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

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<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 Georgia. 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 17 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, effective structural number (SN_{eff}), 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 comparison between GDOT structural index and SCI measured from TSD show that surface distress based index are not sufficient to accurately determine the structural condition of the pavement measured by TSD. The results of the investigation suggested that repeated measurements from the TSD on the same sections in 2014 and 2015 show similar trends. However, one set of measurements can be higher or lower than the other even after temperature correction. This shows that more effort is needed to develop better temperature correction procedures. For pavement management applications, the TSD mostly identifies the same strong/weak sections with repeated runs which suggest it is a good device for network level structural evaluation.
A companion report summarizes the results from transportation pooled fund study in all nine states. The companion report also contains information on interpreting files associated with TSD data, data processing method used in the study and Profilograph program to view the TSD data.</td></tr>
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FIELD DEMONSTRATION OF THE TSD IN GEORGIA

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 Georgia (May 8 and 9, 2014 and July 18 to 21, 2015), and illustrates how the results of the TSD testing can be implemented within 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 Georgia 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 due to an impact load. 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

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roads, and typical thicknesses, 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 temperature-corrected SCI300 measurements performed on the same sections in 2014 and 2015.

4. **How do TSD measurements compare with PMS data?** TSD measurements were compared with pavement management system (PMS) condition data. This was done by comparing TSD calculated SCI300 with the Structural Index obtained based on surface distresses.

5. **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 the effective structural number (SN_{eff}) or 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.

6. **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 Georgia 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 (13,196 to 28,686 lbf) 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. TSD used during testing (left) and computer-generated schematic (right) (Krarup, 2012).

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. The deflection velocity is divided by the instantaneous vehicle speed to give a measurement of deflection slope to remove the dependence on vehicle speed, 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.

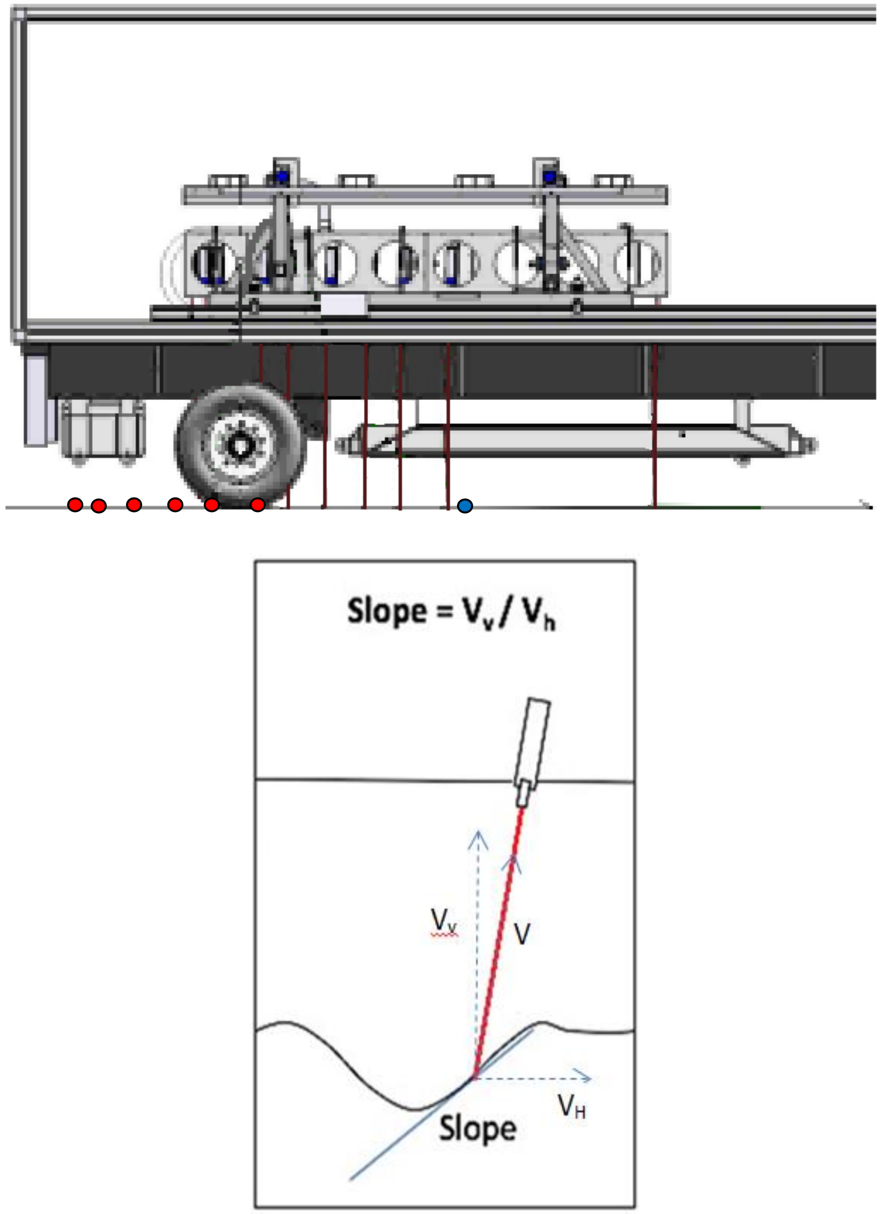


Figure 2. Schematic of the measurement principle of the TSD (Krarup 2012 and modified from Flintsch et al. 2013).

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:

$$d(x) = \int_x^\infty s(y)dy \tag{2}$$

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.

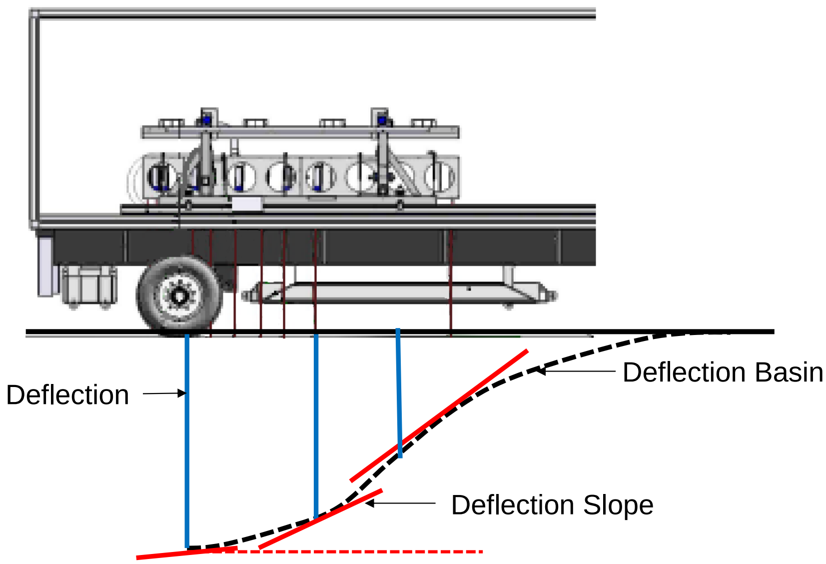


Figure 3. Relationship between the deflection basin, deflection, and deflection slope (modified from Krarup 2012).

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.

$$SCI300 = D0 - D300 \tag{3}$$

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. Since at the time of the report FWD data are not accessible for the TSD tested sections in Georgia, reader is referred to the summary report (Katicha et al. 2017) for the comparison between FWD and TSD. Note that 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. 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 Deflection Slope Index (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:

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

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, for flexible pavements 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:
   $$E_f = c \times \varepsilon^d \quad (6)$$
   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:
   $$T_c = 19.791\left(e^{-0.043T_r} - e^{-0.043T_f}\right) \quad (7)$$
   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:
   $$E_r = \frac{E_f}{1 - T_c} \quad (8)$$
4. Compute the strain, ε_r, at the selected reference temperature by rearranging Equation 6 as follows:
   $$\varepsilon_r = \left(\frac{E_f}{c}\right)^{\frac{1}{d}} \quad (9)$$
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):

T_f = 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:
T_f = 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 Engineering 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 is 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 (10) to calculate mid-depth temperature. The computed mid-depth temperature is used with the temperature correction procedure described earlier. 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.
- Pavement layer details were not readily available for all the tested sections and therefore, for the purpose of temperature corrections, all sections were assumed to be flexible pavements. Consequently, the temperature corrected SCI300 should only be used for those pavement sections that Georgia DOT knows to be flexible pavements. For sections that are not flexible pavements, it is recommended to use the uncorrected SCI300 or other indices presented.
- When AC layer thickness information is not available, it is assumed based on the road category
- M&R activities, if any, applied between the time of initial and repeat data collection are not considered in the repeatability analysis.

