Demonstration of Network Level Pavement Structural Evaluation with Traffic Speed Deflectometer in Nevada

Prepared for **the Federal Highway Administration**
Under Contract # DTFH61-11-D-00009-T-13008

By

Virginia Tech Transportation Institute

Subcontractor to

Engineering & Software Consultants, Inc.

June 2017

TABLE OF CONTENTS

<table>
<tr><td rowspan="2">Report No.:</td><td rowspan="2">Report Date:
June 2017</td><td rowspan="2">No. Pages:
25</td><td>Type Report:
Final Contract</td><td>Project No.:</td></tr>
<tr><td>Period Covered:
October 2013 – February 2017</td><td>Contract No.:
DTFH61-11-D-00009-T-13008</td></tr>
<tr><td colspan="4">Title:
Demonstration of Network Level Pavement Structural Evaluation with Traffic Speed Deflectometer in Nevada</td><td rowspan="3">Key Words:
Traffic Speed Deflectometer, Deflection Testing, Non-Destructive Evaluation, Network-Level Decision Making, Structural Capacity Index</td></tr>
<tr><td colspan="4">Author(s): Samer Katicha*, Ph.D., Gerardo Flintsch*, Ph.D., P.E., Shivesh Shrestha*, and Senthilmurugan Thyagarajan**, Ph.D.</td></tr>
<tr><td colspan="4">Performing Organization Name and Address:
Prime Contractor: Engineering & Software Consultants, Inc. (ESCINC)
14123 Robert Paris Court
Chantilly, VA 20151

Subcontractor: Virginia Tech Transportation Institute (VTTI)
3500 Transportation Research Plaza
Blacksburg, VA 24061</td></tr>
<tr><td colspan="5">Sponsoring Agencies' Name and Address:
Sponsoring Agencies' Name and Address:
Office of Infrastructure Research and Development
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101-2296
and the State Department of Transportation of the States of California, Georgia,
Idaho, Illinois, Nevada, New York, Pennsylvania, South Carolina and Virginia</td></tr>
<tr><td colspan="5">Supplementary Notes:
The Contracting Officer's Representative was Nadarajah Sivaneswaran, HRDI-20.
* affiliated with VTTI; ** affiliated with ESCINC</td></tr>
<tr><td colspan="5">Abstract:
The objective of this transportation pooled fund study was to carry out field demonstration of the Traffic Speed Deflectometer (TSD) and present an approach of how the results of TSD testing could be implemented within a pavement management system (PMS). This report summarizes the results from this field demonstration effort in Nevada. Specifically this report 1) describes the TSD and its measurement approach, 2) presents the structural condition of the tested roads as part of the demonstration, 3) evaluates the repeatability of the TSD on a 15 mile repeated section, 4) shows how the information obtained from the TSD can be used from a simple relative ranking of the pavement structural condition to more elaborate approaches that calculate different indices (e.g. SCI300, tensile strain at the bottom of the asphalt layer), and 5) shows how the TSD measurements can be incorporated into a PMS decision process.
The TSD was found to be capable of differentiating between relatively structurally strong and weak sections and provide more detailed assessment when used in conjunction with SHA's PMS data. A companion report documents the overall study effort and summarizes findings from nine participating states. The companion report also provides details on interpreting files associated with the TSD data, data processing method used in the study and the Profilograph program to view the TSD data.</td></tr>
</table>

FIELD DEMONSTRATION OF THE TSD IN NEVADA

Samer Katicha[1], Gerardo Flintsch[1], Shivesh Shrestha[1], and Senthilmurugan Thyagarajan[2]

INTRODUCTION

This report describes the results of the Traffic Speed Deflectometer (TSD) demonstration performed in Nevada (June 9 and 10, 2014 and August 22, 2015) and illustrates how the results of the TSD testing can be implemented into a Pavement Management System (PMS). The focus in this report is on practical implementation of the TSD for production testing on flexible pavement sections with unbound bases (for an investigation that is more focused on accuracy and repeatability, Rada et al. 2016 and Flintsch et al. 2013 are recommended along with the references therein). As the research effort described in this report is part of a pooled fund study with nine state highway agencies participating, a separate report that highlights the results from the overall research effort will be prepared and distributed to the nine participating states and posted to the pooled fund website. The focus of this report is on the results of tests performed in Nevada and on answering the following important questions:

1. **What is the TSD and what does it measure?** The TSD data collection method and recorded measurements are different from those of the more familiar Falling Weight Deflectometer (FWD). The TSD is a continuously moving device that measures the instantaneous pavement vertical velocity under a moving load, whereas the FWD is a stationary device that measures the time history of the pavement's vertical velocity or acceleration at each sensor. The TSD reports instantaneous deflection slopes, while the FWD reports maximum deflections. This report presents the measuring principle of the TSD along with how deflection basin indices, including asphalt strain, can be estimated from the TSD measurements. The method of Rada et al. (2016) to temperature correct the estimated tensile strain at the bottom of the asphalt layer form TSD measurements is also presented.

2. **What is the structural condition of the tested roads?** This report presents the pavement structural condition of the tested roads in terms of the SCI300 surface curvature index (SCI) corrected to a reference temperature of 70°F (21.1°C) using the procedure developed by Rada et al. (2016). This includes SCI300 box plots of the roads tested, typical line plots of SCI300 versus distance, and Google Earth color-coded plots (good, fair, and poor). The colors used are green, yellow, and red to represent good, fair, and poor structural conditions. The thresholds used to classify the condition are based on the estimated remaining fatigue life of the asphalt layer (Katicha et al. 2017). Using typical default average daily truck traffic (ADTT) levels for interstate, primary, and secondary

[1] Virginia Tech Transportation Institute
[2] Engineering & Software Consultants, Inc.

roads, and typical thicknesses (unless thickness is available), sections with an estimated remaining fatigue life less than 2 years are considered to have a poor structural condition, those with an estimated remaining fatigue life of between 2 and 5 years are considered fair, and those with an estimated remaining fatigue life more than 5 years are considered good. These thresholds are provided as initial default estimates, and it is recommended that each state highway agency adjust the thresholds to best represent their pavements and to meet their pavement management needs.

3. **How repeatable are TSD measurements?** Repeatability was estimated by comparing multiple measurements performed on the same sections in 2014 and 2015. This was evaluated for temperature-corrected SCI300.

4. **How can we use the information obtained from TSD measurements?** Information from TSD measurements can help to better manage pavement sections. The best way to use TSD data mostly depends on each agency's approach to managing its pavement sections. In the short term, TSD data can be used to verify and/or adjust the decisions that are largely based on surface condition. TSD measurements can readily be used to obtain a relative ranking between different pavement sections or, with the use of appropriate thresholds, to identify structurally good, fair, and poor segments. When pavement thickness data are available, a more mechanistic approach can be used to estimate tensile strains at the bottom of the asphalt layer and a fatigue equation can be used to estimate remaining fatigue life. All these approaches are illustrated in detail in this report. Since the thickness for the tested roads are not available, default values for interstate, primary and secondary roads were used (see Table 2).

5. **How can we incorporate TSD measurements into a PMS?** The proposed approach to incorporate TSD into the PMS (for flexible pavements) consists of classifying the pavement structural condition into Good, Fair, and Poor categories based on temperature-corrected structural indices derived from TSD measurements. Both SCI300 and the Deflection Slope Index (DSI) were investigated. The results showed that similar conclusions are drawn whether SCI300 or DSI is used; therefore, only the results of SCI300 are presented in this report (results with DSI are provided in the Excel files). Preliminary thresholds that separate between the Good, Fair, and Poor structural condition categories are given in this report based on an estimate of the expected remaining fatigue life of the asphalt layer. This expected remaining fatigue life is related to the tensile strain at the bottom of the asphalt layer, which in turn is related to the SCI300 (or DSI) using the approach developed in Rada et al. (2016). It is recommended that each agency calibrate these thresholds based on their own experience and needs. A decision process based on the currently used process by the Virginia Department of Transportation (VDOT), which already includes structural condition in the PMS decision process for Interstate roads, is provided to illustrate how structural condition can be used in the PMS.

Why Measure the Structural Condition of the Pavement?

Pavement structural capacity has a big effect on the rate of pavement deterioration. In turn, the rate of deterioration of pavement sections is used to estimate the time and type of maintenance activities in a PMS. Due to (until recently) the relative difficulty of measuring the pavement structural condition at the network level, traditional PMS approaches have relied on observation of the pavement surface condition to assess rehabilitation needs. However, the pavement surface condition does not provide a full picture of the causes of deterioration; it is only the symptom. This has been confirmed by a number of studies that showed that the correlation between surface condition and structural measurements of pavement response is weak (Flora, 2009; Bryce et al., 2013) and that the rate of deterioration of pavement sections is affected by the structural condition (Katicha et al., 2016). Therefore, the pavement structural condition is an important aspect of overall pavement health and one of the driving causes of pavement deterioration.

The fact that the structural condition is an important factor alone may not be convincing enough for a highway agency to invest the resources to implement the TSD for network-level pavement structural assessments. Any such endeavor would first have to be justified from an economic perspective that demonstrates that the benefits of incorporating reliable pavement structural condition information in pavement management decision making far outweigh the data collection costs. The pooled fund study whose results are documented in this report grew from the belief that there is enough evidence in the literature that the TSD is a device that could provide valuable pavement structural information at relatively lower cost than deploying the FWD at the network level (Flintsch et al. 2013; Rada et al., 2016). In that respect, the Federal Highway Administration (FHWA) initiated the pooled fund project "*Demonstration of Network Level Pavement Structural Evaluation with Traffic Speed Deflectometer*" to assess the feasibility and demonstrate the use of the TSD for network-level pavement structural evaluation for use in the participating agencies' pavement management application and decision making. This report summarizes the testing performed in the state of Nevada in terms of the research questions presented in the introduction.

