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

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.

July 2017

TABLE OF CONTENTS

Report No.:	Report Date: July 2017	No. Pages: 30	Type Report: Final Contract	Project No.:
			Period Covered: October 2013 – February 2017	Contract No.: DTFH61-11-D-00009-T-13008

Title:
Demonstration of Network Level Pavement Structural Evaluation with Traffic Speed Deflectometer in Illinois

Key Words:
Traffic Speed Deflectometer, Deflection Testing, Non-Destructive Evaluation, Network-Level Decision Making, Structural Capacity Index

Author(s): Samer Katicha*, Ph.D., Gerardo Flintsch*, Ph.D., P.E., Shivesh Shrestha*, and Senthilmurugan Thyagarajan**, Ph.D.

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

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

Supplementary Notes:
The Contracting Officer's Representative was Nadarajah Sivaneswaran, HRDI-20.
* affiliated with VTTI; ** affiliated with ESCINC

Abstract:
The objective of this transportation pooled fund study was to carry out a 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 of this field demonstration effort in Illinois. 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 two sections, 4) compares TSD structural condition information with information obtained from the PMS and the Falling Weight Deflectometer (FWD), 5) 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 6) shows how the TSD measurements can be incorporated into a PMS decision process.
The results of the investigation suggested that the Condition Rating Survey (CRS) data may not be sufficient to accurately characterize the structural condition of the pavement and that TSD measurements favorably compare with FWD measurements. 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.

Field Demonstration of the TSD in Illinois

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 Illinois (June 28 and 30, 2014 and September 24 and 25, 2015), and 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 Illinois 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 section 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 roads, and typical thicknesses, sections with an estimated remaining fatigue life less than 2

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

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 on the same sections in year 2014 and 2015 and looking at measurement trends.

4. **How do TSD measurements compare with PMS and FWD data?** TSD measurements were compared with pavement management system (PMS) condition data. This was done by comparing SCI and effective structural number (SN_{eff}) from TSD data with the Condition Rating Survey (CRS) used in the PMS. TSD D0 measurements were also compared with FWD D0 measurements.

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 Illinois 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, 35.4, 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. 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:

$$S = \frac{V_v}{V_h} \tag{1}$$

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.

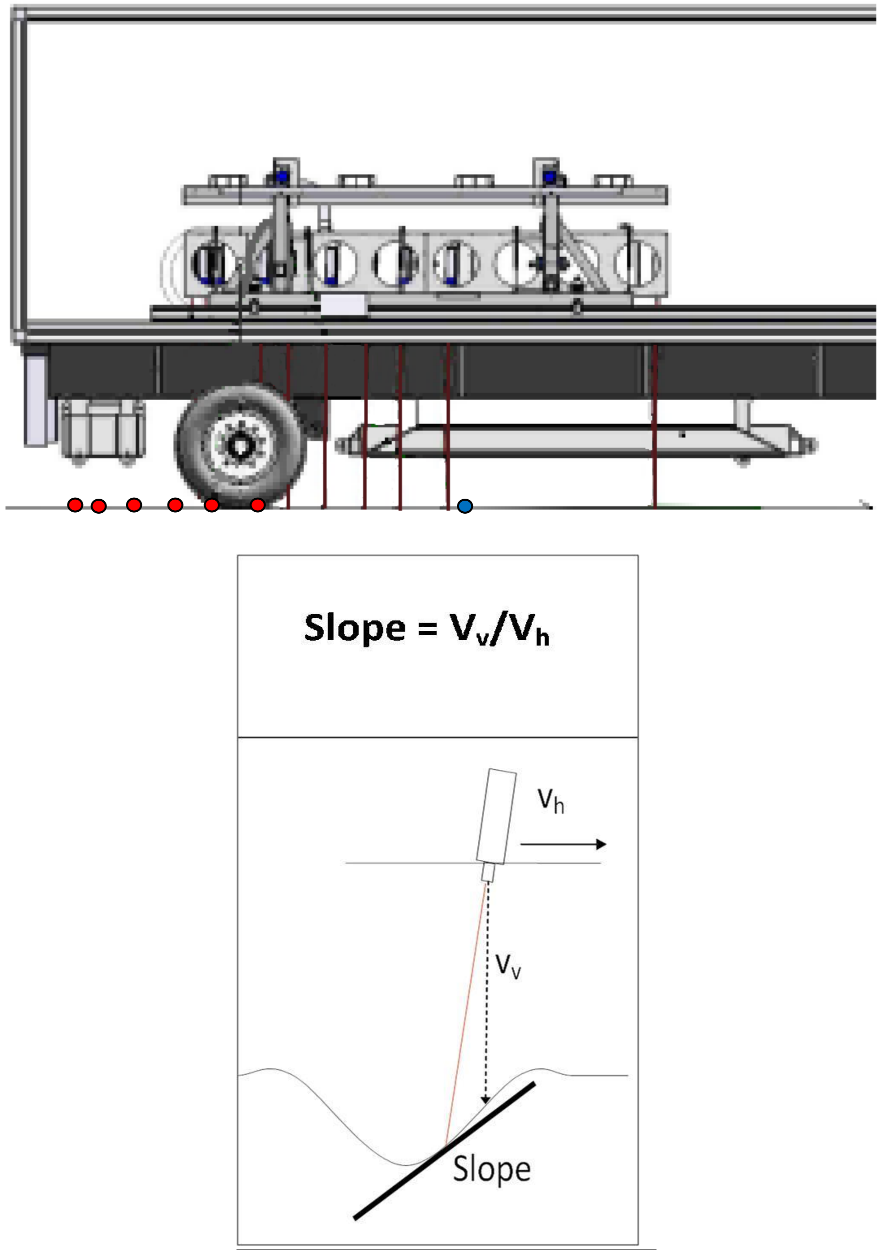


Figure 2. Schematic of the measurement principle of the TSD.

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.

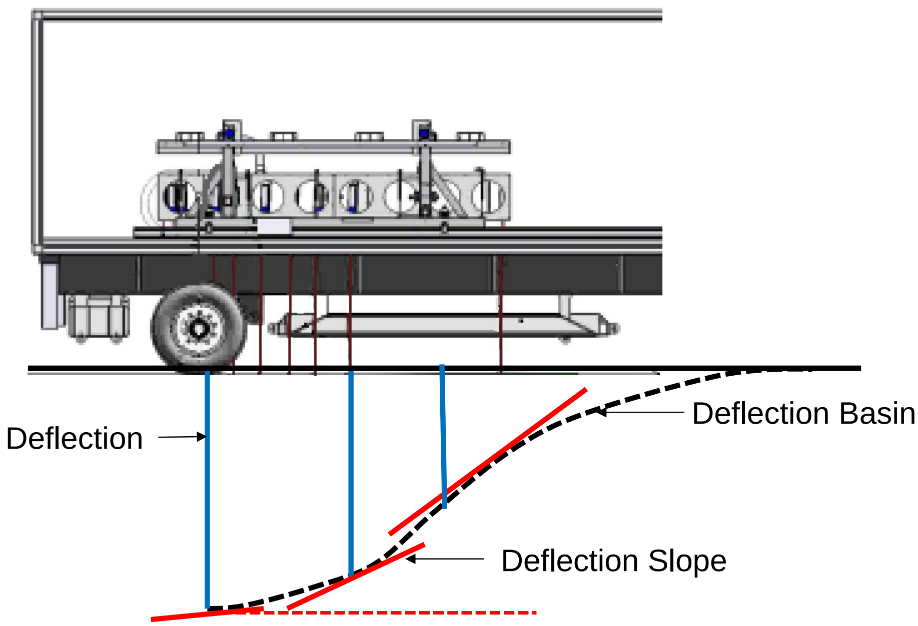


Figure 3. Relationship between the deflection basin, deflection, and deflection slope

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 measure 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 measurements, 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 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.

$$DSI = D100 - D300 \qquad (4)$$

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

$$\varepsilon = a(DSI)^{b} \text{ or } \varepsilon = a'(SCI\,300)^{b'} \qquad (5)$$

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

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

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 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 procedure should be considered as an intermediate solution until an accurate procedure is developed.
- To simplify data processing and analysis, the temperature corrected SCI presented in this report are all corrected to reference temperature of 70°F irrespective of the pavement type. The use of the current strain based temperature correction procedure is intended for flexible pavements and their use for composite pavements is questionable and yet to be verified. Therefore, for sections that are not flexible pavements, it is recommended to use the uncorrected SCI300 or other indices presented.
- 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 388 miles (141 in 2014 and 247 in 2015) were tested.

Overall Structural Condition of Tested Roads

Data processing includes mapping data from different files provided by Greenwood into 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 (ESALs) 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 implementation efforts by individual State highway agencies (SHAs).