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

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 646 miles (329 in 2014 and 317 in 2015) were tested.

Overall Structural 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 Equivalent Single Axle Loads (ESAL's) was used to arrive at a preliminary estimate for threshold between good/fair and fair/poor segments. The remaining ESALs thresholds used in the report are only for illustrative purposes and it is expected that the estimated threshold will be revised based on the experience gained from TSD implementation efforts by individual SHAs.

Initially, three road categories – 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))

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

2014		
Serial No.	Leg number	Link
1.	Leg#2 - I75	https://goo.gl/maps/NR92ofvmr742
2.	Leg#3 - SR16	https://goo.gl/maps/2LXJWXbGQLE2
3.	Leg#4 - SR74	https://goo.gl/maps/u4GLKV8pgcG2
4.	Leg#5 - SR85-SR74	https://goo.gl/maps/RCtqmu2LYs32
5.	Leg#6 - SR54	https://goo.gl/maps/XF67ExBWq7y
6.	Leg#7 - SR54	https://goo.gl/maps/KyfnksSZQjE2
7.	Leg#8 - SR14/ S Fulton Parkway	https://goo.gl/maps/gFPA8QcnPHw
8.	Leg#9 - SR6	https://goo.gl/maps/u3iJ3WLL5c92
9.	Leg#10 -US278	https://goo.gl/maps/1B4CYqjsiVv

2015			
Serial No.	File Name	Road Name	Map Link
1.	T7201507180001	SR54 South – North Main Street – US41	https://goo.gl/maps/8RGq94S2uG42
2.	T7201507180021	SR138 East – SR54 North	https://goo.gl/maps/6HNLQk1wraS2
3.	T7201507200001	I75 South 1	https://goo.gl/maps/pQ2S8jdCD8t
4.	T7201507200002	SR16 West 1	https://goo.gl/maps/cPAJWJSRvgF2
5.	T7201507200003	SR16 East	https://goo.gl/maps/fqHZv1Euvm12
6.	T7201507200004	SR16 West 2	https://goo.gl/maps/4iJ66ys8U8A2
7.	T7201507200005	I75 South 2	https://goo.gl/maps/kcmMjosYgUQ2
8.	T7201507200006	I75 North	https://goo.gl/maps/Hc1WjynN64K2
9.	T7201507200007	US42 South – SR54 South	https://goo.gl/maps/ezmvGtmNJcq
10.	T7201507200008	SR34 West	https://goo.gl/maps/6oW3fbep27H2
11.	T7201507200009	SR34 East	https://goo.gl/maps/Nrix3faoc842
12.	T7201507200010	SR54 North	https://goo.gl/maps/t7YCibGRbQq
13.	T7201507210001	SR74 South	https://goo.gl/maps/azJkphpKdBo
14.	T7201507210002	SR85 South - SR74 North	https://goo.gl/maps/qd1ox5fToG22
15.	T7201507210003	SR14 West (South Fulton Parkway)	https://goo.gl/maps/WMp881PvM782
16.	T7201507210004	SR14 East (South Fulton Parkway)	https://goo.gl/maps/64o7pJzt19A2
17.	T7201507210005	SR6 West	https://goo.gl/maps/kCLK7cq15Cn
18.	T7201507210006	SR6 East	https://goo.gl/maps/wtZyUnHoVhz
19.	T7201507210007	SR6 West – US278 West	https://goo.gl/maps/CaQmhvdo2fk
20.	T7201507210008	US278 East – SR6 East	https://goo.gl/maps/QoGeWwzX7kp

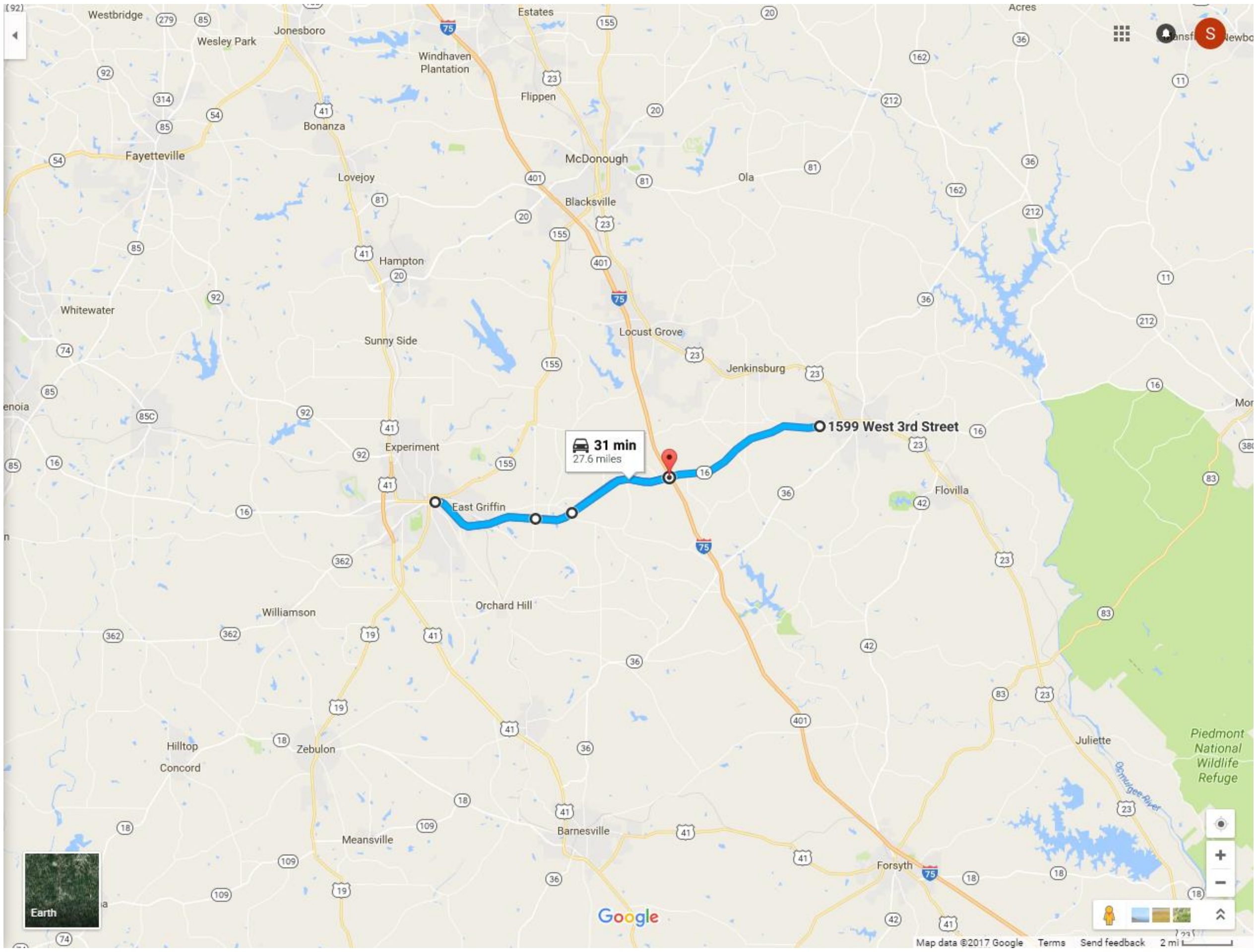


Figure 4. Example showing link for Leg#3 - SR16 from Table 1

$$N_f = C \times 0.00432 \left(\frac{1}{\varepsilon_t} \right)^{3.291} \left(\frac{1}{E} \right)^{0.854} \qquad (10)$$

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: 1.4 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 and Figure 6 show the condition of the tested roads using SCI300 (and DSI) corrected to a reference temperature of 70°F and normalized with the measured dynamic load. Temperature correction uses the asphalt layer thickness which was either provided by Georgia or assumed to be in the range of 3 to 6, 6 to 9 and 9 to 16 inches, for secondary, primary, and interstate roads, respectively. Figure 7 shows a closer look at the structural condition on SR14. 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. Note that the Google Earth files showing the color coded condition and the corresponding Excel files used to perform temperature correction and calculation of SCI300 and DSI for all measurements are provided separately in an external hard drive. Excel files allow changing of the thresholds which will be reflected in the color coded classification in the Excel plots.

Figure 8 and Figure 9 show the overall structural condition in box plot, as indicated by the temperature-corrected SCI300, for the 2014 and 2015 tests, 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. Even though the same road was tested in 2014 and 2015, the figure should be interpreted considering that the length of the road sections may not be necessarily same in both years. Some routes (such as US 278) show significant difference in temperature corrected SCI between year 2014 and 2015, which could be partially attributed to the temperature correction procedure that assumes the segment as flexible pavement while it is a composite pavement. Other possible reasons for the observed differences are explained in the summary report (Katicha et al. 2017; repeatability section).