RESEARCH QUESTION 1: WHAT IS THE TSD AND WHAT DOES IT MEASURE?

The TSD, shown in Figure 1, is an articulated truck with a rear-axle load that can be varied from 58.7 to 127.6 kN by using sealed lead loads. The TSD has a number of Doppler lasers mounted on a servo-hydraulic beam to measure the deflection velocity of a loaded pavement. The TSD evaluated in this study used seven Doppler lasers. Six Doppler lasers were positioned such that they measure deflection velocity at 100, 200, 300, 600, 900, and 1,500 mm (3.9, 7.9, 11.8, 23.6, and 59 inches) in front of the loading axle. The seventh sensor was positioned 3,500 mm (11.5 ft) in front of the rear axle, largely outside the deflection bowl, to act as a reference laser. The beam on which the lasers are mounted moves up and down in opposition to the movement of the trailer in order to keep the lasers at a constant height from the pavement's surface. To prevent thermal distortion of the steel measurement beam, a climate control system maintains the trailer temperature at a constant 20°C (68°F). Data are recorded at a survey speed of up to 96 km/h (60 mph) at a rate of 1000 Hz.

Figure 1. Picture of TSD used during testing and computer-generated schematic.

Measurement Technology

The TSD uses Doppler lasers mounted at a small angle to the vertical to measure the vertical pavement deflection velocity together with components of the horizontal vehicle velocity and the vertical and horizontal vehicle suspension velocity. Due to its location, midway between the loaded trailer axle and the rear axle of the tractor unit, the pavement under the reference laser is expected to be outside the zone of load influence (undeformed), and the reference laser response can therefore be used to remove the unwanted signals from the six measurement lasers. When accurately calibrated, the TSD measures pavement deflection velocities that depend on driving speed. To remove this dependence, the deflection velocity is divided by the instantaneous vehicle speed to give a measurement of deflection slope, as illustrated in the Figure 2. Therefore, the deflection slope is calculated as follows:

$$S = \frac{V_v}{V_h} \qquad (1)$$

where S is the deflection slope, V_v is the vertical pavement deflection velocity, and V_h is the vehicle horizontal velocity. Typically, the deflection velocity is measured in mm/s and the vehicle speed is measured in m/s; therefore, the deflection slope measurements are output in units of mm/m and generally reported at a 10-m (33-ft) interval. At a speed of 80 km/h (50 mph) and a data collection frequency of 1000 Hz, this corresponds to an average of 446 individual measurements over the 10 m section.

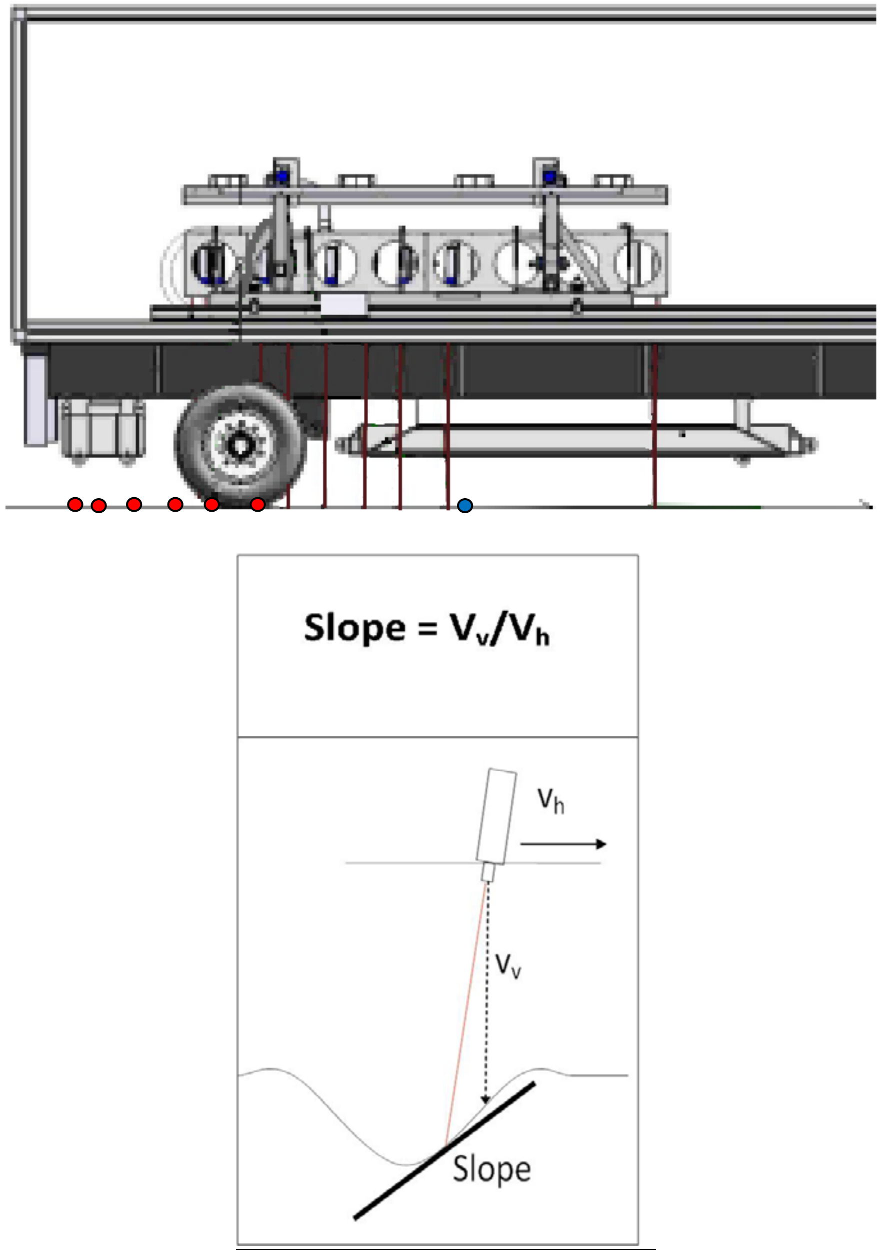


Figure 2. Schematic of the measurement principle of the TSD.

Relationship between Deflection Slope, Deflection, and Other Pavement Structural Condition Indices

As described, the TSD measures the deflection slope of the deflection basin rather than pavement deflection. Figure 3 shows how the deflections and deflection slopes relate to the deflection basin. The deflection at a position on the deflection basin is the vertical distance from that point to the reference undeformed pavement. The deflection slope is the tangent to the deflection basin (i.e., the derivative of the deflection basin). Since the deflection slope is the derivative of the deflection, the deflection can be obtained from the deflection slope by integration as follows:

$$d(x) = \int_x^\infty s(y)dy \quad (2)$$

where,

$s(y)$ = slope at distance y measured from the applied load;

$d(x)$ = deflection at distance x measured from the applied load.

Greenwood engineering uses a parametrized model for the shape of the deflection slope developed by Pedersen et al. (2013) to obtain deflections from the deflection slope by optimizing the model parameters to fit the deflection slope data. The deflections computed from this model are reported in the data file (with extension .tsd.tsddefl.xls) and are used in this report.

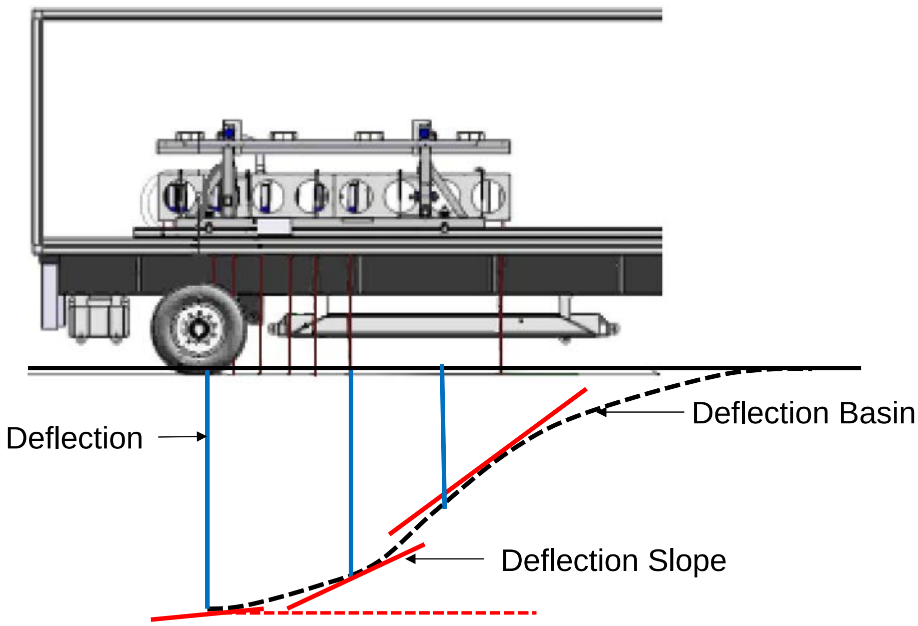


Figure 3. Relationship between the deflection basin, deflection, and deflection slope.

While deflections can directly be used to infer the structural condition and capacity of the tested pavement, a number of studies have shown that deflection-basin-related indices correlate better to the pavement responses that cause load-related distresses (Horak, 1987; Thyagarajan et al., 2011).