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

2014			
S.No.	File Name	Road Name	Map Link
1.	T7201406280001	I57 South 1	https://goo.gl/maps/n6xCNJT1hBF2
2.	T7201406280002	I57 North 1	https://goo.gl/maps/GQPU6pEsd8n
3.	T7201406280003	I57 South 2	https://goo.gl/maps/yF2tdFLbKFJ2
4.	T7201406280004	I57 North 2	https://goo.gl/maps/79mUCNkq2nr
5.	T7201406280005	I57 South 3	https://goo.gl/maps/bxkQf5jynEN2
6.	T7201406280006	I57 North 3	https://goo.gl/maps/CuU1a2bZu5s
7.	T7201406280019	Champaign CH 1	https://goo.gl/maps/mop8QzUAWz72
8.	T7201406300001	I57 South – I74 East	https://goo.gl/maps/8x7anEQRdVD2
9.	T7201406300002	I74 West - I57 North	https://goo.gl/maps/RsNGhrQFfN22
10.	T7201406300003	I57 South 4	https://goo.gl/maps/61dwdSK96XT2
11.	T7201406300004	I72 West	https://goo.gl/maps/h7swrWc3ET82
12.	T7201406300005	SR29 East	https://goo.gl/maps/UmevQei4yYk
13.	T7201406300006	US51 North	https://goo.gl/maps/t1tGvDHatcA2
2015			
S.No	File Name	Road Name	Map Link
1.	T7201509240001	I57 South 1	https://goo.gl/maps/eWxCgQFy4Dv
2.	T7201509240002	Champaign CH 1	https://goo.gl/maps/tNF3mRxXcp82
3.	T7201509240003	I57 South 2	https://goo.gl/maps/5ssnxvDjk6G2
4.	T7201509240007	I74 East	https://goo.gl/maps/P1tcJPMSZo72
5.	T7201509240008	I74 West	https://goo.gl/maps/y6dEqKX2pcN2
6.	T7201509250001	I57 South 3	https://goo.gl/maps/2MTnFmun7px
7.	T7201509250002	US51 South	https://goo.gl/maps/kNaJGaddG5w
8.	T7201509250003	SR29 West	https://goo.gl/maps/w3J3n2hcoRD2
9.	T7201509250004	I72 East	https://goo.gl/maps/AmWu7QPEdR82
10.	T7201509250005	I72 West	https://goo.gl/maps/TjAqDV9kpQ52
11.	T7201509250006	I155 North	https://goo.gl/maps/CWYRN3eLdcU2
12.	T7201509250007	I39 North	https://goo.gl/maps/1oZNxtBp4HQ2
13.	T7201509250008	I39 South	https://goo.gl/maps/1uj1TtpdwFA2
14.	T7201509250009	Champaign CH 1	https://goo.gl/maps/wX8iCjy9sVu
15.	T7201509250010	I57 South 4	https://goo.gl/maps/PCD2C2sQuMP2

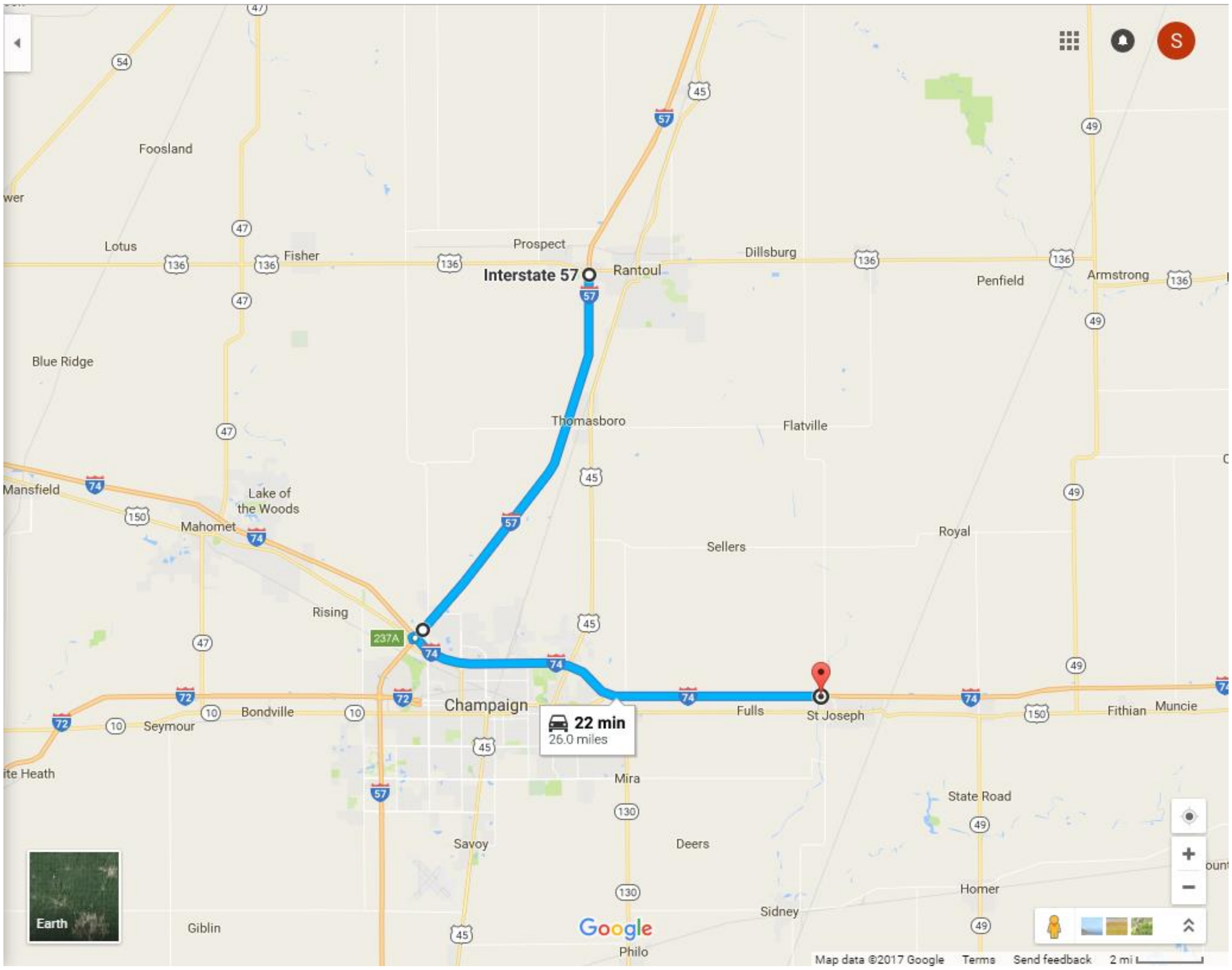


Figure 4. Example showing link for file T7201406300001 of I57S-I74E from Table 1

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 thicknesses) 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 were grouped in one of three road categories based on AC layer thickness as shown in Table 2. In each pavement segment, the number of repetitions to failure, Nf, was computed using the Asphalt Institute equation (Asphalt Institute. 1982).

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

where C is the calibration coefficient, ε_t is the tensile strain and E is the stiffness of the asphalt mixture (psi). The tensile strain at the bottom of the AC layer corresponding to a 9000-lb. loaded dual tire configuration with a 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 wheelpath cracking, respectively (Finn et al., 1977). A C value of 13.3 was chosen for Interstate and Primary road categories and 18.4 for secondary roads. To convert remaining ESALs to remaining life, the following default levels of annual ESAL traffic were considered for the three road categories:

- Interstate: 1.4 million ESALs – equivalent of about 6500 ADTT (or 2000 singles, 4000 doubles and 500 trains or triples)
- Primary: 0.2 million ESALs – equivalent of about 950 ADTT (or 700 singles, 220 doubles and 30 trains or triples)
- Secondary: 0.07 million ESALs – 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 ESALs (annual traffic * 2 years). Similarly, a secondary road is considered as 'fair' condition if the computed N_f is lower than 0.35 million ESALs (annual traffic * 5 years) but greater than 0.14 million ESALs (annual traffic * 2 years). Average index 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 the 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 categorize the pavement segment as good/fair/poor. For example, in a Primary road section, if the SCI computed from TSD measurement is 5.0 mils, then the pavement segment will be categorized as 'Fair'.

Table 2. Thresholds for SCI300 (TSD) and DSI

Road Category	AC layer thickness, inches	Annual Traffic, million ESALs	Threshold for Fatigue Cracking at Wheelpath, %	Threshold for Poor			Threshold for Fair		
				N_f, million ESALs	SCI300, mils	DSI, mils	N_f, million ESALs	SCI300, mils	DSI, mils
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 this procedure. The SCI300 (and DSI) were 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 Illinois 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 two road conditions. 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.

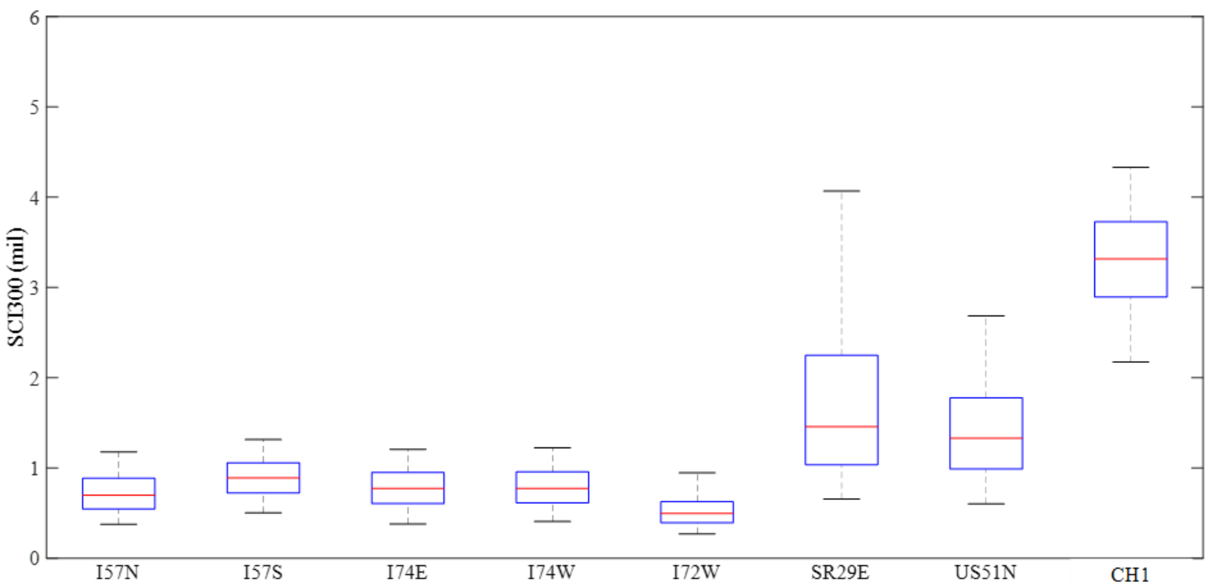


Figure **8** and Figure 9 show the overall structural condition in box plots, as indicated by the temperature-corrected SCI300, for the 2014 and 2015 tests, respectively. The (red) line represents the median of the measurements, the (blue) box represents the 50-percent range (25 to 75 percent), and the (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. Note that 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 the same in both years.

