depth, rut
width, and lane width are modeled as independent variables and the percent deformation
the dependent variable.

In this model, the profile length is the sum of length of FC, arc length of CAD, and length
DG. The straight-line length of FG represents a half lane width. Length of AB is the rut
depth and straight-line length of CD is the rut width. A is the deepest location of the rut
and is located at the center of arc CD. E is assumed the center of the circle to which arc
CD belongs and therefore CE, AE, and DE are assumed the radius of the circle and straight-line EBA is perpendicular to straight-line CBD. The depression is assumed symmetric on both wheel-paths so that the TDF, LDF, and RDF have the same value. Given the rut width and depth, the arc length of CAD is obtained. Based on this model, the deformation can be expressed with a function of rut width, rut depth, and lane width, as shown in Eq. 9.

\[ DP = \left( \frac{\pi aw}{90 (\tan \alpha)} + \frac{\pi ad}{45} - 2w \right)^{100} \frac{1}{l} \]  

Where \( \alpha = 180 \ - \ 2 \tan^{-1} \frac{w}{2d} \); \( DP \) is the percent deformation (TDF, LDF, or RDF); \( w \) is the rut width on a wheel-path; \( d \) is the rut depth on a wheel-path; \( l \) is the full lane width (\( l \geq 2w \)).

Different combinations of one sided rut depth and rut width, and full lane width values are substituted into Eq. 9 to test the range of the percent deformation. To be conservative, all of the tested scenarios assume significant amount of rut depth. The test results are shown in Table 3.

<table>
<thead>
<tr>
<th>Lane width (l, mm)</th>
<th>Rut depth (d, mm)</th>
<th>Rut width (w, mm)</th>
<th>Percent deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3600</td>
<td>100</td>
<td>1500</td>
<td>0.986</td>
</tr>
<tr>
<td>3600</td>
<td>80</td>
<td>1500</td>
<td>0.647</td>
</tr>
<tr>
<td>3600</td>
<td>80</td>
<td>1300</td>
<td>0.728</td>
</tr>
<tr>
<td>3500</td>
<td>100</td>
<td>1500</td>
<td>1.014</td>
</tr>
<tr>
<td>3500</td>
<td>80</td>
<td>1500</td>
<td>0.665</td>
</tr>
<tr>
<td>3500</td>
<td>80</td>
<td>1300</td>
<td>0.749</td>
</tr>
<tr>
<td>3400</td>
<td>100</td>
<td>1500</td>
<td>1.044</td>
</tr>
<tr>
<td>3400</td>
<td>80</td>
<td>1300</td>
<td>0.684</td>
</tr>
<tr>
<td>3400</td>
<td>80</td>
<td>1300</td>
<td>0.771</td>
</tr>
</tbody>
</table>

The maximum percent deformation is 1.044 when the rut depth is 100 mm with the associated 1,500 mm rut width on a 3,400 m wide lane, which is an extreme case in actual pavement. More testing is performed in other scenarios with heavy rut and different combinations of rut width and pavement width, the percent deformation ranges from 0.647 to 1.014. Therefore, any percent deformation with a value greater than 1 is assumed an abnormal value. Thus, if an abnormal value is seen in the attributes, the profile is subject to further investigation.

Based on the observation from substantial amount of data processing, three possibilities are prone to produce abnormal attributes:
• Wrong measurement of lane position. Unlike the other algorithms for rut characterization, the PP69-10 based method is highly dependent on the correct identification of the transverse profile of the lane. In this study, it is found when the lane positioning is semi-automated conducted, the range of the attribute values generally appears reasonable and realistic. Unusual values are always associated with the fully automated data analysis, where the lane extraction is less precise due to various reasons such as vague or missing pavement markings. Errors in lane positioning can result in outliers. This phenomena is apparent in the narrow pavements where no shoulder exists.

• Incomplete removal of outlier values on the raw transverse profiles. Foreign objects on the collected surface or excessive vehicle bumping could lead to the existence of abnormally high or low points shown in the raw profile. However, the straight-line length is usually unaffected under such circumstances. A significant increase of the numerator would result in high deformation value. To reduce errors brought up by the outliers, the complete removal of outliers in the raw profile is a necessity.

• Dramatic deformation of the pavement surface. A third a possibility of abnormal deformation value is that the profile per se is significantly damaged and surface excessively distorted so that a high percent deformation is produced. In this case, human intervention shall be critical to determine the cause of deterioration.

In a network survey, generally, isolated abnormal values in deformation measures are mostly triggered by the first and second causes. If consecutive abnormal values are observed, attention must be given to the possible third cause. With the determination of abnormal values, pavement engineers are able to use the deformation parameters to make preliminary engineering judgment.