What Are Deflection-Basin-Related Indices?

Deflection-basin related indices are indices that are computed from two or more measured deflections. One of the widely used indices with the FWD is SCI300, which is the difference between the deflection under the applied load (i.e., D0) and the deflection 300 mm (12 in.) from the applied load (i.e., D300), shown in Equation 3.

$$SCI300 = D0 - D300 \quad (3)$$

The SCI300 can also be calculated from TSD measurements using the calculated deflections. However, it is very important to point out that while the TSD and FWD both attempt to measure the same metric—pavement structural condition—they are different in how they apply the load and record the pavement response. Although the SCI300 (or any other parameter) obtained from each device would qualitatively agree and have similar trends, quantitatively the two devices will, in general, give different results. Therefore, while this document compares and contrasts FWD- and TSD-based indices, the reader is advised to focus on trends and not the magnitudes (furthermore, the time difference between the two sets of FWD and TSD measurements is more than 7 years). An important consequence of the two devices not giving the same quantitative values is that thresholds based on FWD-derived indices are not directly applicable to TSD-derived indices. The fact that the TSD does not give the same quantitative results as the FWD does not mean either device is not accurate. The accuracy of the TSD has been investigated by Rada et al. (2016), that validated TSD measurements with "ground truth" measurements performed on instrumented pavements.

In addition to SCI300, there are a large number of deflection-basin related indices that have been proposed by researchers; listing these indices is beyond the scope of this report. The interested reader is referred to Table 44 of Rada et al. (2016), where 75 indices, which were evaluated in that study, are listed. Although the number of indices is quite large, most are so highly correlated (some almost identical) that essentially only a small number of the indices are needed to meet the objectives of this effort. For this pooled fund study, the SCI300 and DSI, have been selected and reported. DSI, shown in Equation 4, was recommended by Rada et al. (2016), and is the difference between the deflection at 100 mm (4 in.) from the applied load and the deflection at 300 mm (12 in.) from the applied load.

$$DSI = D100 - D300 \tag{4}$$

The DSI and SCI300 were found to be correlated to the tensile strain at the bottom of the asphalt layer as follows:

$$\varepsilon = a\left(DSI\right)^{b} \qquad \varepsilon = a'\left(SCI\,300\right)^{b'} \tag{5}$$

where *a*, *b*, *a'*, and *b'* are parameters that depend on the thickness of the asphalt concrete layer and are provided in the summary final report of the pooled fund (Katicha et al. 2017).

Temperature Correction of TSD Measurements

Pavement temperature is an important parameter that affects the results of flexible pavement structural evaluations. The deflection indices computed from TSD measurements are a function of pavement temperature at the time of data collection. Consistent evaluation and tracking of the indices computed from TSD measurements over the pavement service life requires that the indices be adjusted to a standard reference temperature. Due to the TSD being a relatively new device, currently there are no proven methods to correct TSD measurements for temperature.

However, Rada et al. (2016) have proposed a method to correct the tensile strain at the bottom of the asphalt layer. The approach is based on the change of the asphalt concrete (dynamic) modulus, which affects the tensile strain at the bottom of the asphalt layer. The steps for this procedure are (from Rada et al. 2016):

1. Compute the asphalt layer dynamic modulus at the test temperature, E_f, based on the calculated strain (from DSI or SCI300 using Equation 5) using the following equation:

   $$E_f = c \times \varepsilon^d \qquad (6)$$

   where *c* and *d*, are model parameters that depend on the asphalt layer thickness. When the thickness is not known, default values are provided.
2. Compute a temperature correction factor, T_c, for the dynamic modulus as follows:

   $$T_c = 19.791\left(e^{-0.043T_r} - e^{-0.043T_f}\right) \qquad (7)$$

   where T_r is the reference temperature (typically 70°F) and T_f is the asphalt temperature during the test.
3. Compute the dynamic modulus, E_r, at the selected reference temperature as follows:

   $$E_r = \frac{E_f}{1 - T_c} \qquad (8)$$

4. Compute the strain, ε_r, at the selected reference temperature by rearranging Equation 6 as follows:

   $$\varepsilon_r = \left(\frac{E_f}{c}\right)^{\frac{1}{d}} \qquad (9)$$

5. Calculate the temperature corrected TSD index using the inverse of Equation 5.

The asphalt temperature T_f is taken as the mid-depth temperature and calculated from the measured surface temperature using the Bells equation (BELLS3):

Td = 0.95 + 0.892 * IR + {log(d) - 1.25}{-0.448 * IR + 0.621 * (1-day) + 1.83 * sin(hr18 - 15.5)} + 0.042 * IR * sin(hr18 - 13.5) (10)

Where:
Td = Pavement temperature at mid-depth d, °C
IR = Pavement surface temperature, °C
log = Base 10 logarithm
d = mid-depth of the AC layer, mm
1-day = Average air temperature the day before testing, °C
sin = Sine function on an 18-hr clock system, with 2π radians equal to one 18-hr cycle
hr18 = Time of day, in a 24-hr clock system, but calculated using an 18-hr asphalt concrete (AC) temperature rise-and-fall time cycle

Greenwood reports GPS location and time at each interval (10m) in the file ending with “.gpsimp.xls”. Note GPS time is presented in Coordinated Universal Time, UTC. Pavement surface temperature are also reported along with the deflection values in the file ending with “tsd.tsd.xls”. The previous day average air temperature was obtained at the closest weather station from National Center for Environmental Information weather site https://gis.ncdc.noaa.gov and used in Bells equation to calculate mid-depth temperature. The computed mid-depth temperature is used with the temperature correction algorithm. The following points should be noted when the results from temperature correction and repeatability analysis are evaluated

- Temperature correction model should be considered as an intermediate solution until an accurate procedure is developed
- All sections used in the analysis are assumed as flexible pavements
- AC layer thickness is assumed based on the road category.
- M&R activities, if any, applied between the years are not considered in the repeatability analysis.

RESEARCH QUESTION 2: WHAT IS THE STRUCTURAL CONDITION OF THE TESTED ROADS?

The tested roads included interstates, primary roads, and secondary roads shown in Figure 3. Table 1 lists the roads tested with corresponding Google Maps© links. Clicking those links will show the corresponding tested road in a Web browser, as illustrated in Figure 4. In total 352 miles (169 in 2014 and 183 in 2015) with most of the section tested performed in 2014 repeated in 2015.

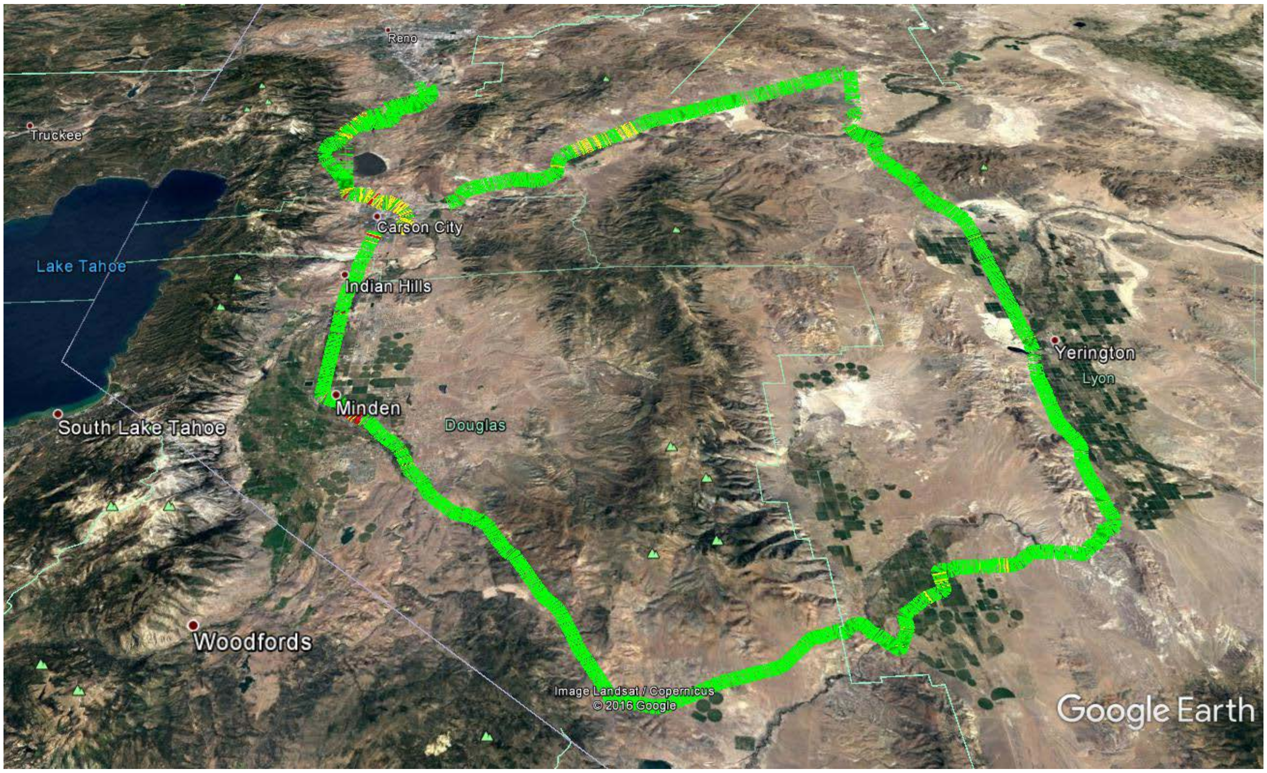


Figure 3. TSD-tested roads shown in Google Earth (© 2016 Google Image Landsat / Copernicus)