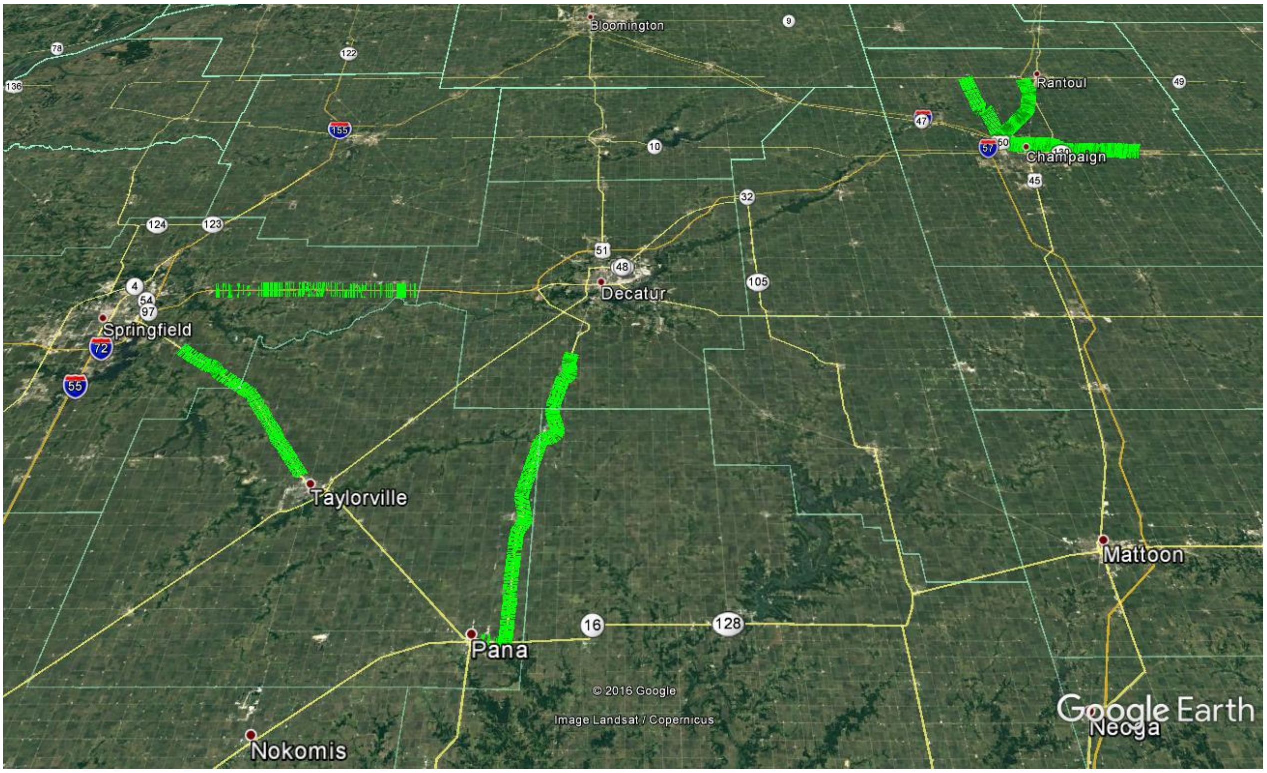


Figure 5. Color-coded estimated structural condition of tested roads in 2014 with Good (green), Fair (yellow), and Poor (red) ratings (© 2016 Google Image Landsat / Copernicus).

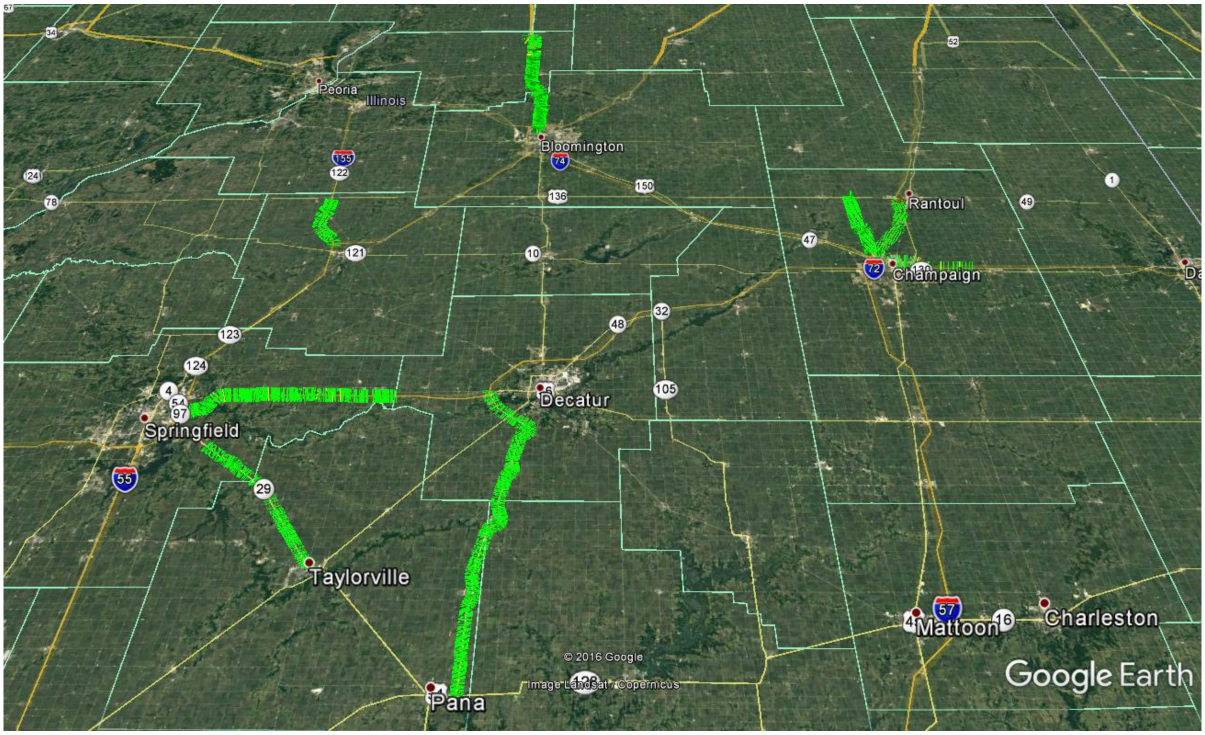


Figure 6. Color-coded estimated structural condition of tested roads in 2015 with Good (green), Fair (yellow), and Poor (red) ratings (© 2016 Google Image Landsat / Copernicus).

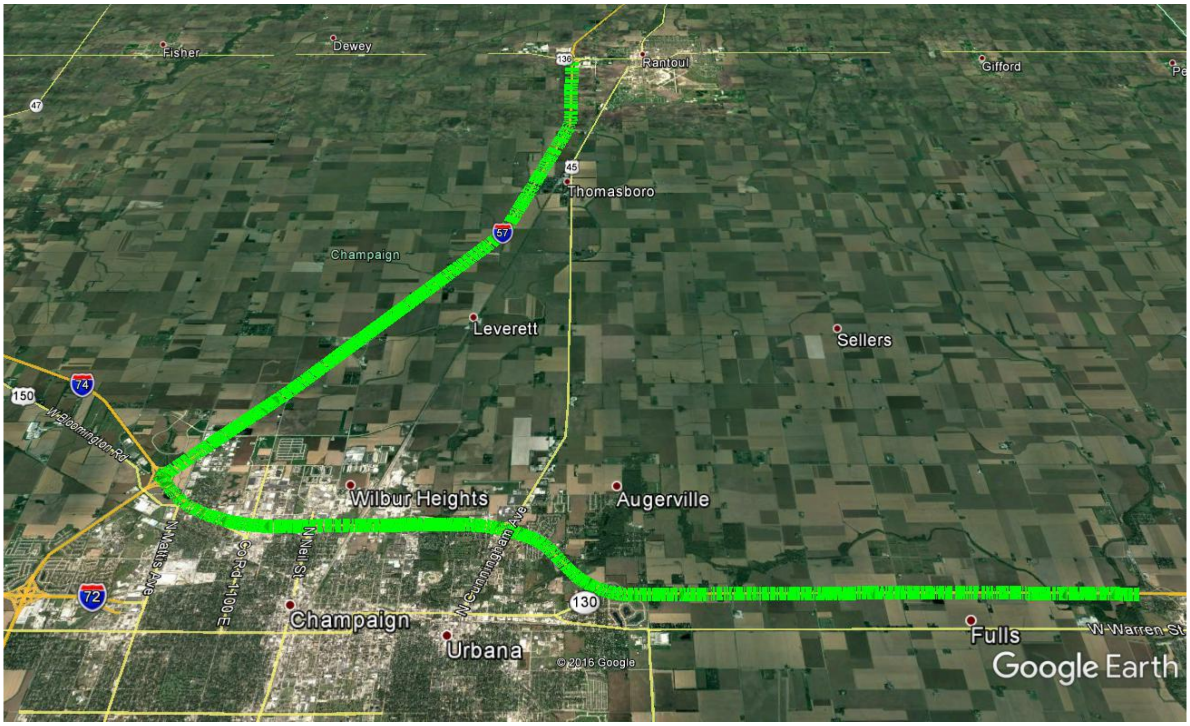


Figure 7. Detailed example of estimated pavement structural condition on I-57 and I-74 near Champaign tested in 2014 (© 2016 Google Image Landsat / Copernicus).