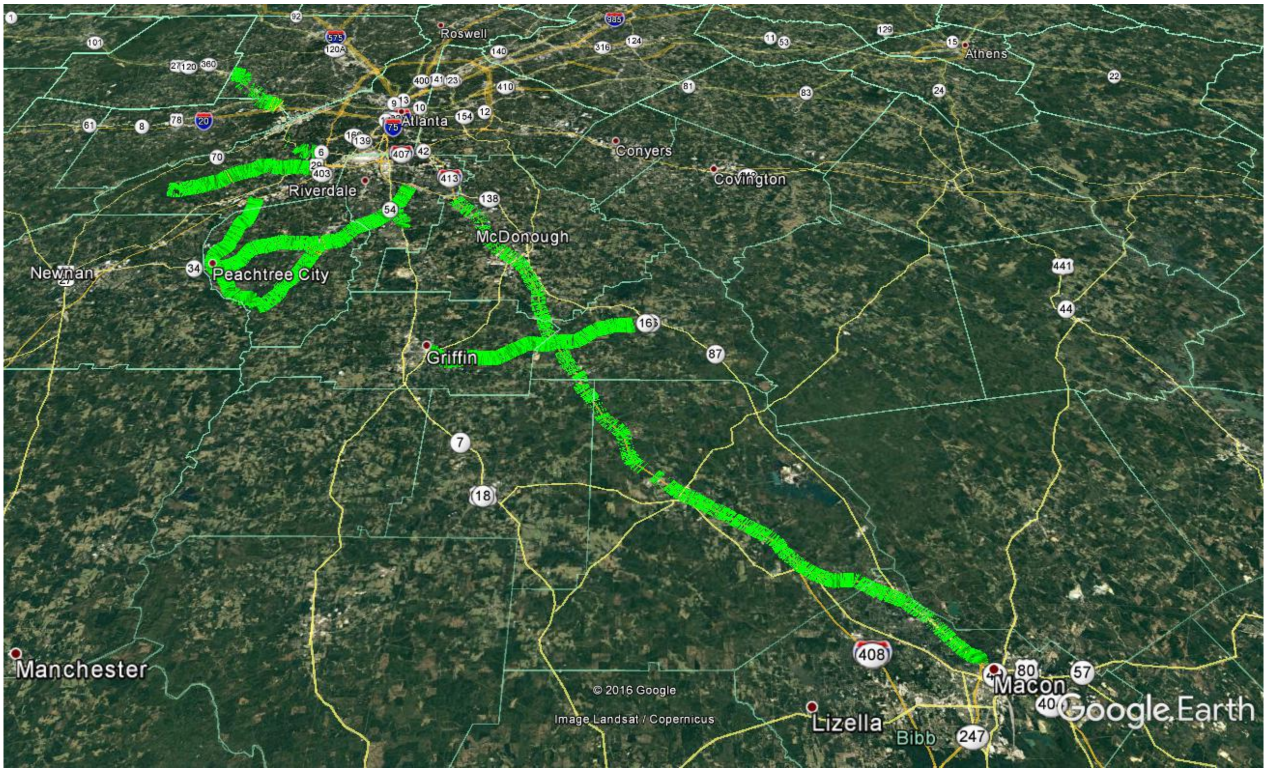


Figure 5. Color-coded estimated structural condition of tested roads in 2014 with Good (green), Fair (yellow), and Poor (red) ratings (© 2016 Google Image Landsat / Copernicus).

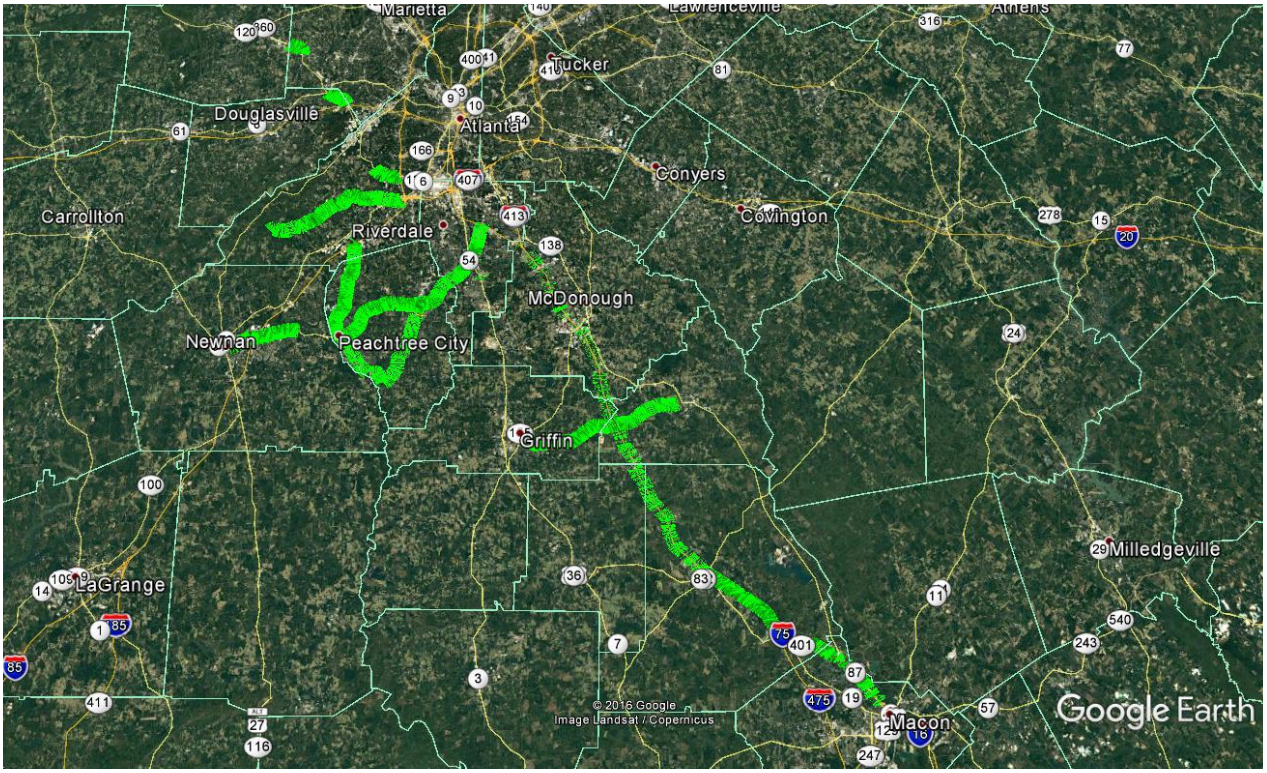


Figure 6. Color-coded estimated structural condition of tested roads in 2015 with Good (green), Fair (yellow), and Poor (red) ratings (© 2016 Google Image Landsat / Copernicus).

Figure 7. Detail example of estimate pavement structural condition on SR14 south east of Atlant tested in 2015 (© 2016 Google Image Landsat / Copernicus).