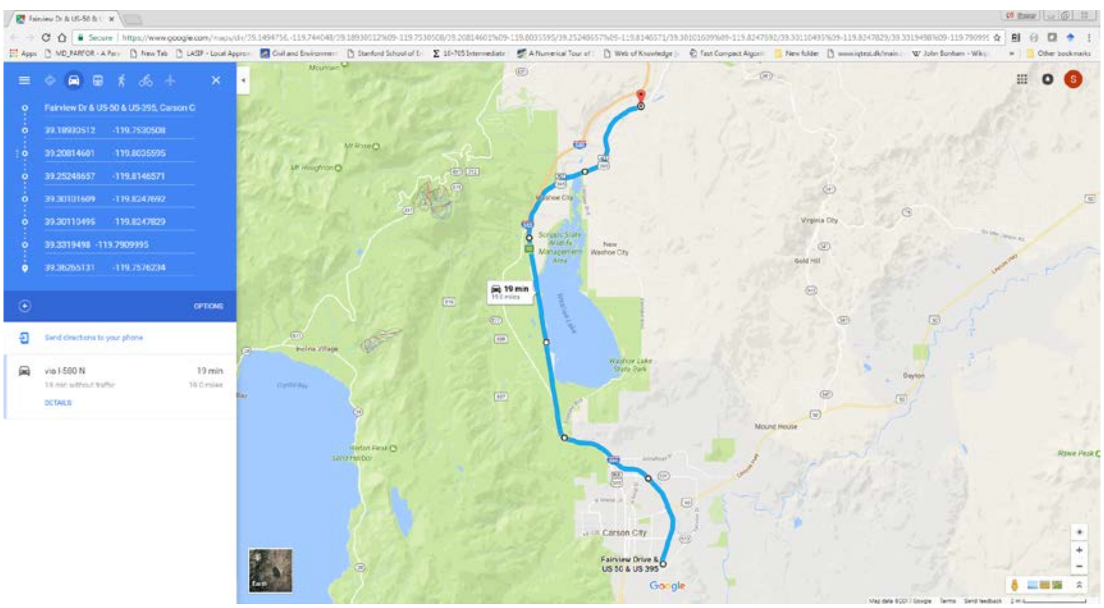


Figure 4. GoogleMaps link showing tested route on I-580 in 2015 (Map data © 2017 Google)

Table 1. TSD-Tested Roads with Test File Information and Google Maps Links

2014			
File	**File Name**	**Road Name**	**Link**
1.	T7201406090008	I580North – US395ALT North – SR431West – I580South – US395ALT South	https://goo.gl/maps/hGAAjhqxxXo
2.	T7201406090009	I580 South	https://goo.gl/maps/PvwNay5oUaA2
3.	T7201406100001	US50East	https://goo.gl/maps/TizDmaFMwJt
4.	T7201406100002	US95ALTSouth	https://goo.gl/maps/Xkcffb7aa5s
5.	T7201406100003	SR339South	https://goo.gl/maps/jFnkWJpox3y
6.	T7201406100004	SR208West	https://goo.gl/maps/euMijZLEyU62
7.	T7201406100005	US395North	https://goo.gl/maps/541i6d6wCx12
2015			
File	**File Name**	**Road Name**	**Link**
1.	T7201508220001	I580 North – US395ALT North	https://goo.gl/maps/YeFNvLtrxdw
2.	T7201508220002	SR431 West – I580 – US395ALT- I580 South	https://goo.gl/maps/f8SxbfavPFK2
3.	T7201508220003	Fairview Dr – I580 North - US50 East – US95ALT South	https://goo.gl/maps/exg6d8iiAht
4.	T7201508220004	SR208 – US395 North	https://goo.gl/maps/jwh4WKiLZq12

Overall Condition of Tested Roads

Data processing includes mapping data from different files provided by Greenwood in to one Excel file as explained in the pooled fund summary report (Katicha et al. 2017). A methodology based on the number of remaining ESAL's was used to arrive at a preliminary estimate for threshold between good/fair and fair/poor segments. It is expected that the estimated threshold will be revised based on the experience gained from implementation effort.

Initially, three road category – Interstate, primary and secondary roads were considered based on AC layer thickness as shown in Table 2. The database generated in Rada et al. (2016) was used. The database contains a range of pavement structures (layer thickness) and material characteristics (layer moduli) values generated using Monte Carlo simulation and corresponding pavement responses (strain and deflections) computed using the layered linear elastic program JULEA. The pavement segments in the JULEA database was grouped in one of three road category based on AC layer thickness as shown in the Table 2. In each pavement segment, number of repetitions to failure, N_f was computed using Asphalt Institute equation (Asphalt Institute. 1982))

$$N_f = C \times 0.00432 \left(\frac{1}{\varepsilon_t}\right)^{3.291} \left(\frac{1}{E}\right)^{0.854} \quad (11)$$

where C is the calibration coefficient, ε_t is the magnitude of the tensile strain repeatedly applied, and E is the stiffness of asphalt mixture (psi). The tensile strain at the bottom of AC layer corresponding to 9000 lb loaded dual tire configuration with 13.5 inch tire spacing and 116 psi tire pressure was used. The calibration factors that account for the effects of boundary difference between field and laboratory were 13.3 and 18.4 corresponding to the failure criteria of 10% and 45% of wheel-path cracking, respectively (Finn et al., 1977). C value of 13.3 was chosen for Interstate and Primary road category and 18.4 for secondary roads. In each road category the following level of annual traffic was considered

- Interstate: 2 million ESAL – equivalent of about 6500 ADTT (or 2000 singles, 4000 doubles and 500 trains or triples)
- Primary: 0.2 million ESAL – equivalent of about 950 ADTT (or 700 singles, 220 doubles and 30 trains or triples)
- Secondary: 0.07 million ESAL – equivalent of about 375 ADTT (or 300 singles, 75 doubles).

The pavement is considered as ‘poor’ or ‘fair’ condition when the computed N_f is lower than the traffic level the pavement can carry in the next 2 and 5 years, respectively in the corresponding road category. For example, an Interstate pavement segment will be considered ‘poor’ if the computed N_f is lower than 2.8 million ESAL’s (annual traffic * 2 years). Similarly, a secondary road is considered as ‘fair’ condition if the computed N_f is lower than 0.35 million ESAL’s (annual traffic * 5 years) but greater than 0.14 million ESAL’s (annual traffic * 2 years). Average indices values were computed within each group and reported as threshold values in the table.

Note that the current threshold cracking % being used to calculate N_f with AI equation would be incremental (delta) cracking not total cracking. Thus when we consider the existing damage, a pavement segment identified as poor could have a fatigue cracking higher than that defined in the table at the end of 2 years.

Once thresholds have been established, the temperature corrected indices (SCI or DSI) can be directly used to categories the pavement segment as good/fair/poor. For example in a Primary road section, if the SCI computed from TSD measurement is 5.0 mil then the pavement segment will be categorized as ‘Fair’.

Table 2. Thresholds for SCI300 (TSD) and DSI

Road Category	AC layer thickness, inch	Annual Traffic, million ESAL	Threshold for Fatigue Cracking at Wheelpath, %	Threshold for Poor			Threshold for Fair		
				N_f, million ESAL	SCI300, mil	DSI, mil	N_f, million ESAL	SCI300, mil	DSI, mil
Interstate	> 9	1.4	10	2.8	3.7	3.0	7.0	2.7	2.2
Primary	6 - 9	0.2	10	0.4	6.2	5.2	1.0	4.9	4.0
Secondary	3 - 6	0.07	45	0.14	9.7	7.7	0.35	7.3	5.8

Figure 5 shows the condition of the tested roads using this procedure with measurements corrected to a reference temperature of 70°F. For interstate, primary and secondary roads, the AC thickness was assumed to be in the range of 9 to 16, 6 to 9 and 3 to 6 inches, respectively. Figure 6 shows a closer look of I580 South going through Carson City. Again, the conditions depicted in the figure are based on preliminary condition thresholds developed to illustrate the concept and should be adjusted to match agency specific thresholds.

Figure 7, Figure 8, and Figure 9 show the overall structural condition, as indicated by the temperature-corrected SCI300, for the Interstate, Primary, and Secondary roads, respectively. The (red) line represents the median of the measurements, the (blue) box represents the 50-percent range (25 to 75 percent), and the (black) whiskers represent the 90-percent range (5 to 95 percent) of the collected data. Note that the vertical SCI300 scales in each figure are different, especially for the Secondary roads, which are generally significantly weaker than the Primary and Interstate roads.