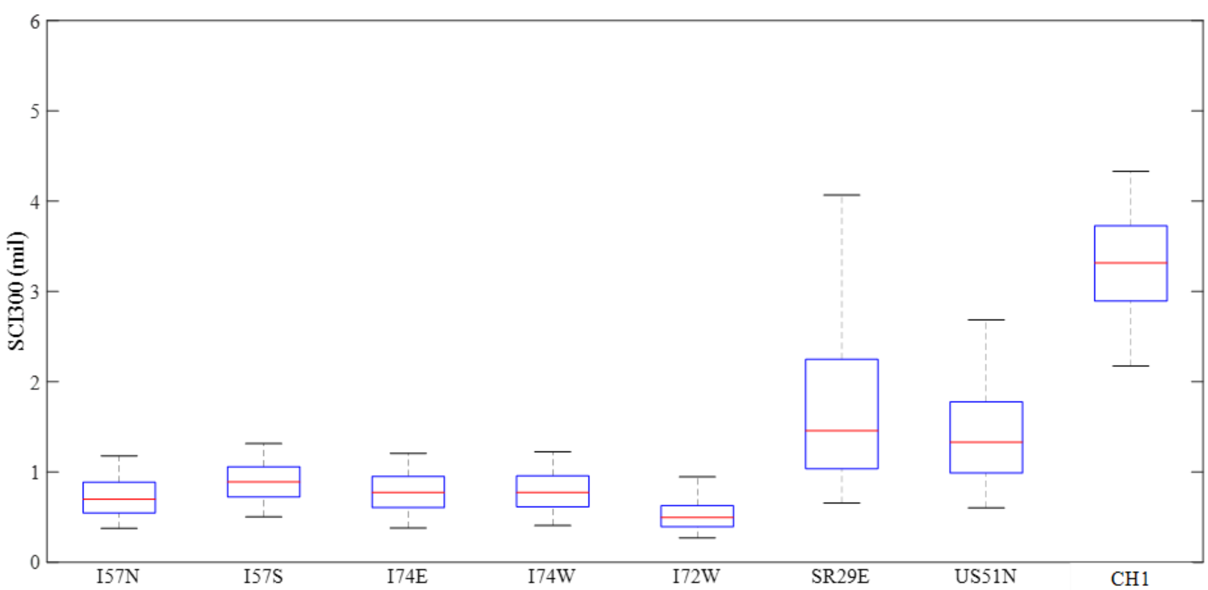


Figure 8. SCI300 box plot of tested roads in 2014.

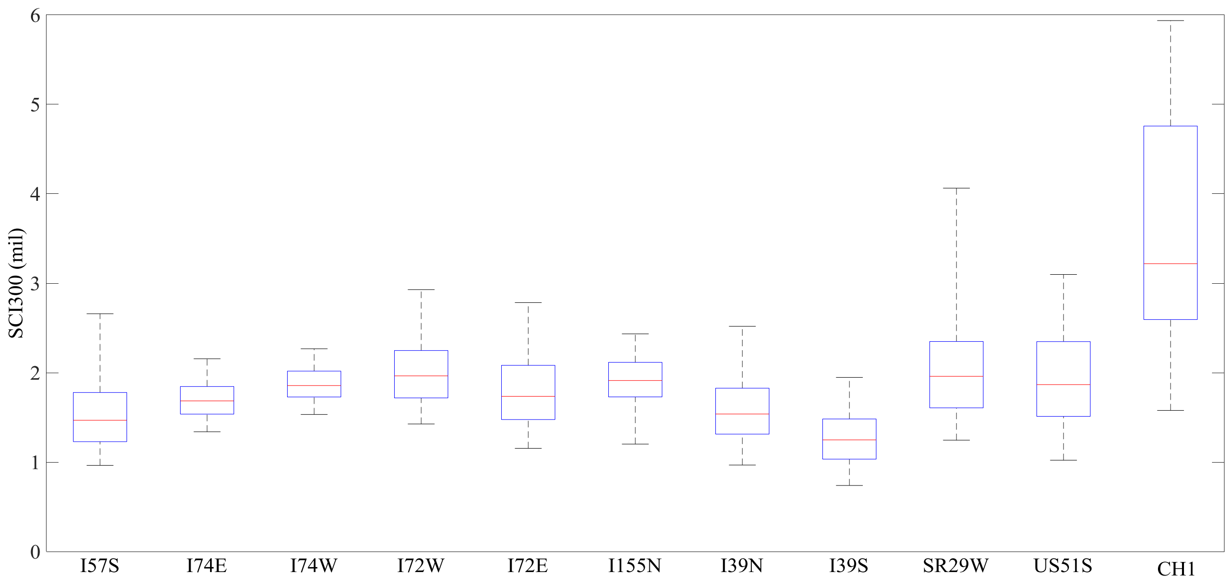


Figure 9. SCI300 box of tested roads in 2015.

RESEARCH QUESTION 3: HOW REPEATABLE ARE TSD MEASUREMENTS?

Figure 10 shows the temperature corrected SCI300 repeated measurements (in 2014 and 2015) on an 11-mile section of Champaign CH1 (Figure 11). The measurements in the two years follow similar trends showing good repeatability of the TSD, except around 5 mile distance.

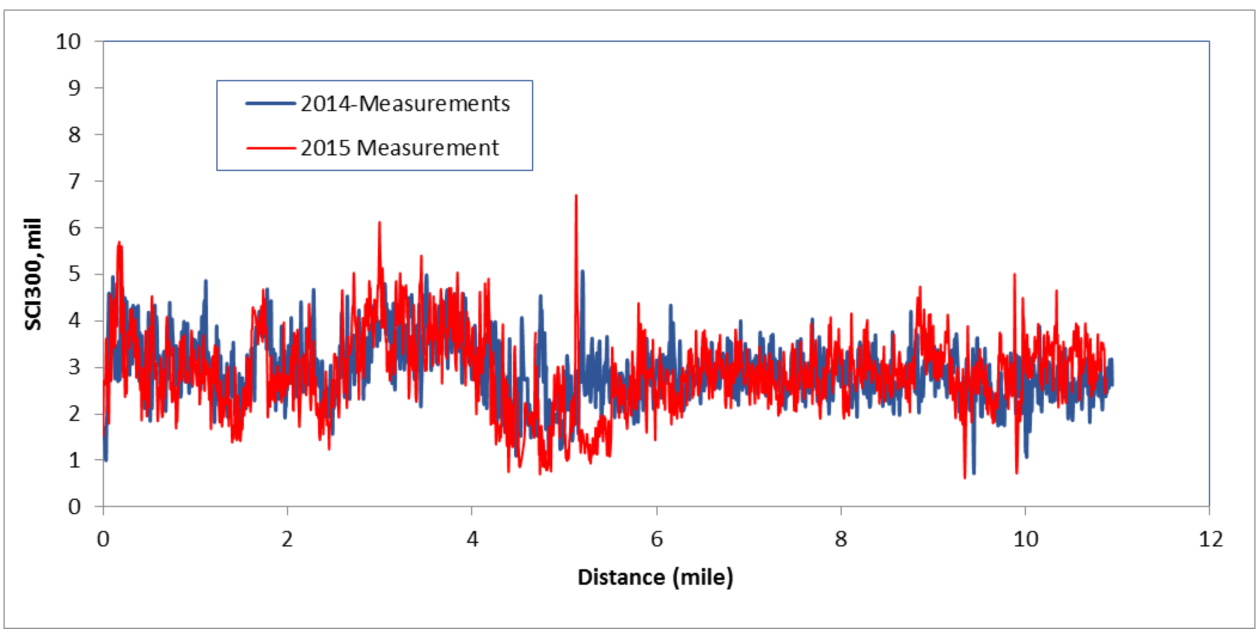


Figure 10. Temperature corrected repeated TSD tests (SCI300) on Champaign CH1

(https://goo.gl/maps/mop8QzUAWz72)

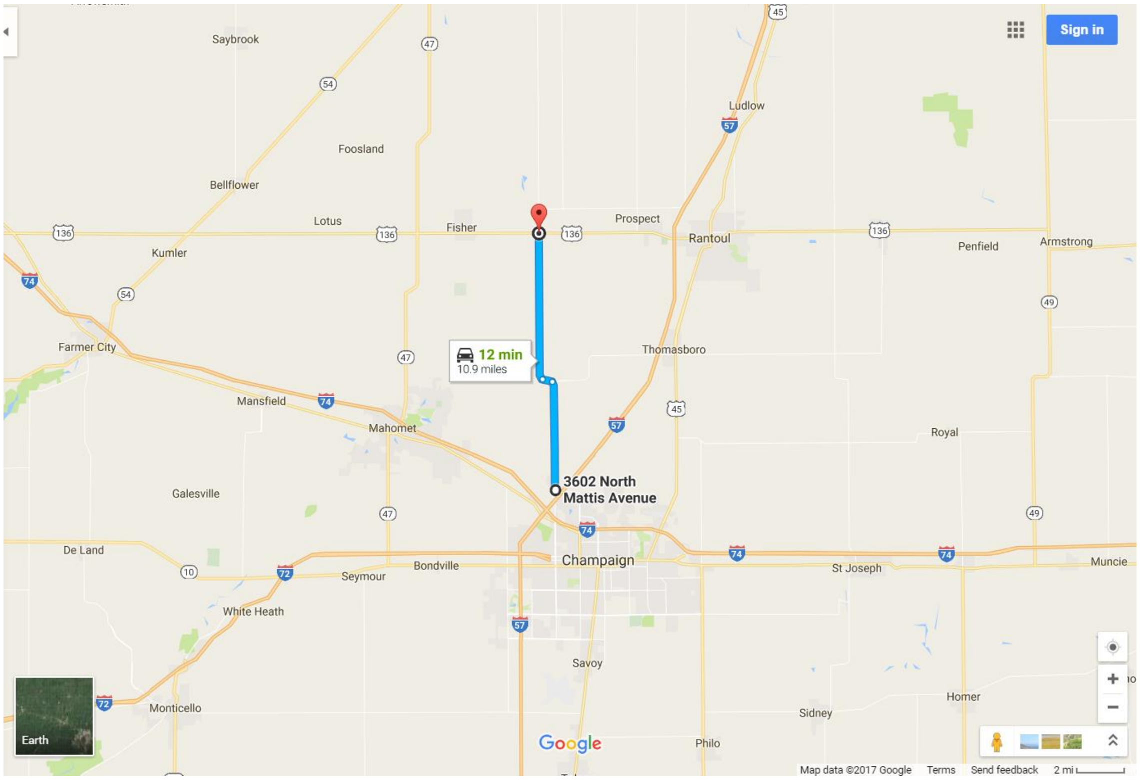


Figure 11. Repeated tested section on Champaign CH1 with results shown in Figure 10