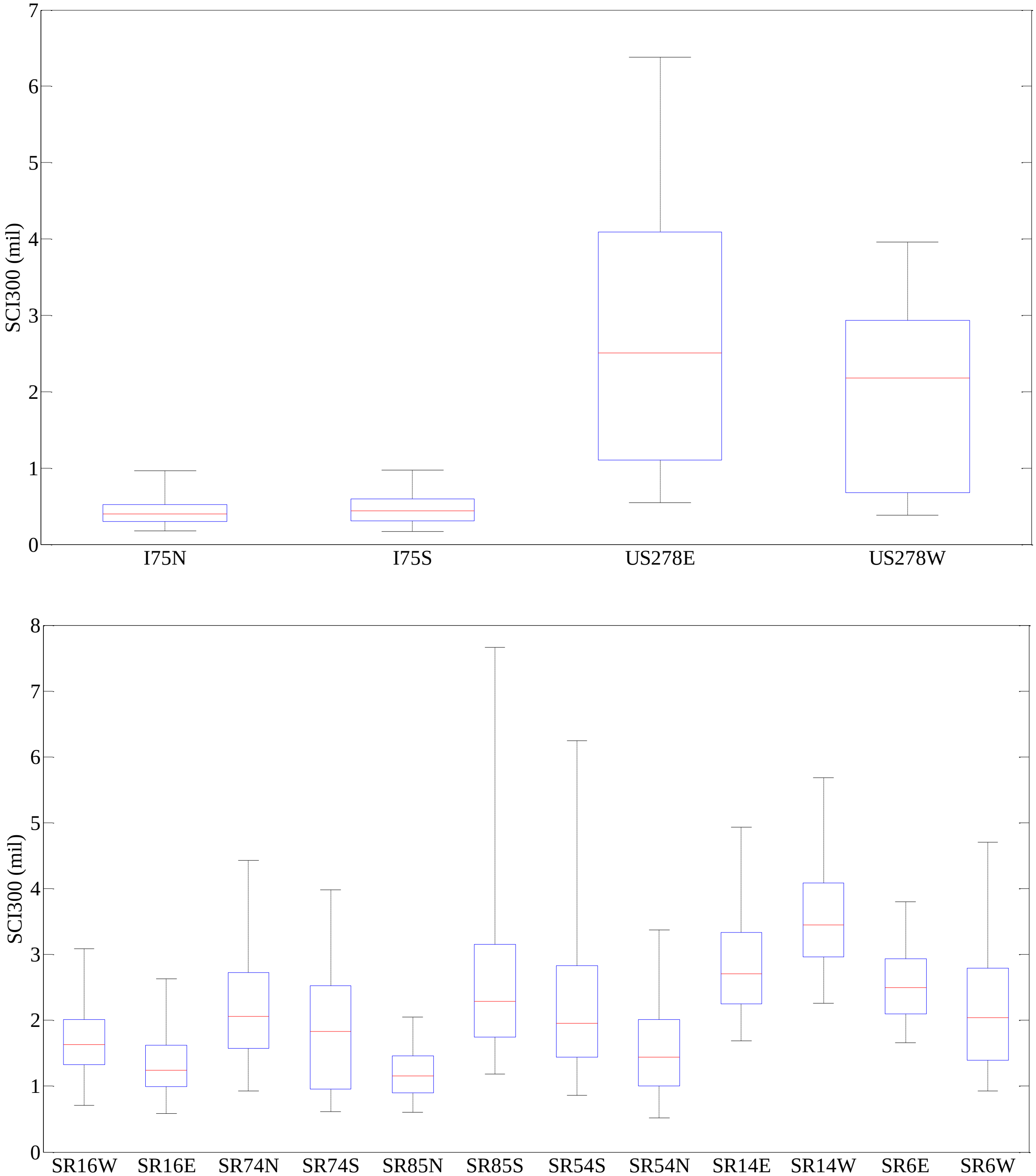
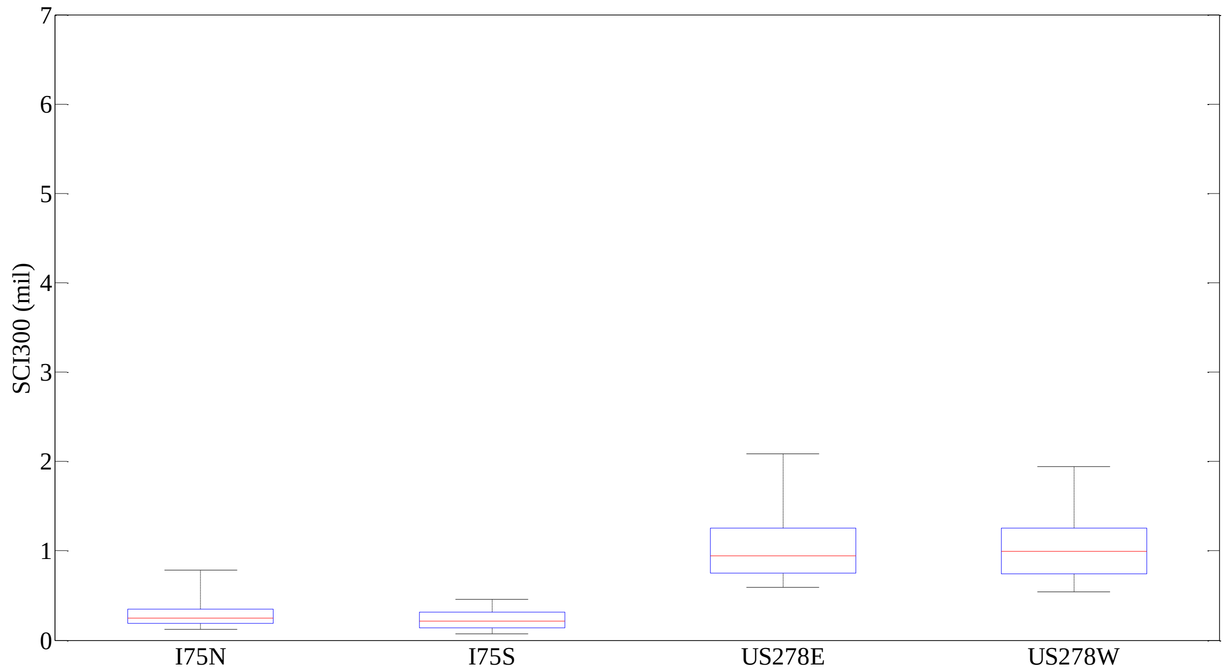


Figure 8. SCI300 box plot of tested roads in 2014.



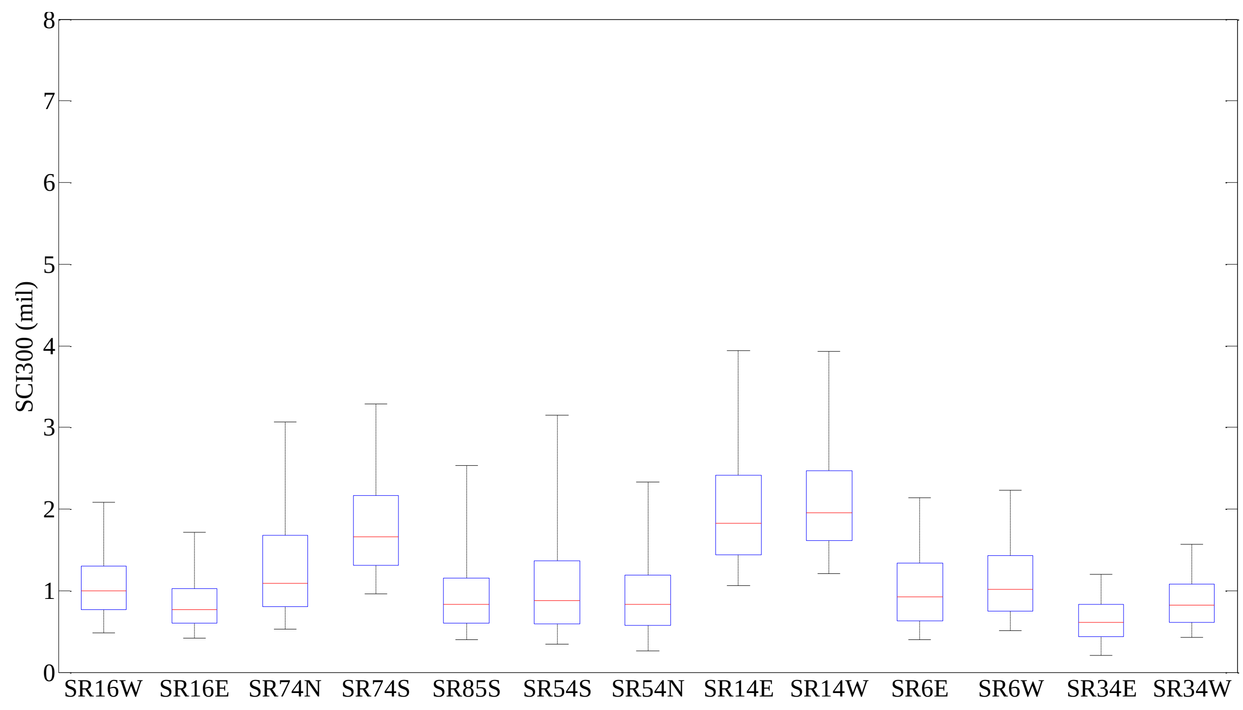


Figure 9. SCI300 box of tested roads in 2015.

RESEARCH QUESTION 3: HOW REPEATABLE ARE TSD MEASUREMENTS?

Figure 10 shows the repeated measurements of SCI300 corrected for temperature on a SR16 East (Figure 11). The measurements were taken in 2014 and 2015. The two sets of measurements follow similar trends although not exactly the same values. The measurements taken in 2015 are lower than the measurements taken in 2014. This could be due to temperature correction procedure which is still an experimental equation.