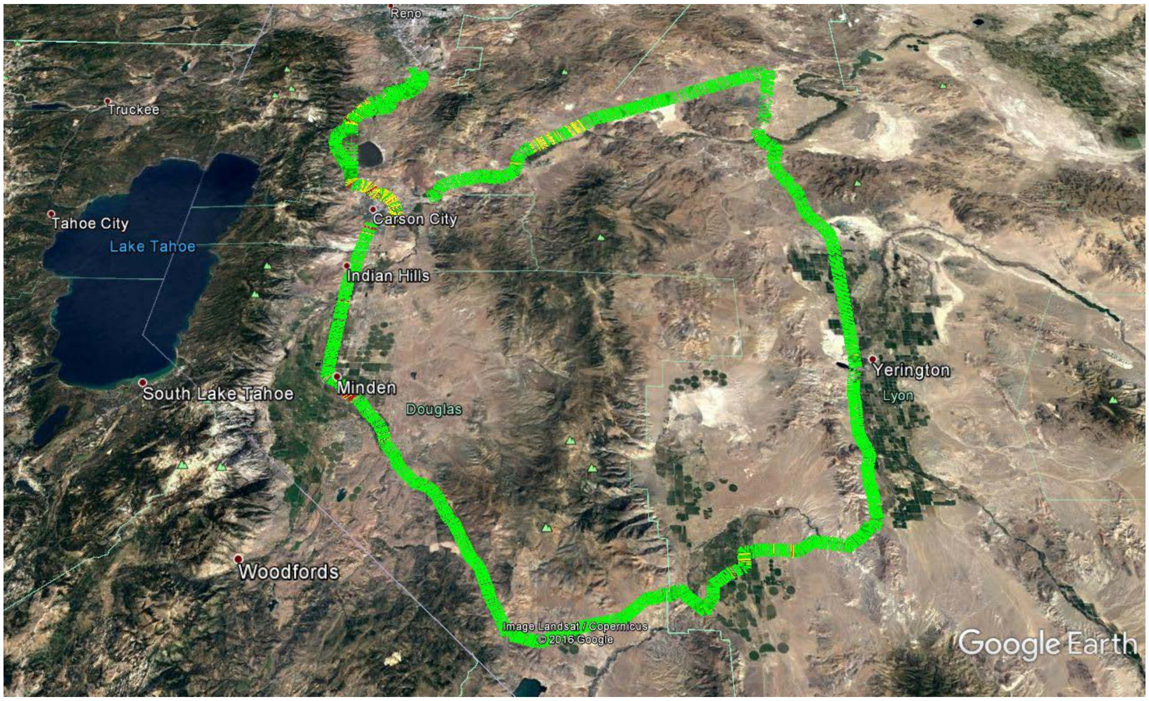


Figure 5. Color-coded condition of tested pavements in 2014 with Good (green), Fair (yellow), and Poor (red) ratings (© 2016 Google Image Landsat / Copernicus).

Figure 6. Detail example of pavement condition near Carson City in 2014 (© 2016 Google Image Landsat / Copernicus).

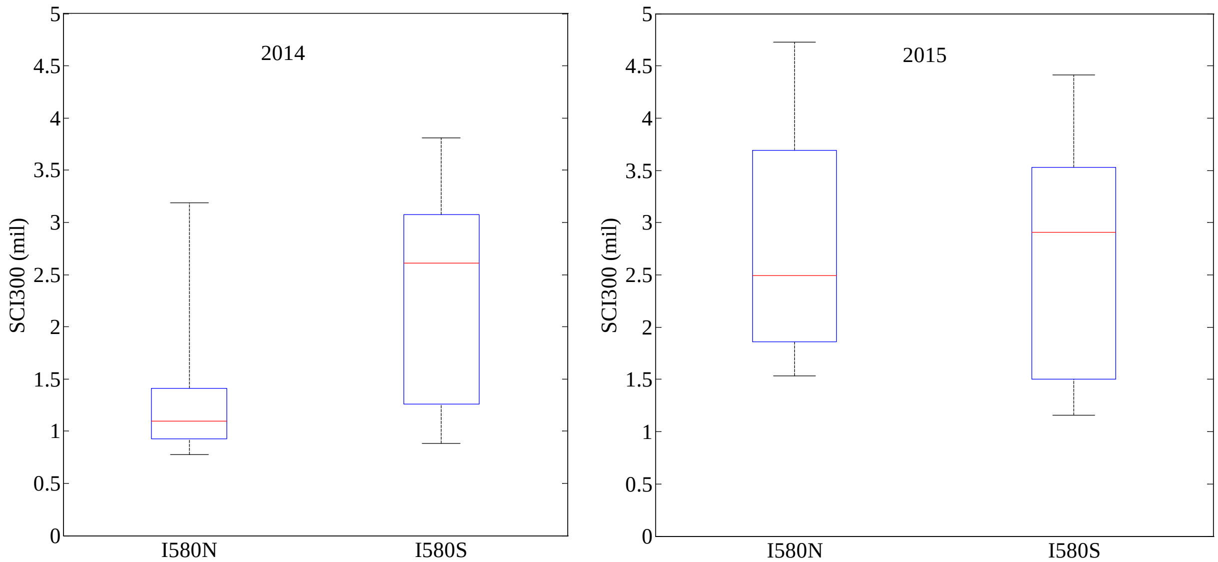


Figure 7. SCI300 box plot of Interstate routes.

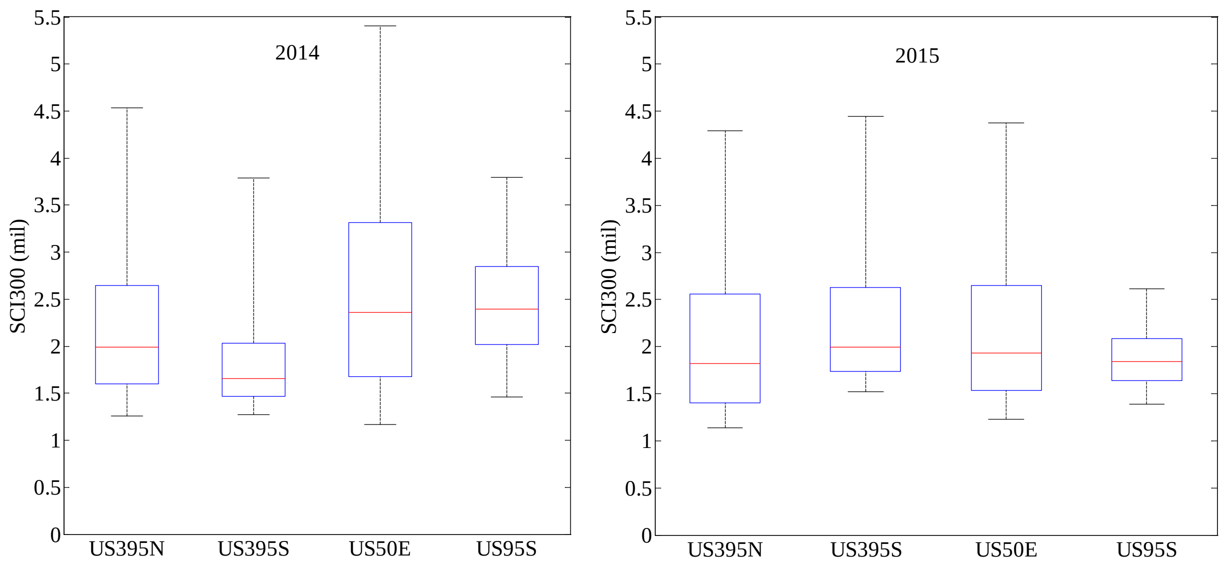


Figure 8. SCI300 box plot of Primary routes.

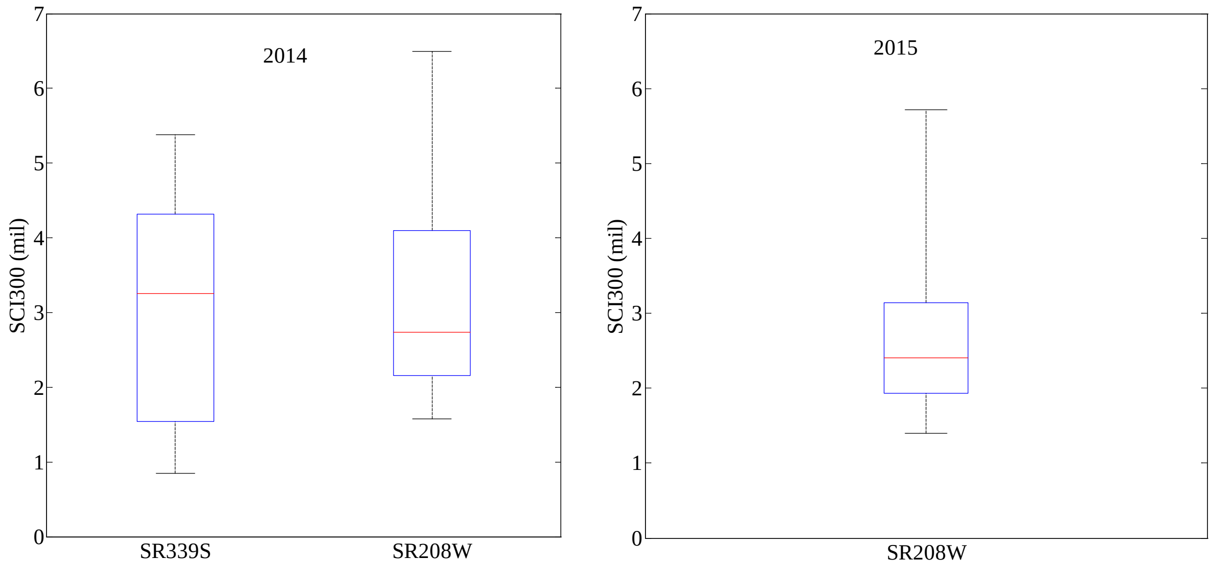


Figure 9. SCI300 box plot of Secondary routes.

RESEARCH QUESTION 3: HOW REPEATABLE ARE TSD MEASUREMENTS?

Figure 10 shows the repeated measurements of SCI300 corrected for temperature on a section of I580. The measurements in the two years follow similar trends showing good repeatability of the TSD. The two sets of measurements follow similar trends although not exactly the same values. The measurements taken in 2014 are slightly lower than the measurements taken in 2015. This could be due to the TSD temperature correction procedure which still needs to be refined.