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

Pavement management data was provided by Illinois for some of the tested roads. Figure 12 shows a comparison between the TSD calculated SCI300 and the CRS used by Illinois to rate the road condition on US51 south (see Figure 14). CRS uses a scale from 1 to 9 with 9 being new pavement. The SCI300 and the CRS do not reflect the same condition. For example the road section between mile 12 and 17 has low CRS (4.1) and is in poor condition, however the SCI300 shows the road in a good structural condition. Also, from distance 17 to 27 the SCI300 was uniform, while CRS varies from 6.3 to 8.8.

Figure 13 shows the TSD calculated SN_{eff} for the same road. The SN_{eff} takes into account the pavement deflection as well as the pavement thickness. The calculation of the TSD SN_{eff} is performed using the method of 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.

d(0) used in the calculation was corrected to a reference temperature of 68°F using the procedure described in Lukanen et al. (2000). $d(1.5H_p)$ was assumed to be farther enough and less influenced by the AC layer, consequently less affected by AC layer temperature. Hence it was not temperature corrected. This assumption was necessary until a robust temperature correction method is developed for correcting SIP.

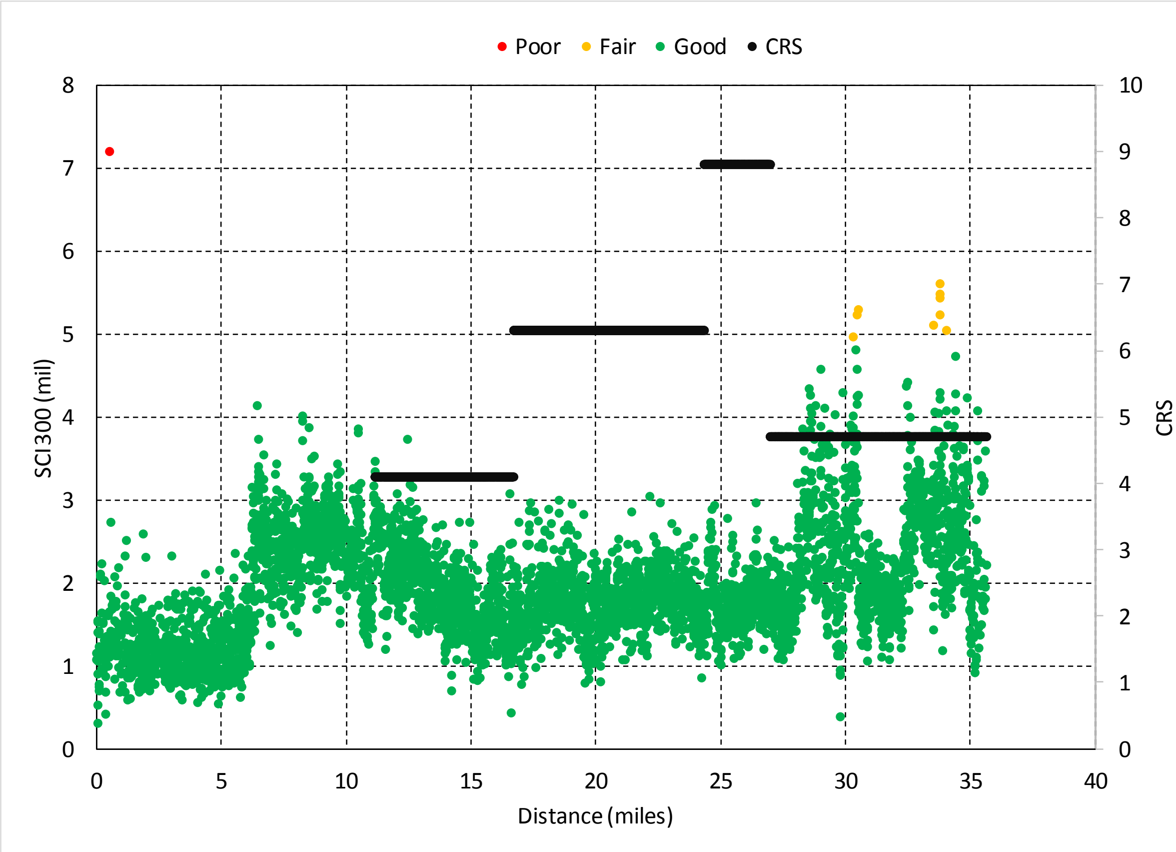
2. Determine the existing pavement SN_{eff} as;

$$SN_{eff} = k_1 SIP^{k_2} H_p^{k_3}$$

where for asphalt pavements, k_1 = 0.4728, k_2 = -0.4810, k_3 = 0.7581

Since the CRS data consists of 4 sections with uniform CRS, the best four sections decomposition of TSD calculated SN_{eff} is also shown in Figure 13. Clearly the decomposition of TSD calculated SN_{eff} is very different from the CRS sections that were based on surface condition, which shows the benefits of performing network level structural evaluation in better characterizing structural condition compared to only rating the surface condition.

Figure 13 also includes SN_{eff} computed 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 lower than the one estimated based on layer thickness information and default layer coefficients, indicating structural deterioration since initial construction. Also, the structural deterioration is non-uniform over the pavement segment length. Note that the pavement section from distance 27 miles until the end is a composite pavement consisting of 8.5 inches of asphalt concrete and 8.0 inches of Portland cement concrete. Therefore, the calculation of SN_{eff} in that section should be considered for illustrative purposes rather than providing accurate structural condition, because the temperature correction on D0 assumes it is a flexible pavement.



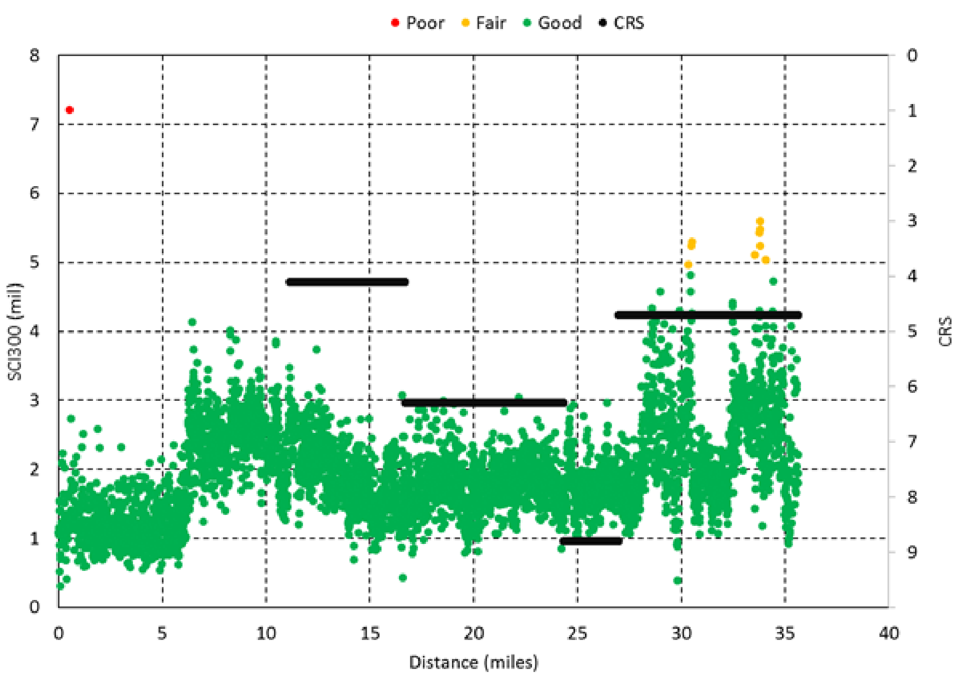


Figure 12. Comparison of TSD SCI300 measurements collected in 2015 and CRS on US51 (https://goo.gl/maps/kNaJGaddG5w).