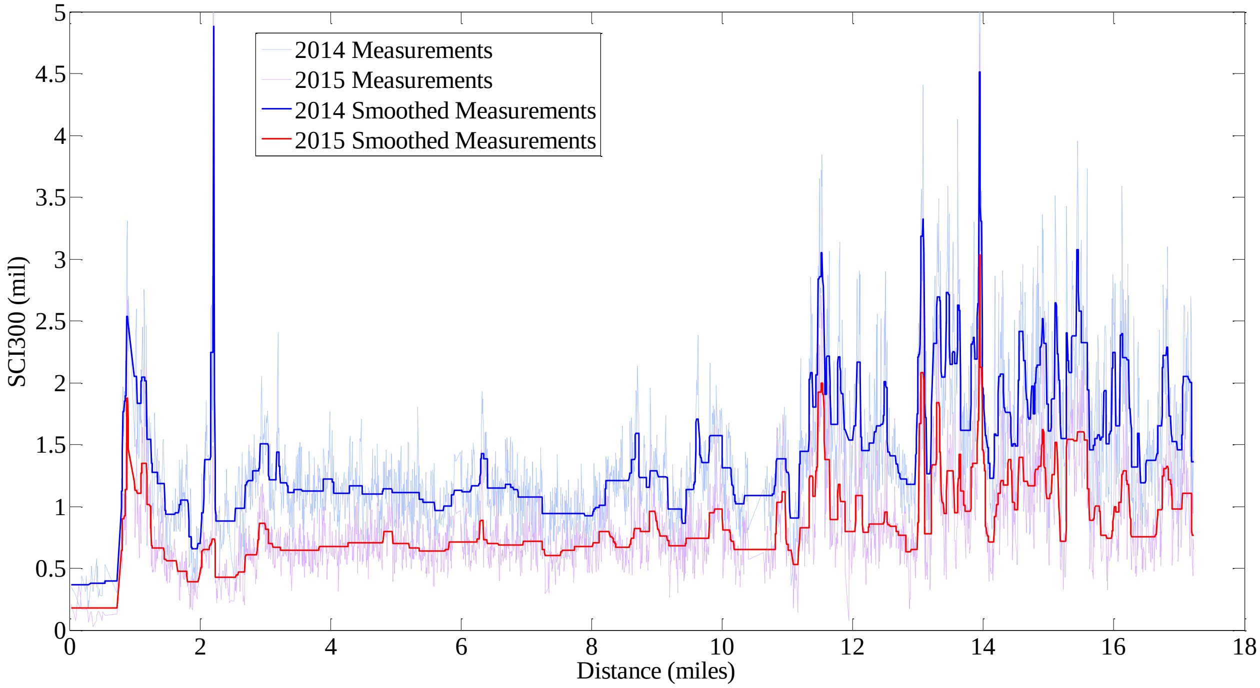


Figure 10. Temperature corrected repeated TSD tests (SCI300) on SR16E (https://goo.gl/maps/2LXJWXbGQLE2)

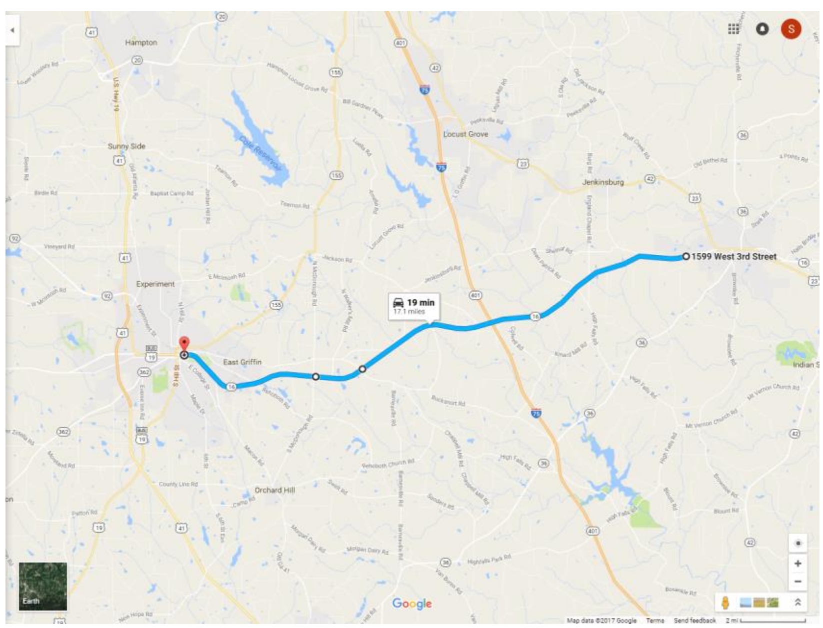


Figure 11. Repeated tested section on SR16E with results shown in Figure 10

RESEARCH QUESTION 4: HOW DO TSD MEASUREMENTS COMPARE WITH PMS DATA?

Pavement management data was provided by Georgia DOT for R74 in Fayette County. Figure 12 shows a comparison between the TSD calculated SCI300 and the Structural Index measured based on observed surface distresses. The TSD measured data was collected from about 1.8 miles before the Fulton county line to SR54. The results show the TSD provides a different picture than what is implied from the surface distresses. For example, the distance 6 to 7 mile show poor Structural index while the SCI measured from TSD show good structural condition based on the preliminary threshold. The TSD can also identify localized soft spots. This shows that surface distresses are not sufficient to accurately determine the structural condition of the pavement and therefore highlight the usefulness of a device like the TSD to measure network level structural condition.