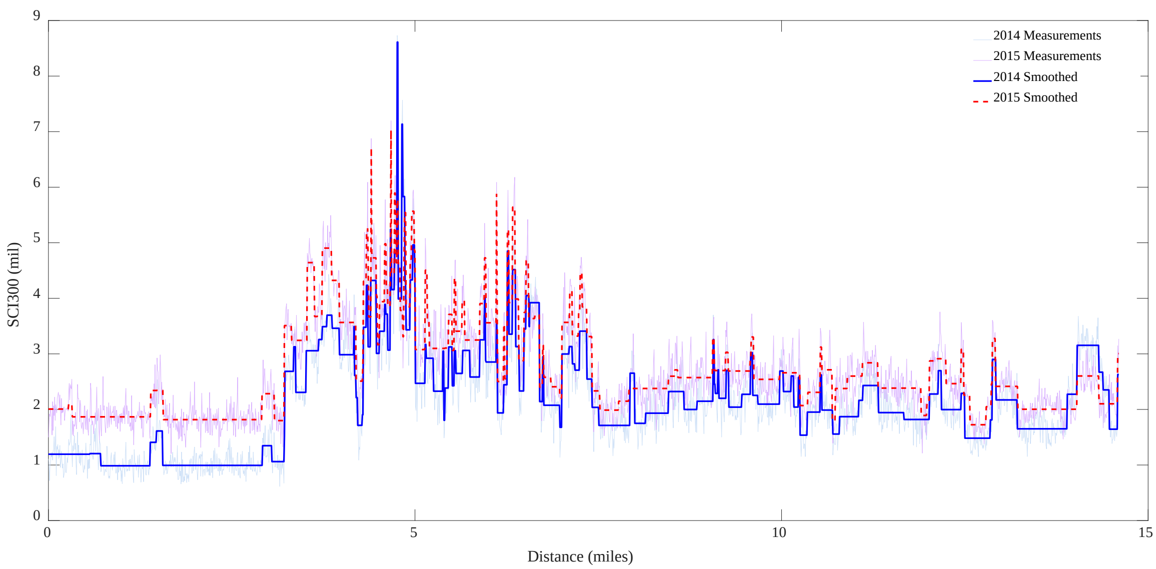


Figure 10. Temperature corrected repeated TSD tests on I580 (https://goo.gl/maps/ijJg4qGkYjG2).

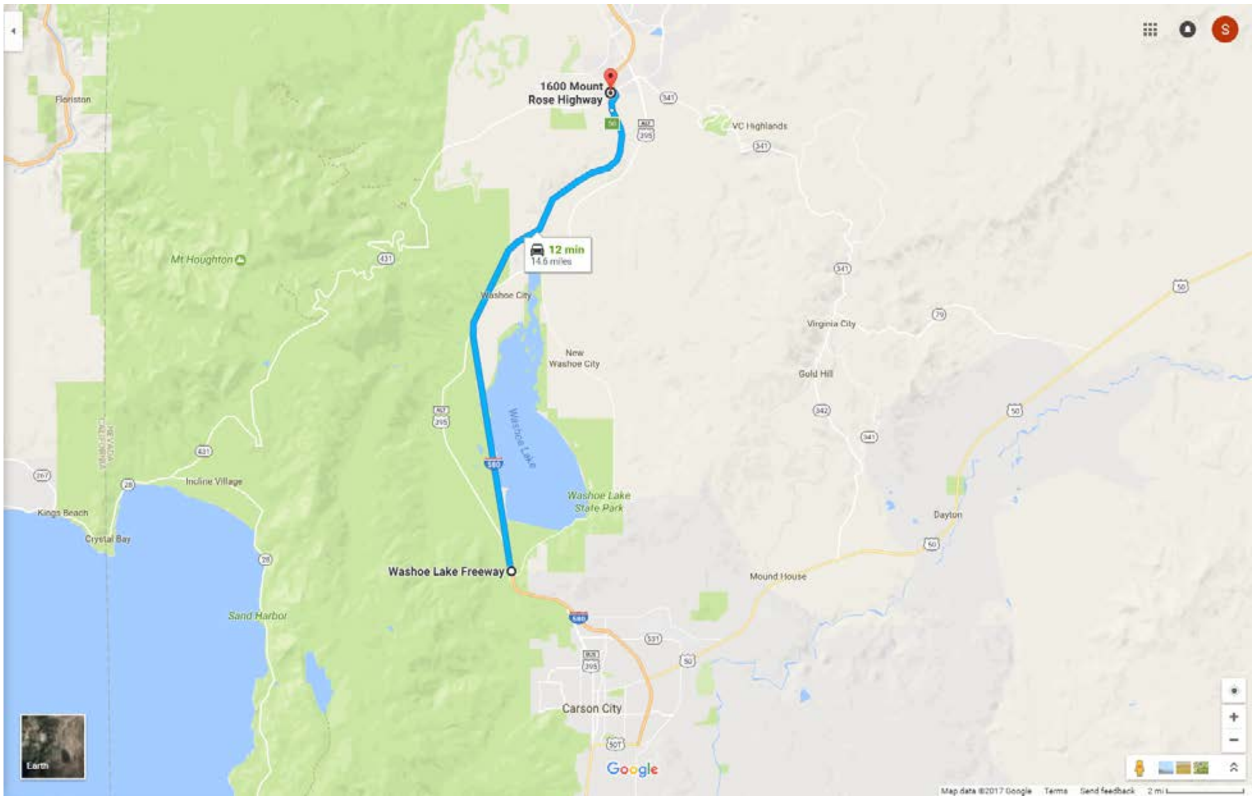


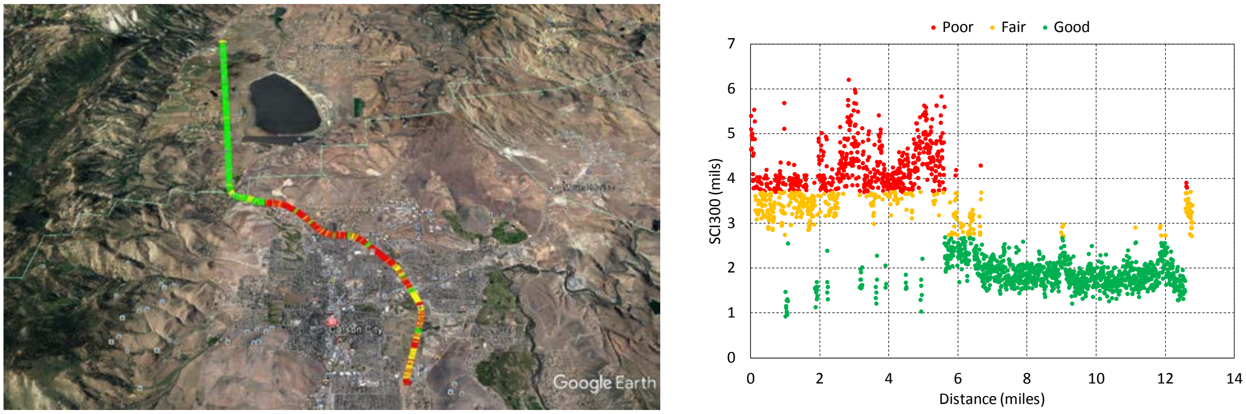
Figure 11 Repeated tested section on I580 with results shown in Figure 10.

RESEARCH QUESTION 4: HOW CAN WE USE THE INFORMATION OBTAINED FROM TSD MEASUREMENTS?

In this section we present examples on how TSD measurements can be used to help better manage pavement sections.

Identification of Strong and Weak Sections

TSD measurements can be used to classify pavement sections into structurally strong, fair, and weak categories (good, fair, and poor). Figure 12 shows an example of such a classification with measurements collected on I580 North near Carson City in 2015 and thresholds based on expected remaining fatigue life obtained from Table 2 (similar figures are provided in Excel files for all tested roads). Another method to determine thresholds could be based on percentiles. Figure 13 shows a classification based on percentiles where the 25th percentile is used to separate Good and Fair sections, and the 90th percentile is used to separate Fair and Poor sections. The classification could be used to determine, at the network level planning state, the required type of treatments, if any. For example, identified weak sections could be assigned as candidate sections for heavier structural treatments; sections identified as fair could be assigned as candidates for lighter treatments, such as corrective or preventive maintenance or minor rehab based on surface distress measurements.



(a) (b)

Figure 12. Identified Strong (green) and Weak (red) sections on I580 North based on thresholds obtained from Table 2 from 2015 testing: (a) Google Earth plot (© 2016 Google Image Landsat / Copernicus); (b) figure plot

Figure 13 Classification of structural condition on I580 North south based on percentile: 25th percentile and lower represents good structural condition and 90th percentile and higher represents poor structural condition

Another validation of the capabilities of the TSD to classify sections is shown in Figure 14. Strong spots identified by the TSD near Carson City are highlighted with the red circle. Upon further investigation, these spots were found to correspond to bridges, which in general are known to exhibit lower deflections than flexible pavement sections. The same was observed for most bridges on all tested roads.