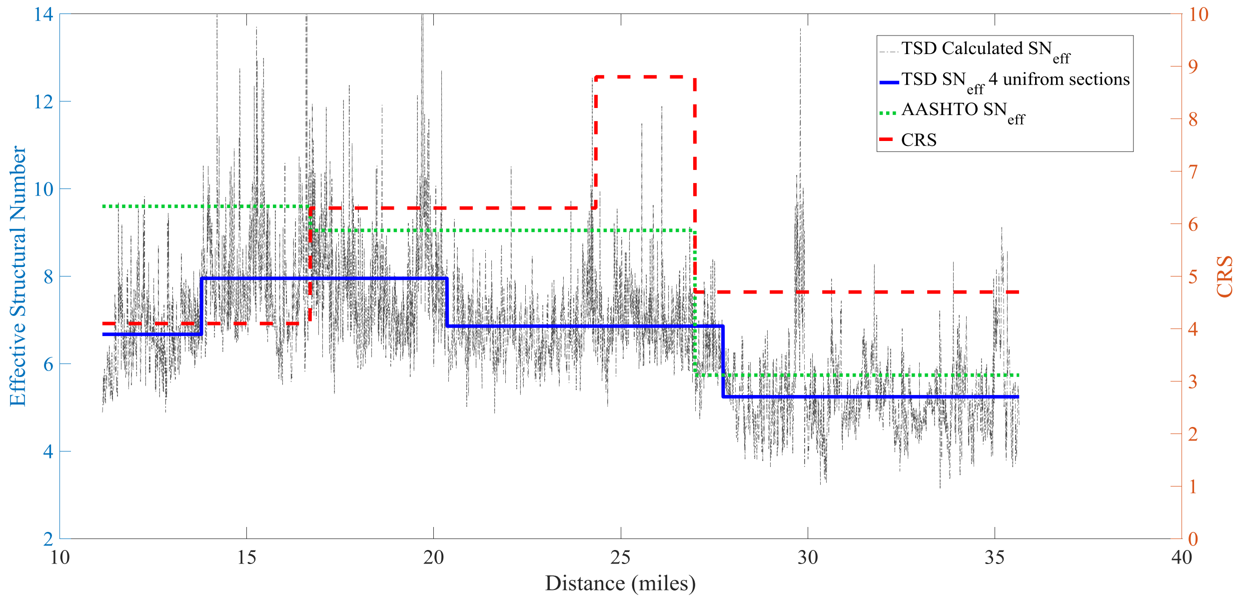


Figure 13. Calculated SNeff on US51 South with measurements collected in 2015 (https://goo.gl/maps/kNaJGaddG5w).

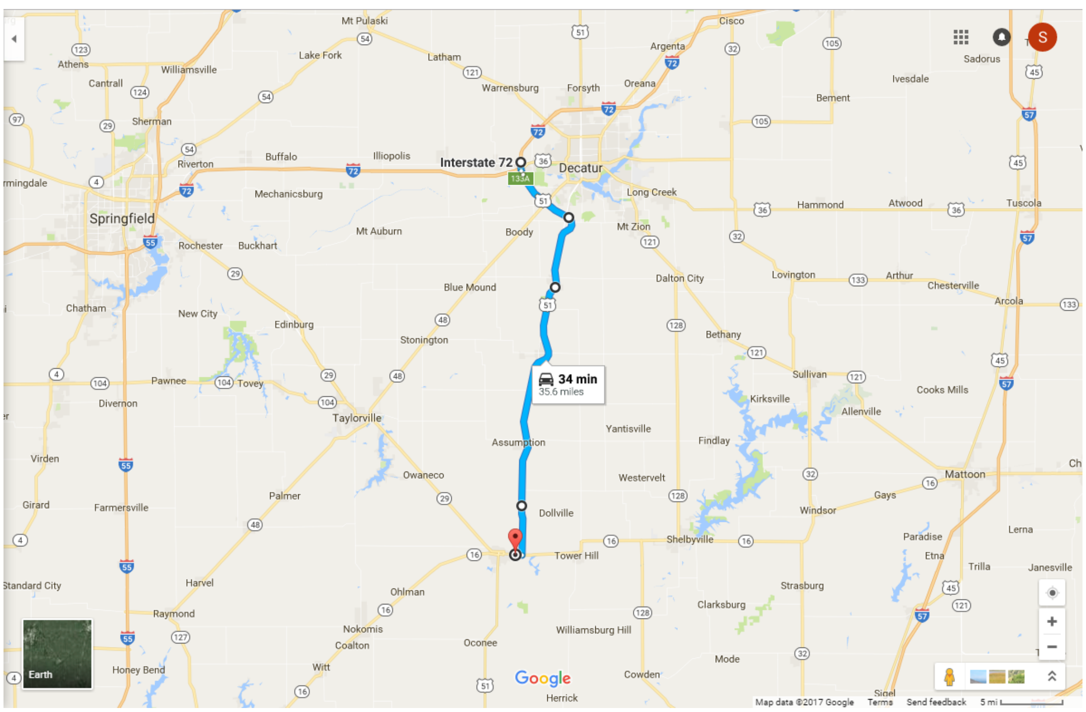


Figure 14. Location of calculated SNeff shown in Figure 13 on US51 South

Figure 15 shows TSD and FWD D0 measurements on SR29 East. The TSD measurements correspond to the file designated by “T7201406300005”. FWD measurements were collected at 0.1 mile intervals on August 19 and August 21, 2014 while TSD measurements were collected at 33 ft (10 m) intervals on June 30, 2014. The moving average of TSD measurements shown in Figure 15 uses a 0.1 mile window which reflects the FWD test spacing. The two devices show similar D0 trends especially in the highlighted area between miles 11 and 16. Figure 16 shows the Area Under Pavement Profile (AUPP), calculated using equation 12, obtained from TSD and FWD measurements on SR29. Due to inherent differences between the two devices, the comparison should be limited to only trends as explained before. Also, the measurements were not corrected for temperature or seasonal variation expected between the time of FWD and TSD tests.

$$AUPP = \frac{5d_0 - 2d_{300} - 2d_{600} - d_{900}}{2} \quad (12)$$

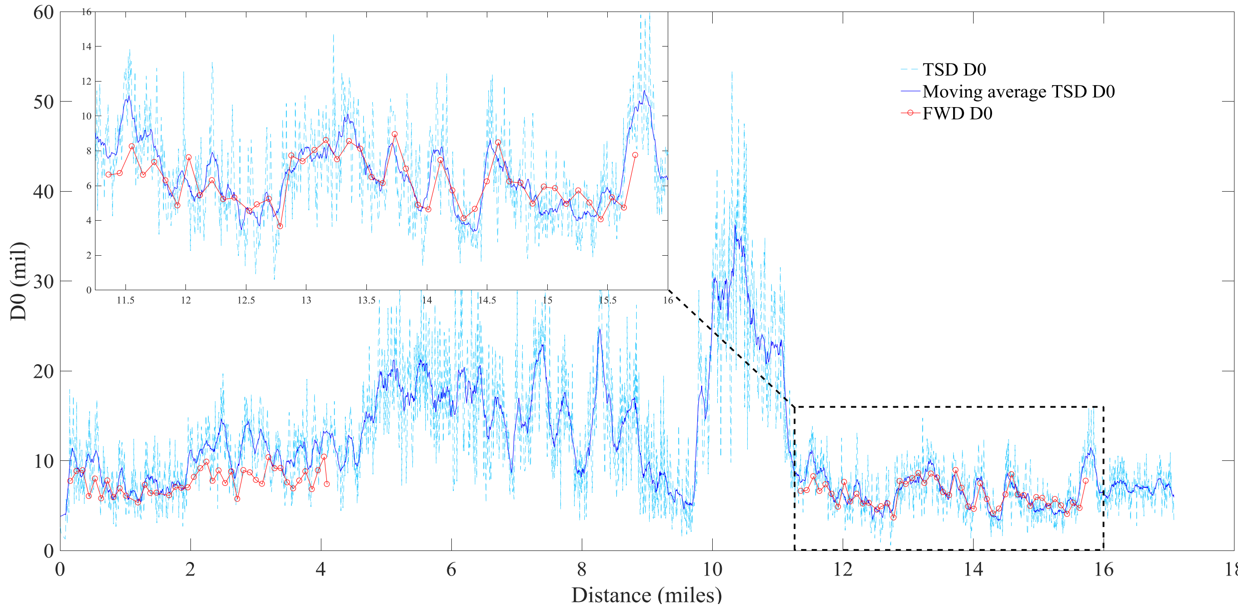


Figure 15 Comparison of TSD D0 and FWD D0 on R29 East (https://goo.gl/maps/UmevQei4yYk)

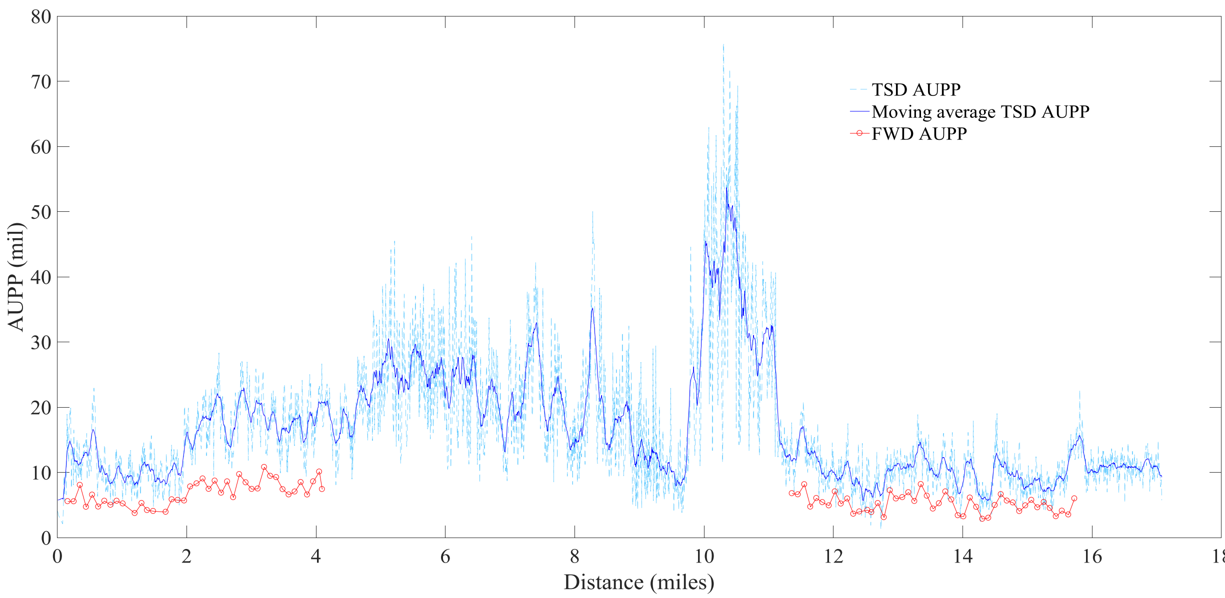


Figure 16 Comparison of TSD AUPP and FWD AUPP on SR29 East
(https://goo.gl/maps/UmevQei4yYk)

The fundamental differences between FWD and TSD measurements are how the load is applied and how the pavement response to the load is measured. Figure 17 shows the time history during a typical FWD test. Dynamic loading causes the peak deflections to lag the peak applied load with the effect becoming more pronounced for the sensors farther away from the applied load. For FWD calculations of AUPP, the peak deflection of each sensor is used. In the TSD calculations of AUPP, the measurements are made at the time of peak load when the pavement deflections are yet to reach their peak values. Therefore, the results from each device represent a different stage of the pavement response to the applied load. Furthermore, the FWD applies an impact load at a static location while the TSD load is continuously moving. These differences among others lead to differences in the reported deflections and indices from each device. However, the two devices should show similar trends for deflections and indices as observed in the two figures (i.e. they are correlated).