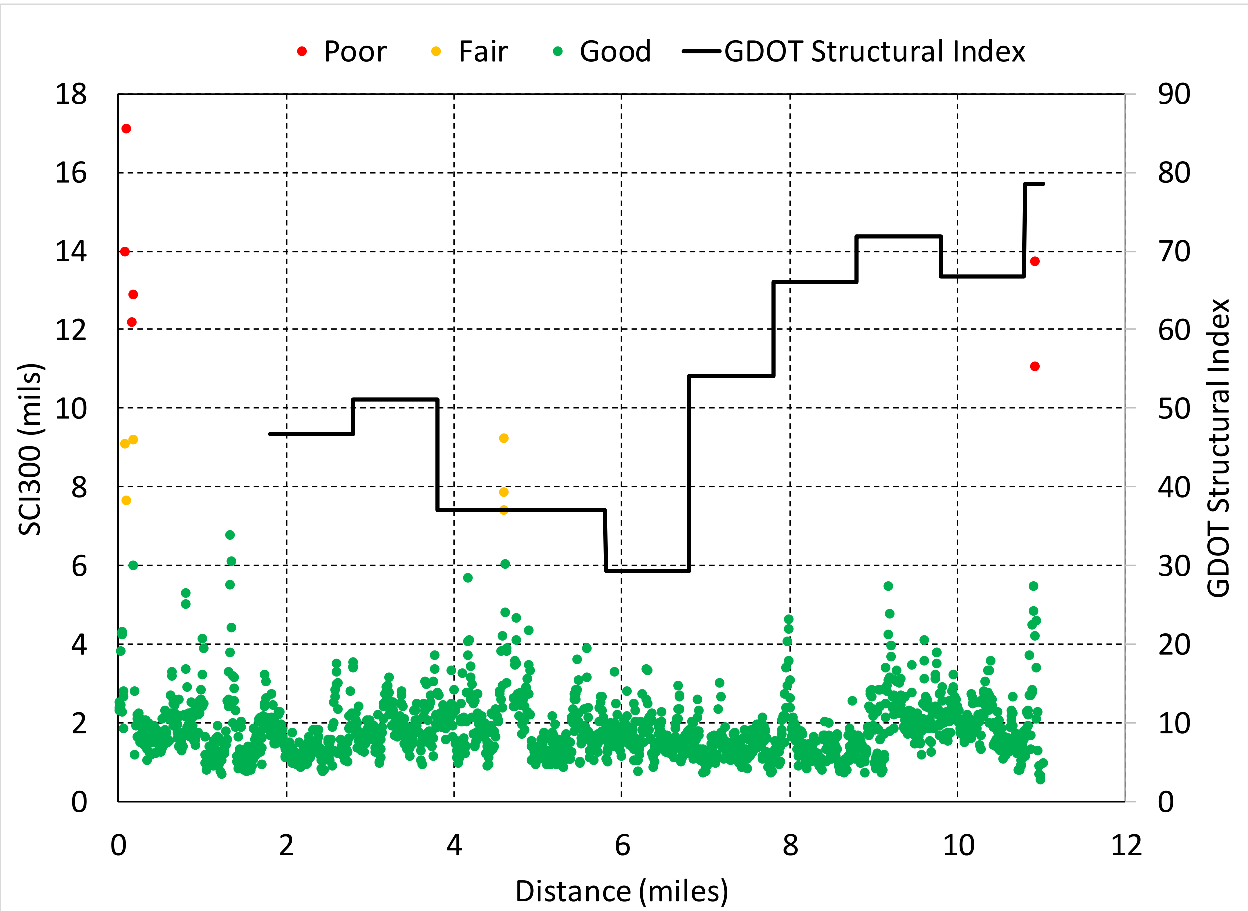


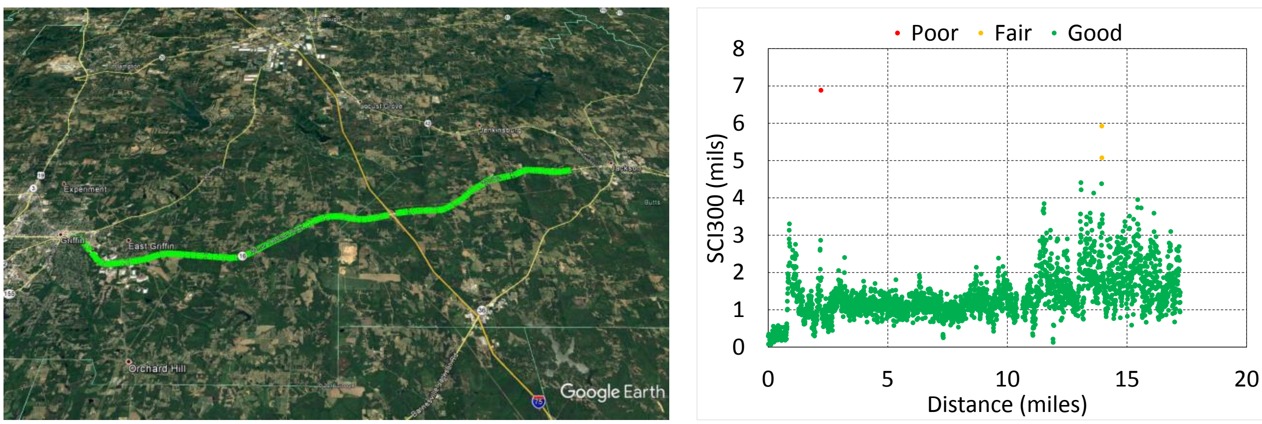
Figure 12 Comparison on SR74 in Fayette County between TSD SCI300 measured in 2015 and Structural Index obtained from surface distresses (https://goo.gl/maps/azJkphpKdBo)

RESEARCH QUESTION 5: 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 13 shows an example of such a classification with measurements collected on SR16E in 2014 and thresholds based on expected remaining fatigue life obtained from Table 2 (similar figures are provided in Excel files for all tested roads). Figure 14 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 13. Identified Strong (green) and Weak (red) sections on SR16 east based on thresholds obtained from Table 2: (a) Google Earth plot (© 2016 Google Image Landsat / Copernicus); (b) figure plot

Another validation of the capabilities of the TSD to classify sections is shown in Figure 15. A spot identified by the TSD on SR16 west is highlighted with the red box. Upon further investigation, this spot was found to correspond to a bridge, which in general is known to exhibit lower deflections than flexible pavement sections.

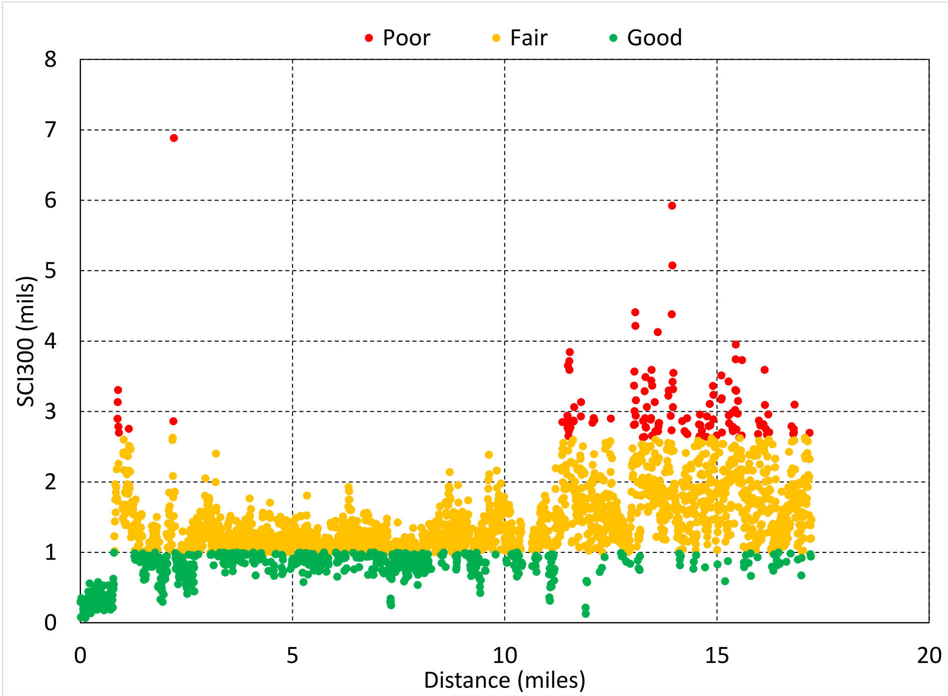


Figure 14 Classification of structural condition on SR16 East based on percentile: 25th percentile and lower represents good structural condition and 90th percentile and higher represents poor structural condition

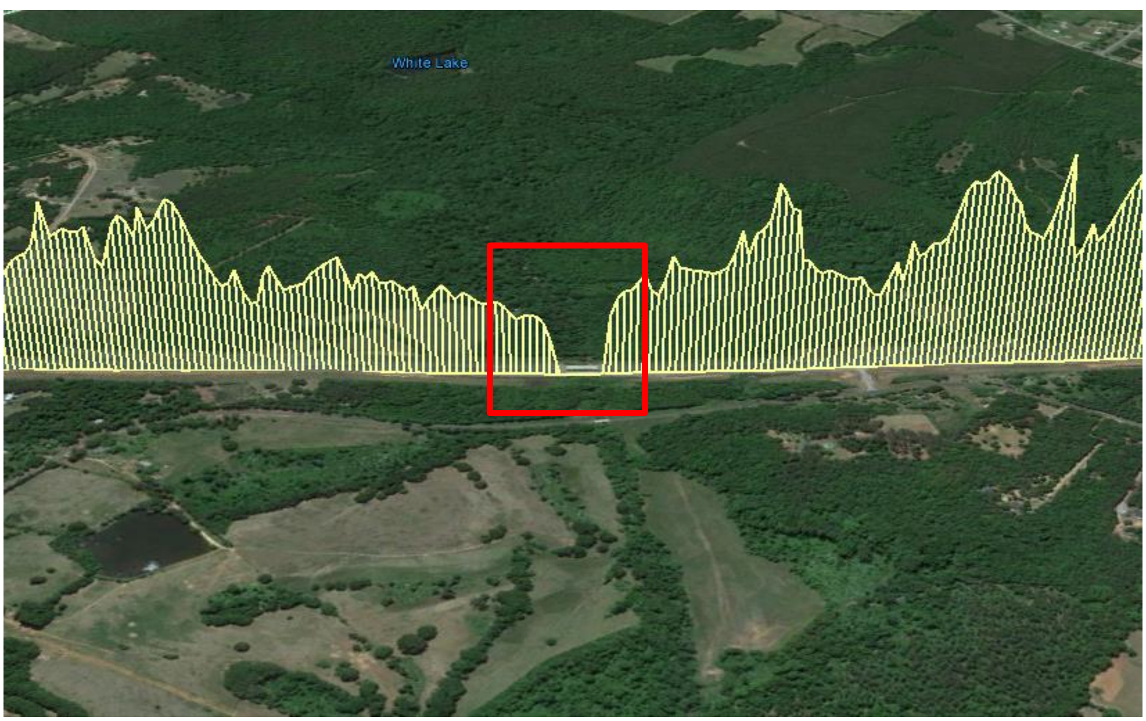


Figure 15. Identified Strong section corresponding to bridges on SR16 west (© 2016 Google Image Landsat / Copernicus).