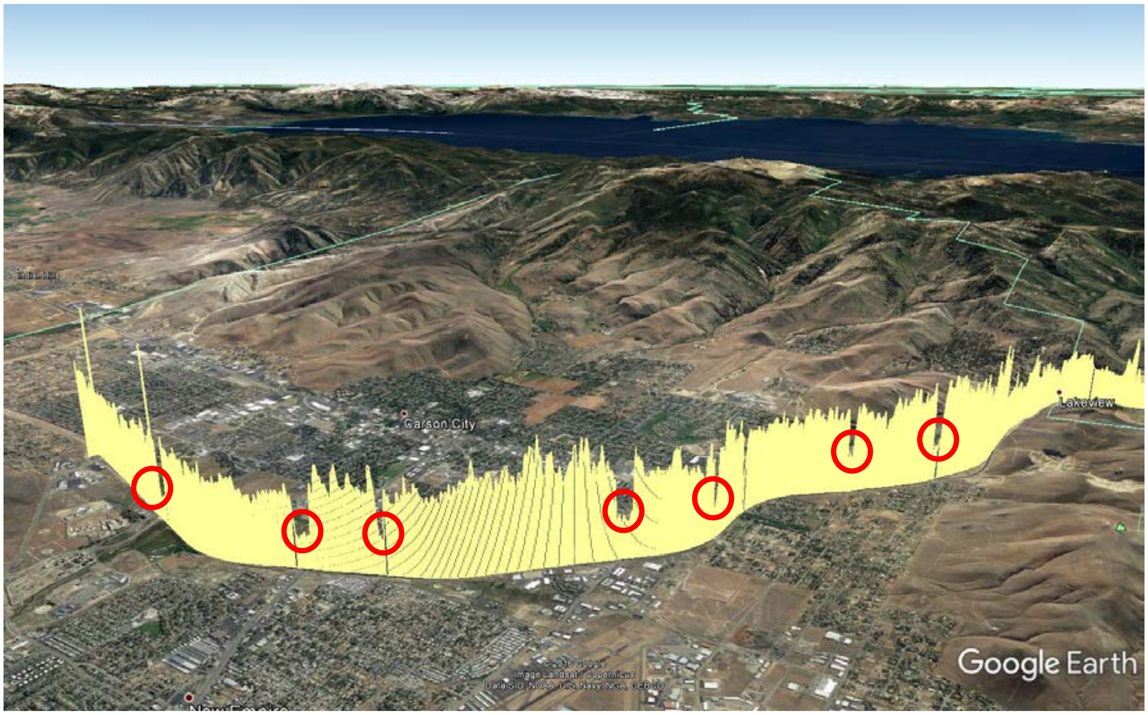


Figure 14. Identified Strong section corresponding to bridges (© 2016 Google Image Landsat / Copernicus).

Mechanistic Analysis with Asphalt Layer Tensile Strains

Work by Rada et al. (2016) has shown that the tensile strain at the bottom of the asphalt layer is highly correlated with pavement structural indices such as SCI300 or DSI that can be obtained from TSD measurements (see Equation 5 earlier). Figure 15 shows an example of the estimated tensile strain profile for I-580 (corrected to a reference temperature of 70°F). Thresholds of 100 and 200 microstrains, respectively, have been used to separate between good, fair, and poor structural conditions (although these thresholds are somewhat arbitrary, the 100 microstrain was chosen because it is the recommended microstrain for dynamic modulus testing of asphalt specimens to limit specimen damage). Again, the threshold should be based on the AC layer thickness and should be adjusted with experience.

Another advantage of the strain approach is that it can be used with a locally calibrated fatigue life equation to provide a better estimate of the remaining fatigue life of the pavement section than the estimate obtained using the generic Equation 11. This provides a link between the TSD-measured condition with an estimate of the remaining structural life of the pavement as illustrated in Figure 16. Practical implementation of this procedure would be in the development of a structural index relationship with remaining fatigue life as illustrated in Figure 17 for DSI.

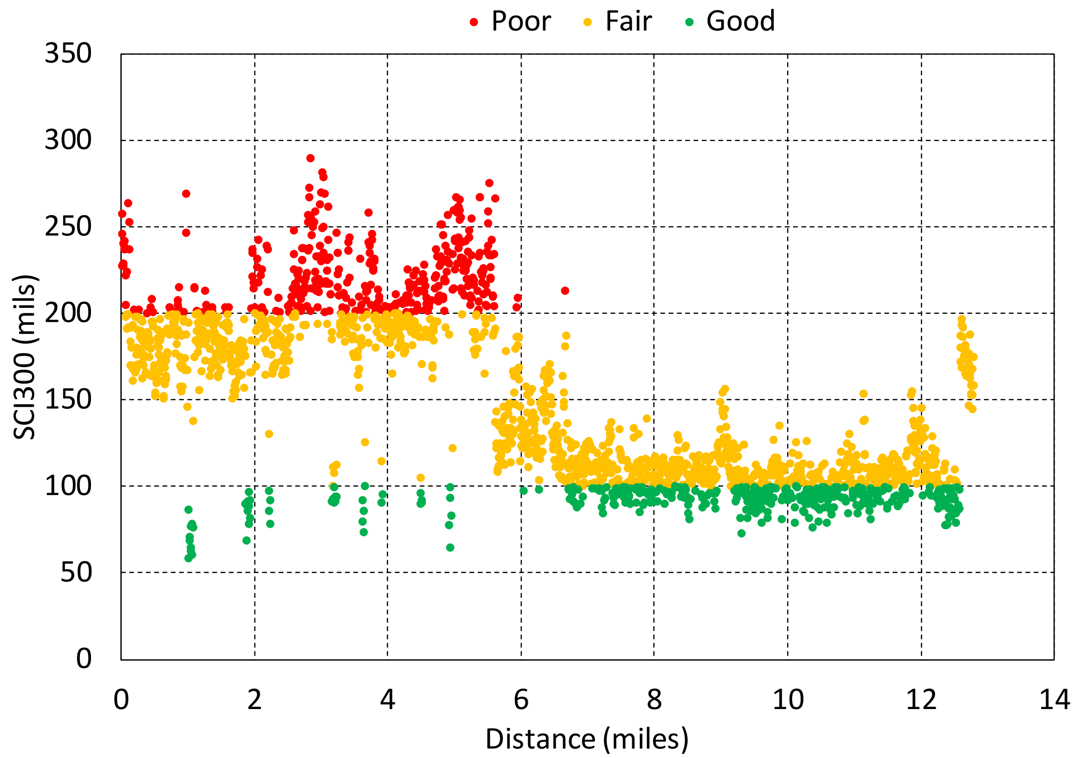


Figure 15. Estimated tensile strain at bottom of asphalt layer on I-585 near Carson City showing effect of temperature correction.

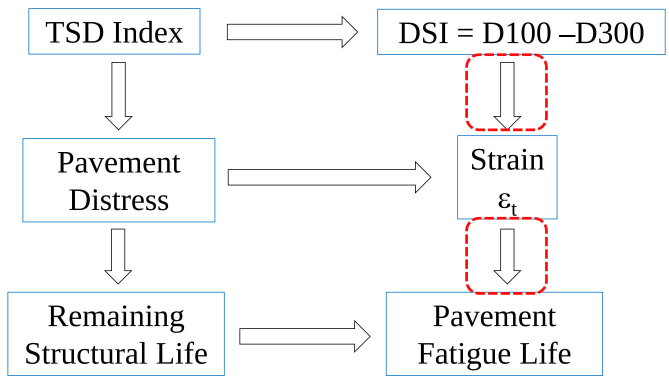


Figure 16. Link between DSI and estimated pavement fatigue life.

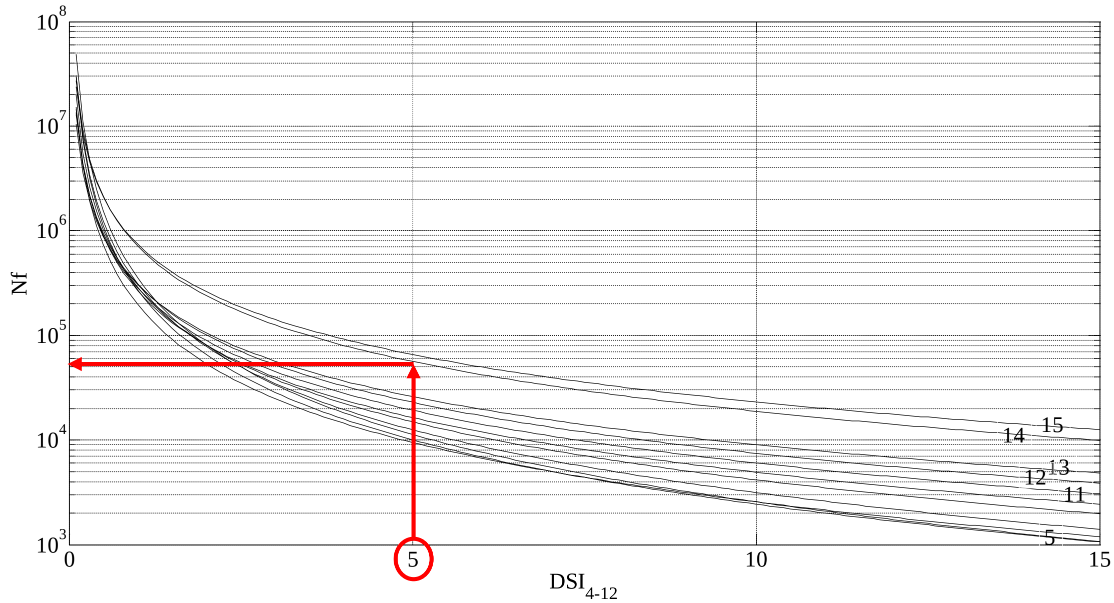


Figure 17. Fatigue life curves for TSD DSI.

RESEARCH QUESTION 5: HOW CAN WE INCORPORATE TSD MEASUREMENTS INTO A PMS?