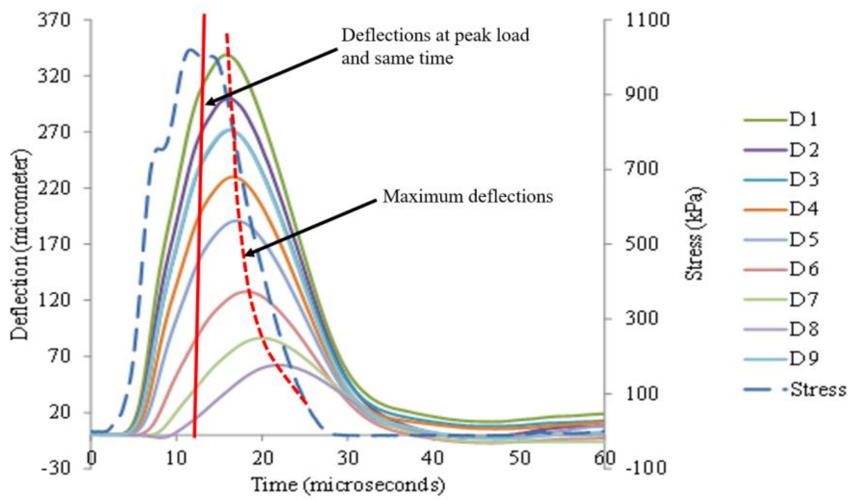


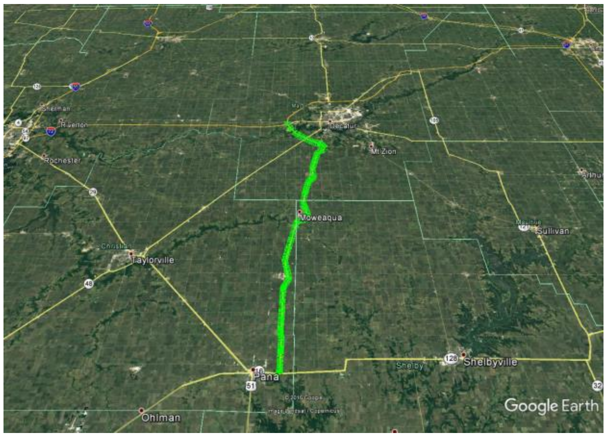
Figure 17 Example of FWD time history from LTPP section 169034 taken from Chatti et al. (2017)

RESEARCH QUESTION 5: HOW CAN WE USE THE INFORMATION OBTAINED FROM TSD MEASUREMENTS?

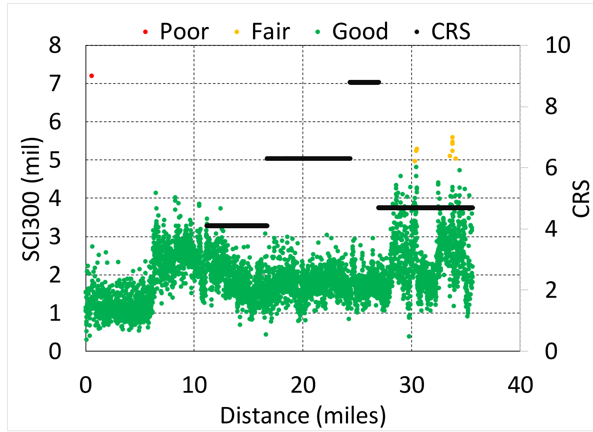
In this section we present examples on how TSD measurements can be used to help better manage pavement sections.

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 18 shows an example of such a classification with measurements collected on US51 south 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 19 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 18. Identified Strong (green) and Weak (red) sections on US51S based on thresholds obtained from Table 2: (a) Google Earth plot (© 2016 Google Image Landsat / Copernicus); (b) scatter plot

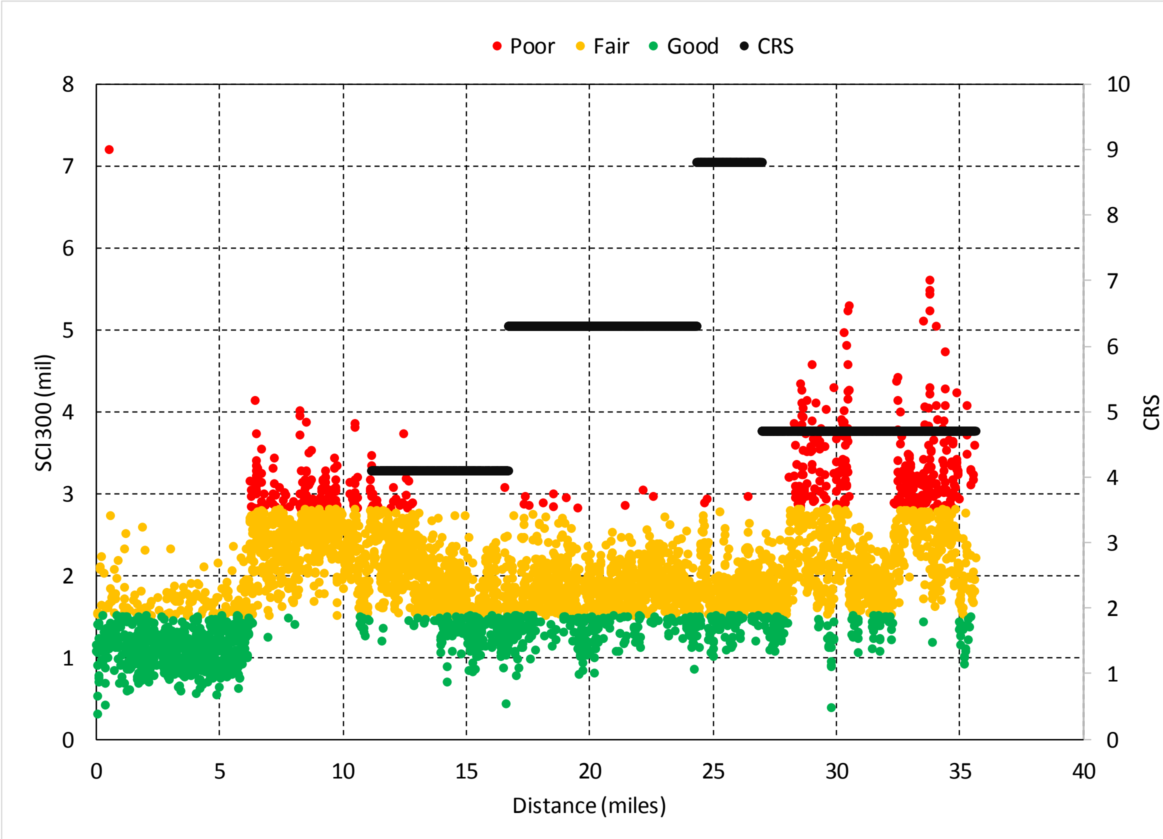


Figure 19 Classification of structural condition on US51S south based on percentile: 25th percentile and lower represents good structural condition and 90th percentile and higher represents poor structural condition

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 20 shows an example of the estimated tensile strain profile for US51 south (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 conditions and an estimate of the remaining structural life of the pavement as illustrated in Figure 21. Practical implementation of this procedure would be in the development of a structural index relationship with remaining fatigue life as illustrated in Figure 22 for DSI.