Calculation of Effective Structural Number

With pavement layer thickness information, the effective structural number (SN_{eff}) can be calculated and used as a structural condition index to be implemented in the PMS. Figure 16 shows an example of calculated SN_{eff} on SR16E using the method developed Rohde (1994) as follows:

1. Determine the structural index *SIP* of the pavement as follows;
   $$SIP = d(0) - d(1.5H_P)$$
   where:
   $d(0)$ = peak deflection under the 9,000 lb load
   $d(1.5H_p)$ = deflection at lateral distance of 1.5 times the pavement depth.
   H_p = Pavement depth – thickness of all layers above the subgrade.
2. Determine the existing pavement SN_{eff} as;
   $$SN_{eff} = k_1 SIP^{k_2} H_p^{k_3}$$
   where for asphalt pavements, k_1 = 0.4728, k_2 = -0.4810, k_3 = 0.7581

d(0) is temperature corrected to 68°F using the procedure stated in AASHTO 1993 pavement design guide (AASHTO 1993).

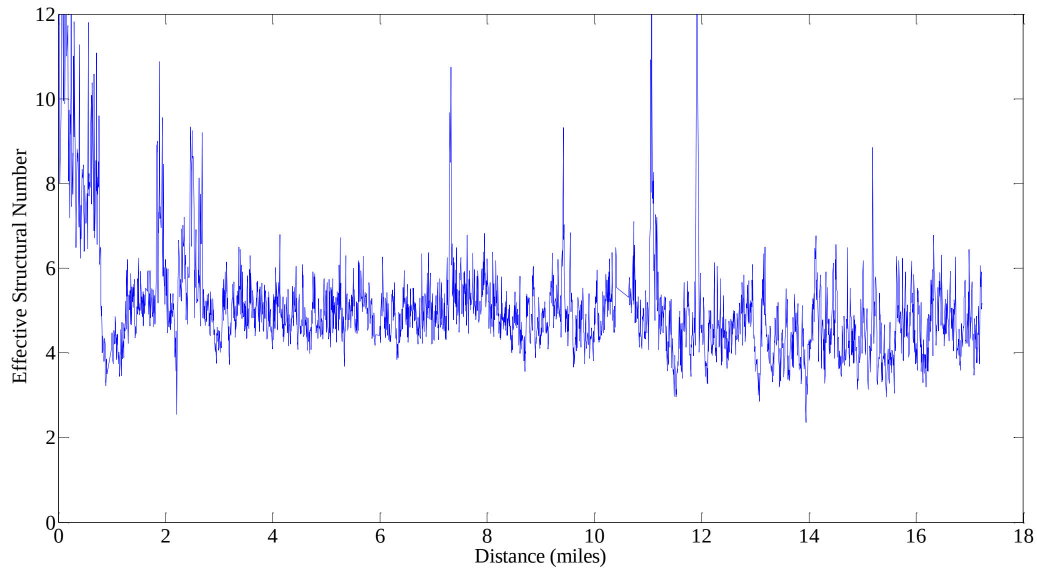


Figure 16 Effective Structural Number on SR16E calculated from measurements collected in2015

Figure 17 shows SN_{eff} for a section of SR74S computed from the TSD and using default layer coefficients as suggested in AASHTO 1993, which represents initial SN_{eff} of the pavement when constructed. The results shows that the TSD SN_{eff} is relatively uniform but different from the one estimated based on layer thickness information and default layer coefficients. The TSD SN_{eff} indicates the pavement has deteriorated compared to the initial design SN_{eff}. The figure also shows the GDOT Structural Index calculated from observed surface distresses do not reflect the structural condition obtained from the TSD as in SCI300 comparison (Figure 12).

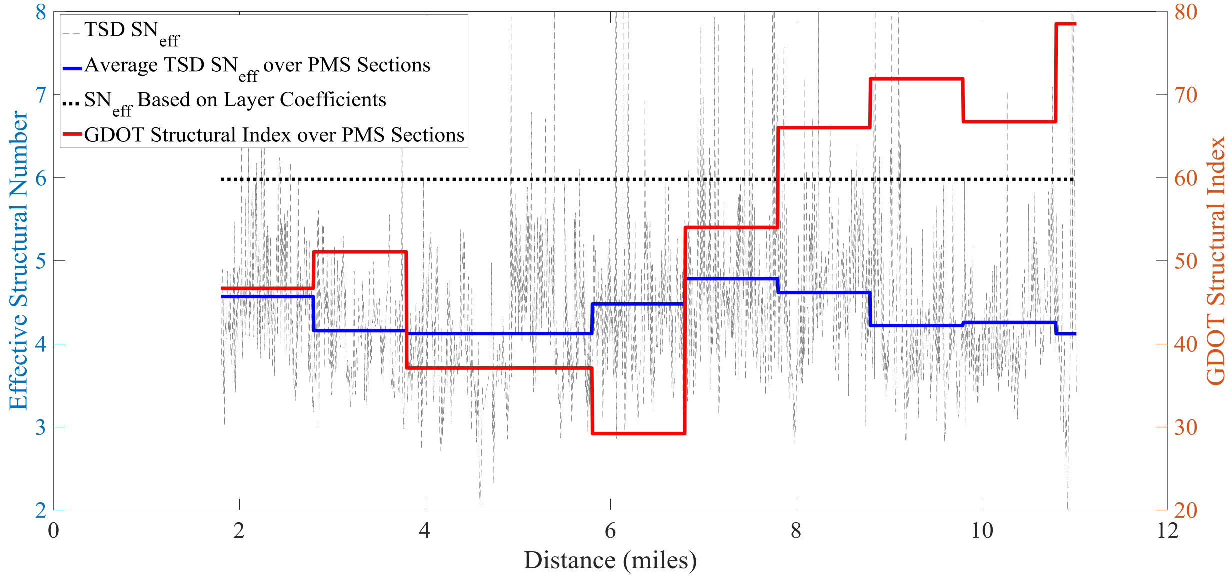


Figure 17 Comparison of Effective Structural Number on SR74S calculated from TSD measurements collected in 2015 and GDOT Structural Index

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 18 shows an example of the estimated tensile strain profile for SR16 east (corrected to a reference temperature of 70°F). Thresholds of 100 and 300 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 19. Practical implementation of this procedure would be in the development of a structural index relationship with remaining fatigue life as illustrated in Figure 20 for DSI.

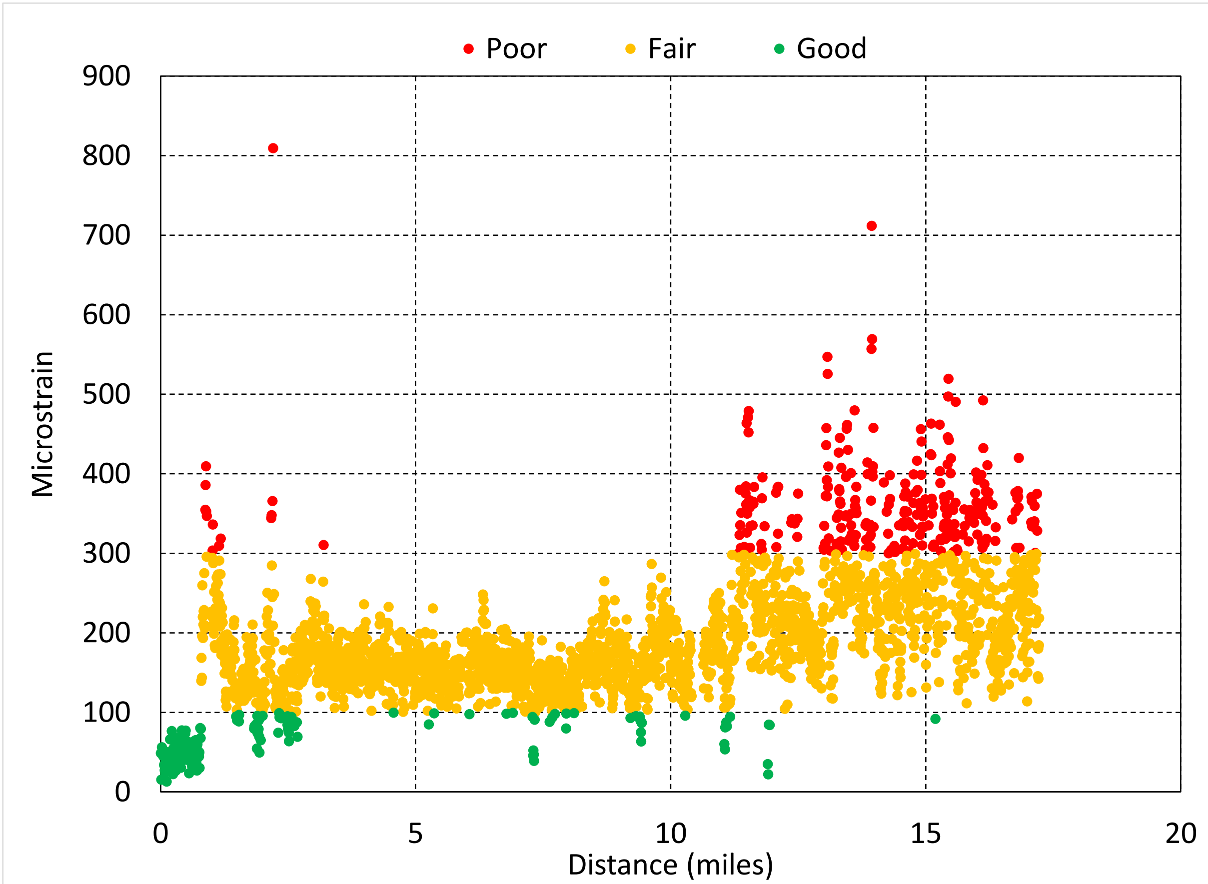


Figure 18. Estimated tensile strain at bottom of asphalt layer on SR16 east.