COMPARISON OF RUT DEPTH MEASURES FROM DIFFERENT METHODS

Since the AASHO Road Test, rut depth has been measured as the only widely used and the most important indicator for pavement permanent deformation (16, 18). The straightedge and stringline methods, especially the straightedge method, are the traditionally dominating approaches to deriving rut depth from collected transverse profiles. In PP69-10, the rut depth is the only indicator that is comparable with the traditional rut depth measure. However, the rut depth calculation in PP69-10 is very different from the traditional method. For field application of the new PP69-10 measures, the following questions may be asked: what is the relationship between the traditionally calculated rut depth and the PP69-10 rut depth? Are the values derived from the two methods close to or distinct from each other? Is it feasible to convert the traditional rut depth to the new PP69-10 rut depth or vice versa? Indeed, the conversion among different measures is highly demanded as the consistency in the pavement management database is critical to data application.

Commonly used traditional methodologies for rut depth calculation include the 1.2m (4ft) straightedge, 1.8m (6ft) straightedge, and the 3.7m (12ft) stringline. Simpson compared the differences of the three measures based on a large sample of LTPP data (16). It was
found that 1.2m straightedge is inaccurate and is discarded in later analysis. Rut depth measures from 1.8m straightedge and 3.7m stringline are highly correlated with correlation coefficients 0.964 and 0.956 for left and right wheel-path, respectively. In this research the rut depth derived from 1.8m straightedge method is compared with those derived according to PP69-10. A fictive straightedge is used to semi-automated measure the rut depth on the transverse profiles collected by 3D Ultra. Due to the work load of semi-automated process, one fourth of the selected transverse profiles are analyzed per definition of Simpson’s straightedge method (16). In total 2,240 transverse profiles are used for this purpose. Correlation analysis is used to examine the interrelationship among the four measures: straightedge depth (SLRD), right straightedge depth (SRRD), left PP69-10 rut depth (LRD), and right PP69-10 rut depth (RRD). Correlation coefficients of two pairs are very high: LRD and SLRD, and RRD and SRRD. The reminders are moderately high, ranging from 0.67 to 0.69. In addition, paired t-tests are employed to check if the mean values of the data sets are statistically different. The $p$-values of the two tailed paired t-test are all 0.00.

First, it can be seen that for both straightedge and PP69-10 measures, the correlation of left and right rut depth measures are moderate. The $p$-values indicate that the left and right rut depth measures are statistically different. These findings are in concert with Simpson’s (16) and Ali and Tayabji’s (13) conclusions. It is observed that the right rut depth is much greater than left rut depth. The mean difference is 13mm and 12mm for straightedge and PP69-10 method, respectively.

With respect to the comparison of straightedge measures and PP69-10 measures, both left and right rut depth measures show strong correlation. The correlation coefficients are 0.97 and 0.98 for left and right rut depth measures, respectively. In other words, the rut depth measures from PP69-10 can be converted to straightedge rut depth measures and vice versa.

The plots of the measures for left and right rut depth are given in Figure 4. Linear regression models are developed (Eq.10-11). Their $R^2$ values are 0.94 and 0.96, respectively. The results indicate it is robust to use the straightedge rut depth measures to estimate PP69-10 rut depth measures. This is significant to practitioners since most of the current pavement management databases only contain the straightedge-based rut depths.

\[
L_{RD} = 1.01S_{LRD} - 1.2, \quad R^2 = 0.94 \\
R_{RD} = 1.05S_{RRD} - 1.42, \quad R^2 = 0.96
\]
INTERRELATIONSHIP AMONG PP69-10 RUT ATTRIBUTES

Statistics of PP69-10 Attributes

Before conducting descriptive and quantitative analysis, the abnormal profiles are removed. Based on the outlier defined above, a profile with any percent deformation greater than 1 is removed from the data set. In total 131 profiles (1.5%) are removed from

Figure 4. Plot of Rut Depth Measures with Straightedge and PP69-10 Method
the 8,960 profiles and 8,829 profiles remain for further investigation. As shown in Table 4, statistics data show that all the attributes are slightly right skewed. The ranges of three deformation parameters are close to each other. TDF has higher mean and median values than those of the left and right deformation. The rut depth measures are generally congruent with above and Simpson’s research (16), where right rut depth is significantly higher than the left rut depth in terms of mean and median values. However, it is found that their standard deviations are close to each other, 10.32 mm and 11.56 mm for left rut depth and right rut depth, respectively. The rut cross-sectional area measures show the same trend in terms of mean and median values. However, their standard deviations have a larger difference. It is interesting to notice that both the average and median values of RDF are smaller than LDF. This difference implies that the shape of right rut is more regular than that of the left wheel-path. In other words, the left wheel-path may contain more irregular deformation such as lateral movement than the right wheel-path.

Furthermore, correlation analysis is used to examine the interrelationships among the parameters. As shown in Table 5, four pairs of correlation coefficients are high (greater than 0.7) in the correlation matrix.