The Virginia Department of Transportation (VDOT) pavement management decision process is used to illustrate how TSD measurements could be used into a PMS. VDOT uses a set of pavement management decision matrices with distresses as inputs and treatment activities as outputs. Different matrices are used for the following roadway classifications: Interstate Routes, Primary Routes, Secondary Routes, and Unpaved Roads, in addition to the following pavement types: bituminous-surfaced (BIT), bituminous-surfaced composite pavements (with jointed concrete pavement below the surface, BOJ), bituminous-surfaced composite pavements (with continuously reinforced concrete pavement below the surface, BOC), continuously reinforced concrete (CRC), and jointed concrete pavements (JCP). The decision process is a two-phase approach (Figure 18). In 2008, this two-phase approach was modified to include structural condition and truck traffic volumes, and the enhanced decision tree was integrated into the process. One of the main features of the approach is that the addition of the pavement structural information did not alter the core of the decision process already in place but provided an additional step that can be used when pavement structural condition is available. If structural information becomes unavailable, the decision process can revert to the core process already in place. VDOT currently uses the following five treatment categories (from do nothing to heavier treatments): Do Nothing (DN), Preventive Maintenance (PM), Corrective Maintenance (CM), Rehabilitation Maintenance (RM), and Reconstruction (RC). At the preliminary treatment stage, one of these five categories is selected based on the condition index and the decision matrices. In the enhanced decision process, based on the structural condition (and traffic level and construction history), the selected preliminary treatment can be either retained or modified to a heavier or lighter treatment.

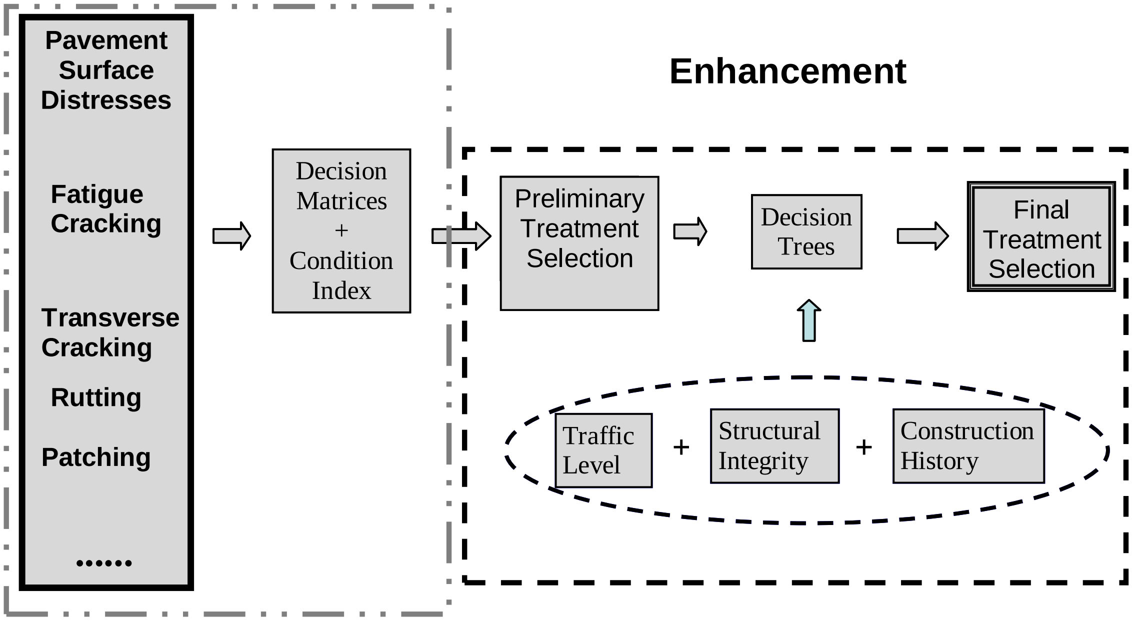


Figure 18. DOT two-phase decision process (Virginia Department of Transportation, 2008).

CONCLUSION

This report summarizes the results of TSD testing performed in Nevada. The report focuses on answering the following important questions:

1. What is the TSD and what does it measure?
2. What is the structural condition of the tested roads?
3. How repeatable are TSD measurements?
4. How can we use the information obtained from TSD measurements?
5. How can we incorporate TSD measurements into a PMS?

A summary of the answers to these questions follows.

1. **What is the TSD and what does it measure?** The TSD is an articulated truck with a loaded rear-axle that can measure the pavement structural condition at or near the traffic speed. Unlike the FWD, the TSD is a moving device (the FWD is stationary) and measures the deflection slope (the FWD measures the deflection) from which the deflections can be calculated.

2. **What is the structural condition of the tested roads?** Most tested roads had a structural condition classified as good except for I580 going through Carson city which had significant portion of the tested sections classified as poor. The classification was obtained after temperature correcting the measurements based on an experimental temperature correction equation developed for the TSD in Rada et al. (2016). It should be noted that the thresholds used for structural condition classification are preliminary (based on Table

2) and should further calibrated based on Idaho needs. The structural condition of the tested roads was summarized in box plots showing the median, 50% range, and 90% range of SCI300. These give a quick overview of the pavement condition. Color coded Google Earth figures for pavements estimated to be in Good, Fair, and Poor conditions are also provided showing the overall pavement condition of the tested roads.

3. **How repeatable are TSD measurements?** Repeated measurements on a 15 miles section of I580 north show good repeatability of TSD calculated SCI300. Some of the discrepancies between the repeated SCI300 could be due to the procedure used for temperature correction which is still preliminary.

4. **How can we use the information obtained from TSD measurements?** TSD measurement information can help to better manage pavement sections. TSD measurements was used to identify strong and weak sections. From the VA study, the comparison with the FWD showed that identified weak and strong sections are compatible with FWD-identified sections (se Katicha et al. 2017). Furthermore, TSD measurements clearly identified tested bridges as strong pavement sections, as would be expected. An approach to estimate the remaining fatigue life of the pavement based on estimated temperature-corrected strains using the method developed by Rada et al. (2016) was also illustrated.

5. **How can we incorporate TSD measurements into a PMS?** The PMS approach of the VDOT was used to illustrate how structural information obtained from the TSD could be used to enhance the decision process from the PMS (more details of the proposed PMS approach can be seen in the pooled fund summary report [see Katicha et al. 2017]).

REFERENCES

Asphalt Institute. (1982). Research and Development of the Asphalt Institute’s Thickness Design Manual (MS-1) (Research Report No. 82-2). 9th edition.

Bryce, J., Flintsch, G.W., Katicha, S., and Diefenderfer, B. (2013). *Network-Level Structural Capacity Index for Network-level Structural Evaluation of Pavements*, Final Contract Report VCTIR 13-R9, Virginia Center for Transportation Innovation and Research, Charlottesville, VA.

Finn, F.N., Saraf, C., Kulkarni, R., Nair, K., Smith, W., & Abdullah, A. (1977). The use of distress prediction subsystems for the design of pavement structures. Proceedings of the 4th International Conference on the Structural Design of Asphalt Pavements (pp. 3–38), Vol. I, August. Ann Arbor, MI: University of Michigan.

Flintsch, G.W., Katicha, S.W., Bryce, J., Ferne, B., Nell, S., and Diefenderfer, B. (2013). *Assessment of Continuous Pavement Deflection Measuring Technologies*, Second Strategic

Highway Research Program (SHRP2) Report S2-R06F-RW-1, The National Academies, Washington, D.C.

Flora, W. (2009). *Development of a Structural Index for Pavement Management: An Exploratory Analysis*, Master's Thesis, West Lafayette, Indiana: Purdue University.

Horak, E. (1987). "The use of surface deflection basin measurements in the mechanistic analysis of flexible pavements," *Proceedings of the Sixth International Conference Structural Design of Asphalt Pavements,* Vol. 1, University of Michigan, Ann Arbor, Michigan, USA.

Katicha, S.W., Ercisli, S., Flintsch, G.W., Bryce, J., and Diefenderfer, B. (2016). *Development of Enhanced Pavement Deterioration Curves*, Final Contract Report VCTIR 17-R7, Virginia Center for Transportation Innovation and Research, Charlottesville, VA.

Katicha, S.W., Flintsch, G.W., Shrestha, S., and Thygarajan, S. (2017) "Field Demonstration of the TSD: Final Report" Draft Report Under Review.

Pedersen, L., Hjorth, P. G., and Knudsen, K. (2013). *Viscoelastic Modelling of Road Deflections for use with the Traffic Speed Deflectometer*. Kgs. Lyngby: Technical University of Denmark. (IMM-PHD-2013; No. 310).

Rada, G. R., Nazarian, S., Bisintine, B. A., Siddharthan, R.V., and Thyagarajan, S. (2016). *Pavement Structural Evaluation at the Network Level: Final Report*, FHWA-HRT-15-074, Federal Highway Administration, McLean, Virginia, USA. https://www.fhwa.dot.gov/pavement/pub_details.cfm?id=1000

Rohde,G.T. (1994). Determining pavement structural number from FWD testing, Transport Research Record no 1448, Washington DC.

Virginia Department of Transportation. (2008). *Supporting Document for the Development and Enhancement of the Pavement Maintenance Decision Matrices Used in the Needs Based Analysis*. Richmond, VA.

Thyagarajan, S., Sivaneswaran, N., Petros, K., and Muhunthan, B. (2011). "Development of a simplified method for interpreting surface deflections for in-service flexible pavement" ICMPA129.