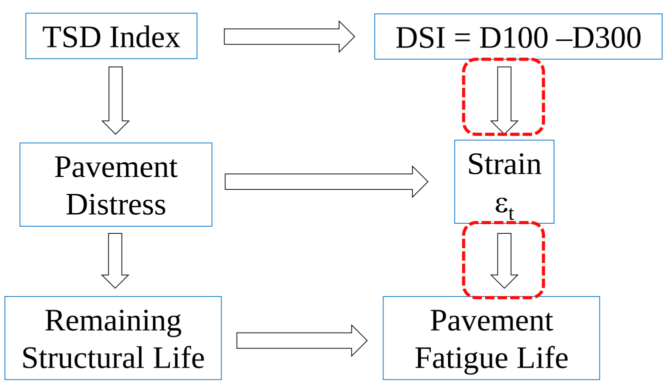


Figure 19. Link between DSI and estimated pavement fatigue life.

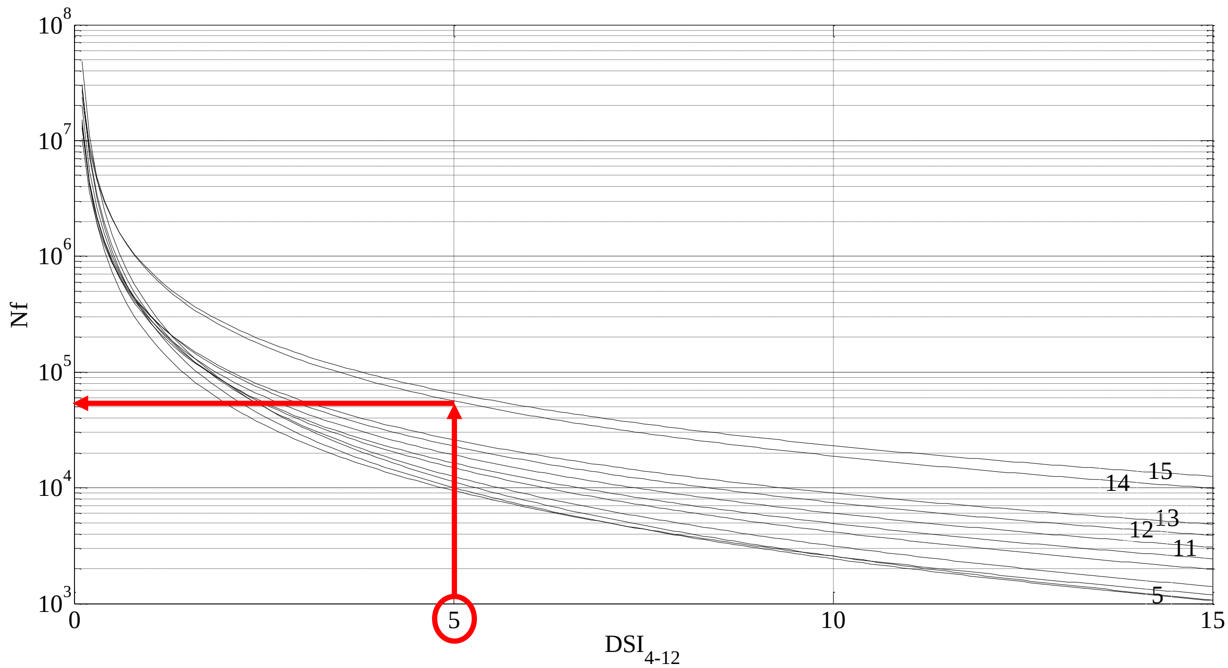


Figure 20. Fatigue life curves for TSD DSI.

RESEARCH QUESTION 6: 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 21). 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. Additional details of the proposed PMS approach can be seen in the pooled fund summary report (Katicha et al. 2017).

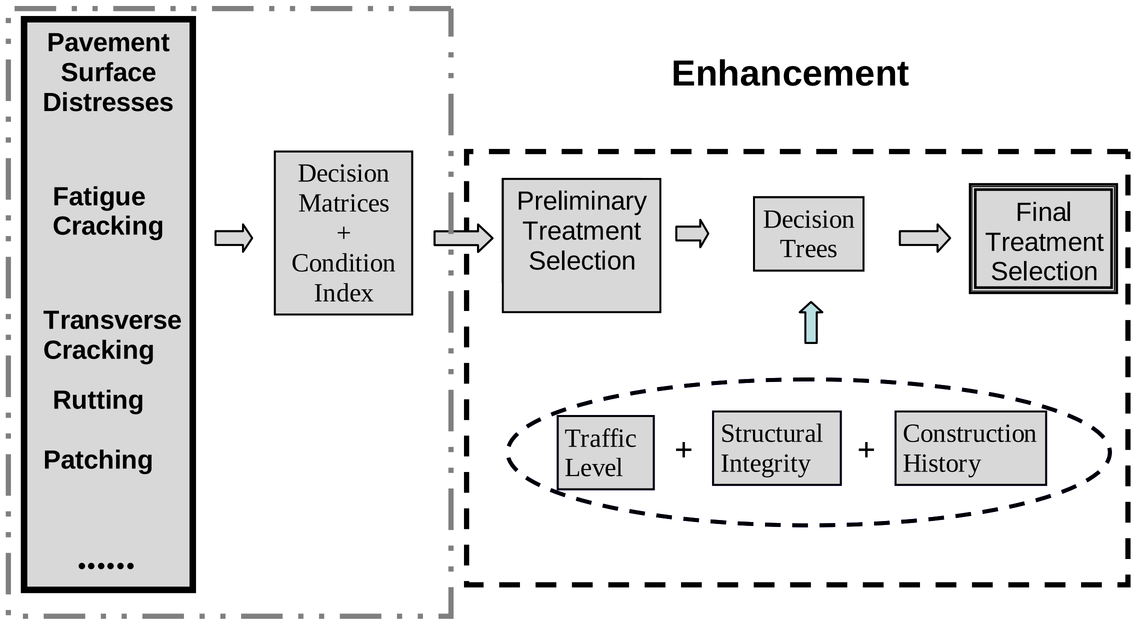


Figure 21. DOT two-phase decision process (Virginia Department of Transportation, 2008).

CONCLUSION

This report summarizes the results of TSD testing performed in Georgia. 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 do TSD measurements compare with PMS data?
5. How can we use the information obtained from TSD measurements?
6. 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 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. 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 TSD measurements on SR16 East followed similar trends for SCI300. There was, however, some difference with measurements performed in 2014 on average higher than measurements performed in 2015 (with both measurements corrected for temperature). In general reasonable repeatability was observed in flexible sections of other states and differences are observed in composite pavements (Katicha et al. 2017). More work needs to be performed on approaches to corrected measurements for the effect of temperature however for network level applications the TSD gives acceptable repeated results.

4. **How do TSD measurements compare with PMS data?** Comparing TSD SCI300 with the Structural Index obtained from surface distresses on SR74 showed that the condition recorded in the PMS through Structural Index does not accurately reflect the measured structural condition by the TSD. This reinforces the need to perform network level structural evaluation to obtain the pavement structural condition and therefore better characterize the overall condition of the pavement (both structural and functional condition).

5. **How can we use the information obtained from TSD measurements?** TSD measurement information can help to better manage pavement sections. For example TSD measurements can be used to identify strong and weak sections based on developed thresholds for a chosen index (e.g. SCI300, SN_{eff}) or based on percentages of observed condition. 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.

6. **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 PMS decision process. The approach consists of a two stage process where the structural condition is used to verify and/ modify a preliminary selection of the appropriate treatment based on the functional condition (surface condition). This allows easier integration of structural information without disrupting the current approach based on functional condition. Additional details of the proposed PMS approach can be seen in the pooled fund summary report (Katicha et al. 2017).

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