Table 4. Statistical Analysis of PP69-10 Rut Attributes

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>Median</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDF</td>
<td>0.33</td>
<td>0.981</td>
<td>0.098</td>
<td>0.303</td>
<td>0.124</td>
</tr>
<tr>
<td>LDF</td>
<td>0.311</td>
<td>0.998</td>
<td>0.077</td>
<td>0.282</td>
<td>0.131</td>
</tr>
<tr>
<td>RDF</td>
<td>0.285</td>
<td>0.998</td>
<td>0.066</td>
<td>0.248</td>
<td>0.145</td>
</tr>
<tr>
<td>LRD (mm)</td>
<td>12.79</td>
<td>52.52</td>
<td>0.00</td>
<td>11.80</td>
<td>10.32</td>
</tr>
<tr>
<td>RRD (mm)</td>
<td>21.99</td>
<td>71.37</td>
<td>0.00</td>
<td>19.64</td>
<td>11.56</td>
</tr>
<tr>
<td>LRA (sq mm)</td>
<td>10058.62</td>
<td>45210.79</td>
<td>0.00</td>
<td>9365.69</td>
<td>8076.05</td>
</tr>
<tr>
<td>RRA (sq mm)</td>
<td>18695.05</td>
<td>67967.50</td>
<td>0.00</td>
<td>16508.70</td>
<td>11019.85</td>
</tr>
</tbody>
</table>

Table 5. Correlation Analysis of PP69-10 Rut Attributes

<table>
<thead>
<tr>
<th></th>
<th>TDF</th>
<th>LDF</th>
<th>RDF</th>
<th>LRD</th>
<th>RRD</th>
<th>LRA</th>
<th>RRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDF</td>
<td>1.00</td>
<td>0.89</td>
<td>0.91</td>
<td>0.57</td>
<td>0.61</td>
<td>0.52</td>
<td>0.53</td>
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<tr>
<td>LDF</td>
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<td>0.65</td>
<td>0.58</td>
<td>0.48</td>
<td>0.52</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>RDF</td>
<td>1.00</td>
<td>0.48</td>
<td>0.66</td>
<td>0.44</td>
<td>0.44</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>LRD</td>
<td>1.00</td>
<td>0.42</td>
<td>0.94</td>
<td>0.38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RRD</td>
<td>1.00</td>
<td>0.37</td>
<td>0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LRA</td>
<td>1.00</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RRA</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Estimating New PP69-10 Measures with Rut Depth

Literature review indicates rut depth is the only measure for most of the State agencies, which means it is the only retrievable technical parameter for analysis and comparison in current Pavement Management Systems (PMS). For the purpose of applying PP69-10, it is necessary and meaningful to establish quantitative relationships between the rut depth...
and the other newly proposed attributes in PP69-10 such that the parameters like rut
cross-sectional area and percent deformation can be estimated by rut depth measures.

Based on the physical significance of the attributes, linear regression is employed to use
rut depth measures to predict the new attributes. The regression analysis is conducted
based on the attributes of the 8,829 transverse profiles. The relationships among rut depth,
rut cross-sectional area, and deformation are developed.

Rut depth and percent deformation (Eq.12-14):

\[
LDF = 0.0074 \times LRD + 0.2172, \ R^2 = 0.34
\] ....................................................... (12)

\[
RDF = 0.0084 \times LRD + 0.1008, \ R^2 = 0.44
\] ....................................................... (13)

\[
TDF = 0.0045 \times LRD + 0.0049 \times RRD + 0.1602, \ R^2 = 0.49
\] ....................................................... (14)

Rut depth and rut cross-sectional area (Eq.15-16):

\[
LRA = 738.53 \times LRD + 615.88, \ R^2 = 0.89
\] ....................................................... (15)

\[
RRA = 901.81 \times RRD - 1131.2, \ R^2 = 0.90
\] ....................................................... (16)

It can be seen that the rut cross-sectional area measures can be satisfactorily
approximated by the rut depth measures. The R^2 values are close to 0.9 for both wheel-
paths. Therefore, it is promising for agencies to estimate the rut cross-sectional area with
collected rut depth. This would be helpful to the estimate in maintenance and
rehabilitation. The R^2 values for TDF and RDF are moderate, which demonstrate that it is
feasible but need to be cautious when use rut depth measures to predict those values. For
the LDF with low R^2 values, it is not recommended to conduct the predictions.

CONCLUSIONS AND RECOMMENDATIONS

In this study, seven rut parameters are derived according to the new AASHTO rut
protocol PP69-10. Based on the bulks of data produced with PaveVision3D Ultras system,
three research objectives are implemented. First, the reasonable value range for
deformation parameter is identified. This range is effective for pavement engineers to
identify abnormal transverse profiles. Second, the rut depth measures derived from
traditional straight-edge method and PP69-10 method are compared. It is uncovered that
strong relationship exists between two approaches. It is robust to use the straight-edge rut
depths to estimate the PP69-10 rut depth. This finding is encouraging to those agencies
especially those who are incapable of adopting the high resolution devices. It will be
beneficial to promote PP69-10 based practice. Third, the statistics of PP69-10 parameters
are presented. The interrelationship among different parameters are examined. The rut
cross-sectional area can be estimated in a robust manner, which is also salient to highway
agencies. The abovementioned insights are significant to practitioners in terms of
changing to new 3D technologies.

REFERENCES

University of Texas at Austin in partial fulfillment of the requirements for the degree of Doctor of Philosophy. 2001.