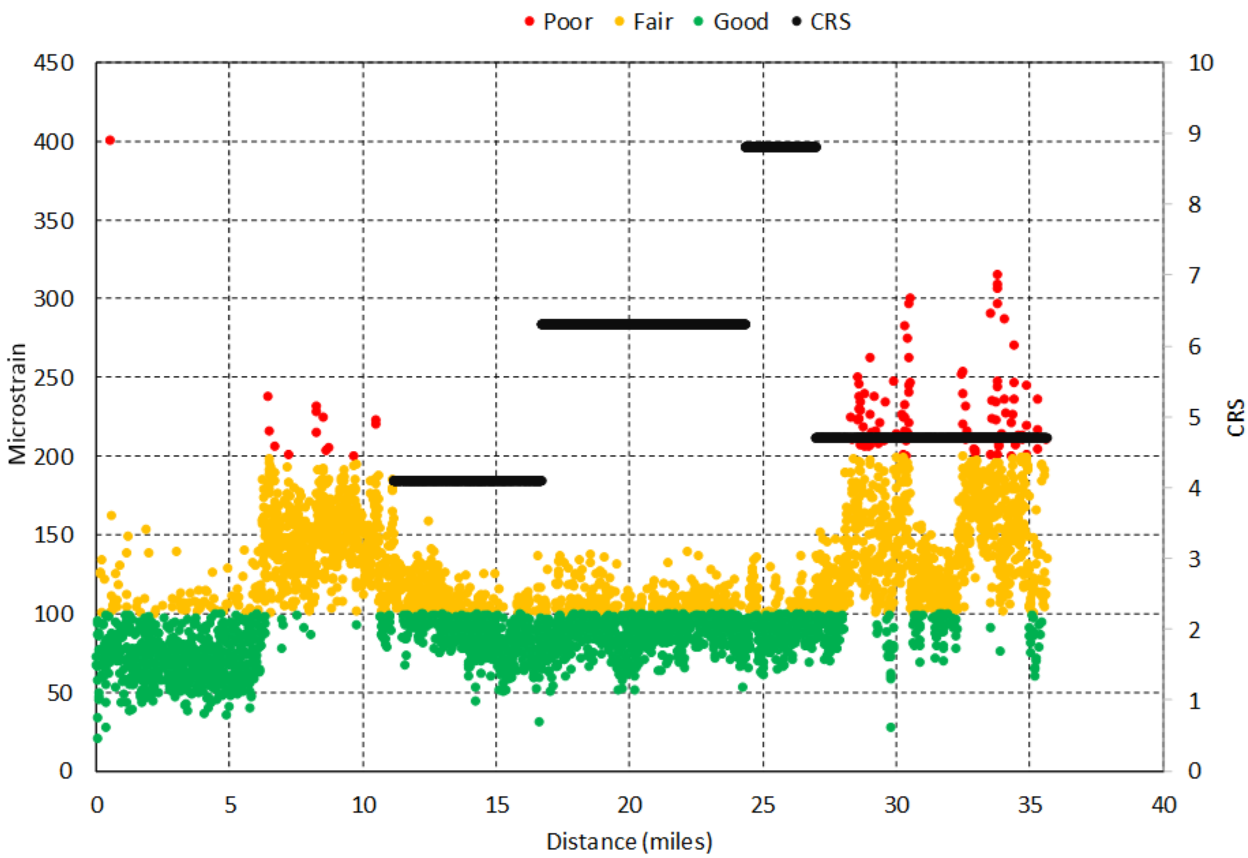


Figure 20. Estimated tensile strain at bottom of asphalt layer on US51S

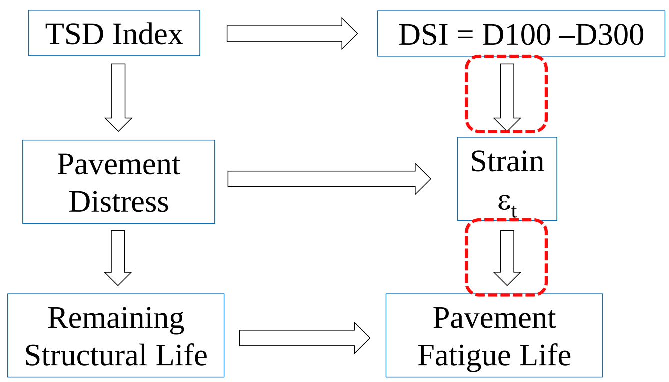


Figure 21. Link between DSI and estimated pavement fatigue life.

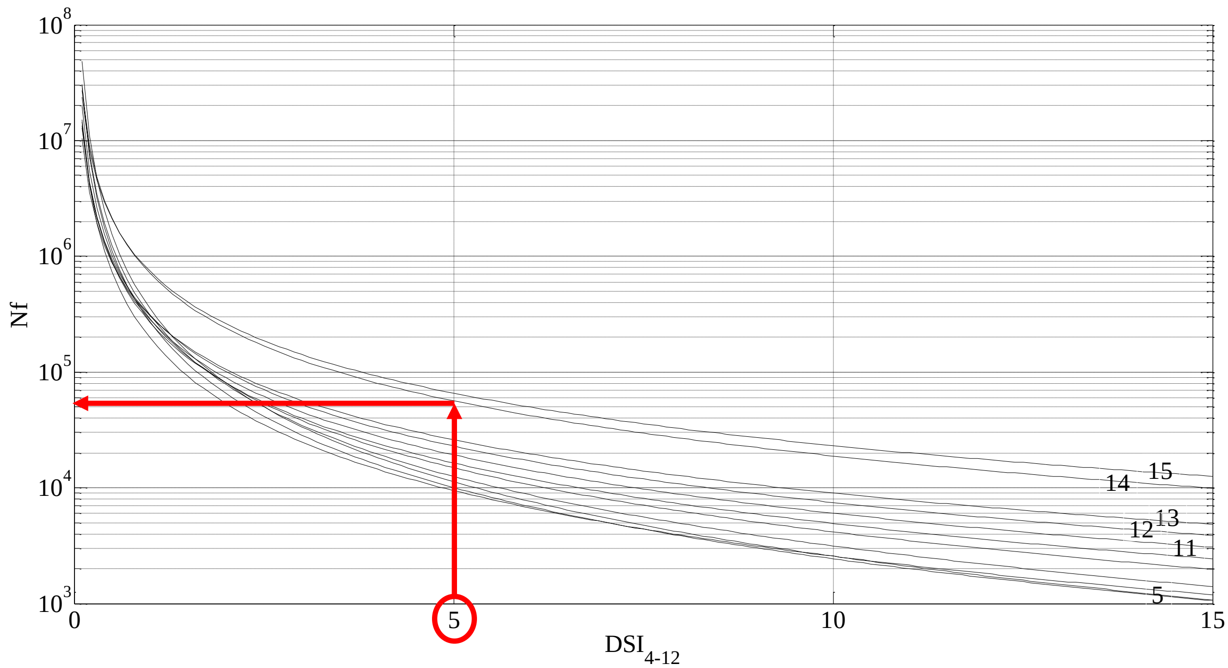


Figure 22. Fatigue life curves for TSD DSI (Number on the curves represent AC layer thickness).

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 within 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 23). 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).

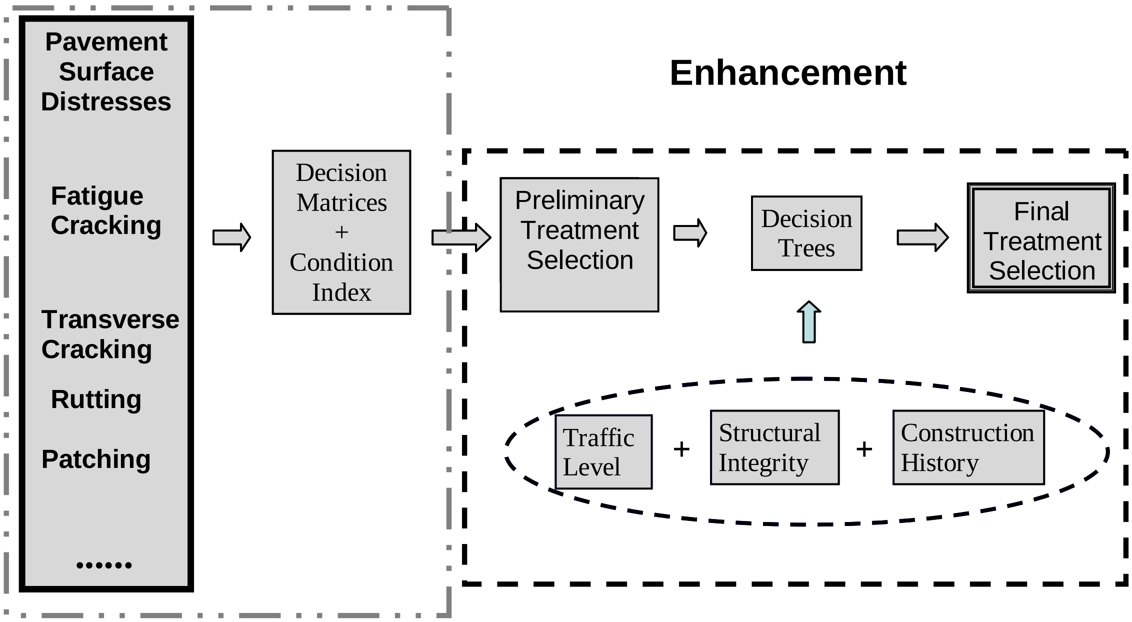


Figure 23. DOT two-phase decision process (Virginia Department of Transportation, 2008).

CONCLUSION

This report summarizes the results of TSD testing performed in Illinois. 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 and FWD 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 (the FWD measures the deflection) from which the deflections can be indirectly 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 measurements on an 11-mile section of Champaign CH1 show good repeatability of TSD calculated SCI300 between 2014 and 2015. Results presented in the summary report for the project include more testing from other states that also show good repeatability in flexible pavements (Katicha et al. 2017).

4. **How do TSD measurements compare with PMS and FWD data?** Comparing TSD indices SCI300 and SN_{eff} with CRS on US51 showed that the condition recorded in the CRS may 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 (i.e. structural and functional condition). Comparison between the TSD and FWD shows the two devices produce similar trends of D0 and AUPP. This agreement with the FWD (de facto "reference device") validates the use of the TSD to evaluate the network level structural condition.

5. **How can we use the information obtained from TSD measurements?** TSD measurement information can help to better manage pavement sections. TSD measurements were used to identify strong and weak sections. 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 decision process from the PMS (more details of the proposed PMS approach can be seen in the pooled fund summary report).

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.

Chatti, K., Kutay, E., Lajnef, N., Zaabar, I., Sudhir, V., Lee, H. (2017) *Enhanced analysis of falling weight deflectometer data for use with the Mechanistic-Empirical Flexible pavement design and analysis and recommendations for improvements to falling weight deflectometers*, Final Contract Report FHWA-HRT-15-063, Federal Highway Administration, Washington, DC 20590.

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, Transportation 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.