

VIRGINIA TECH

OVERVIEW OF TSDD TECHNOLOGIES AND THEIR NETWORK- AND PROJECT-LEVEL APPLICATIONS

TPF-5(385) Pavement Structural Evaluation with Traffic Speed Deflection Devices

TASK 1: LITERATURE REVIEW

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Overview of TSDD Technologies and Their Network and Project Level Applications

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Abstract

This document provides an overview of continuous deflection measuring devices (traffic speed deflection devices, TSDDs) tailored for department of transportation engineers that deal with pavement design, evaluation, and management. The review includes information on 1) recently available TSDDs, 2) data analysis methods used with TSDDs, 3) evaluations of the devices, and 3) applications. To limit the length of the document and keep the focus on practice, only the most important concepts are presented. The aim is to offer a working knowledge of the devices and the data they collect, show examples of evaluations of the devices (repeatability and comparison with the falling weight deflectometer), and show how the data is used to obtain structural indicators that can support engineering decisions (network and project level). The TSDD devices described are the traffic speed deflectometer (TSD), the rolling wheel deflectometer (RWD), and the Raptor, with more focus on the TSD because it is the device that has been most extensively used and tested and the only one currently available in the United States.

Introduction

It is widely accepted in the pavement engineering community that the structural condition of the pavement is an important indicator of the health of the pavement network that can help select more cost-effective maintenance and rehabilitation treatments (Zaghlou et al., 1998; Bryce et al., 2013; Katicha et al., 2020; Maser et al., 2017; Shrestha et al., 2019; Zhang et al., 2016; Elseifi et al., 2011, 2019; Thyagarajan et al., 2019; Steele et al., 2015). The falling weight deflectometer (FWD) has historically been the device of choice for structural evaluation of pavements. However, the FWD is a stationary testing device that is not well-suited for network-level testing. This drawback of the FWD is one of the main factors that led to the development of traffic speed deflection devices (TSDDs) that can evaluate the pavement structural condition while moving at or near traffic speed.

As a result of long-accumulated experience with the FWD, many of the methods used to analyze FWD deflection data have been modified to analyze TSDD deflection data. Modifications are needed because, while both devices apply a load to the pavement and measure its response, the way the load is applied and what response is measured are not exactly the same. Generally, modifications consist of recalibrating models developed for the FWD using TSDD-collected data. This approach, when done appropriately, is important for the initial adoption of TSDDs for pavement management applications and to a more limited extent, project-level applications. It is expected that improved, more direct methods of analyzing TSDD data will be developed and refined in the future, providing better support for engineering design and rehabilitation decisions.

This document presents an overview of 1) TSDDs, 2) data analysis methods used to interpret TSDD measurements, 3) results of studies that have evaluated the repeatability and reproducibility of TSDDs, and 4) network-level and project-level applications of TSDDs.

Available Devices

Currently, the Greenwood Traffic Speed Deflectometer is the only available TSDD in the United States. However, this document also describes the ARA Rolling Wheel Deflectometer, and the Dynatest Raptor, as these devices could potentially become available in the future. The ARA

RWD had been under development and demonstration since 2002, but was decommissioned in 2020. The Raptor was built in 2018, and limited demonstrations were performed in the United States in 2019. As of October 2020, the Raptor has been purchased by the European company Rambol and sent back to Europe. Future availability of the device in the United States is not known. To date, one RWD, three Raptor devices, and 18 TSD devices have been built, with one TSD operating in the United States.

Rolling Wheel Deflectometer

The first working prototype of the RWD was launched in 2003 for demonstration projects at numerous field tests throughout the United States (Jitin et al., 2006; Rada and Nazarian, 2011; Wilke, 2014; Steele et al., 2015; Flintsch et al., 2013; Rada et al., 2016). The first generation RWD used distance laser measurements with an accuracy of 18 μm (0.7 mils) to determine the pavement response to loading. As shown in Figure 1, the first-generation RWD consisted of a single double-wheeled axle trailer 53-ft (16-m) long. The data sampling frequency was 2 kHz, and the deflection measurements were reported every 100 ft (30.5 m) (Jitin et al., 2006; Flintsch et al., 2013; Rada et al., 2016), or at 0.1-mi (0.16 km) intervals by averaging the individual laser measurements (Steele et al., 2015; Rada et al., 2016). Averaging reduced the random errors in the measurements and the error caused by other factors such as the texture, roughness, and dynamic movement of the RWD trailer. The lasers used were 16-kHz LMI-Selcom lasers mounted on a longitudinal beam ahead of the trailer's rear axle. The pavement deflection was calculated using the "spatially coincident methodology," illustrated in Figure 2. Three reference sensors—A, B, and C—were used to determine the reference profile of the undeflected pavement. As the RWD moves forward, Sensors B, C, and D measure the distances previously measured by Sensors A, B, and C. The pavement deflection is then calculated as follows:

$$Deflection = [(B_2 - 2C_2 + D_2) - (A_1 - 2B_1 + C_1)] \quad (1)$$

where

A_1, B_1, C_1 = initial readings of Sensors A, B, and C (see Figure 2) at time t_0; and

B_2, C_2, D_2 = readings of Sensors B, C, and D (se Figure 2) at time t_1 after the RWD has traveled 8 ft.

After a comprehensive evaluation by Rada et al. (2016), the RWD underwent a major redesign. That second-generation RWD relied on imaging technology to determine the pavement response to the wheel load and was field tested in 2019. The results of this field testing are reported by Steele et al. (2020). In 2020, the RWD was decommissioned.

Figure 1. RWD (from Steele et al., 2002).

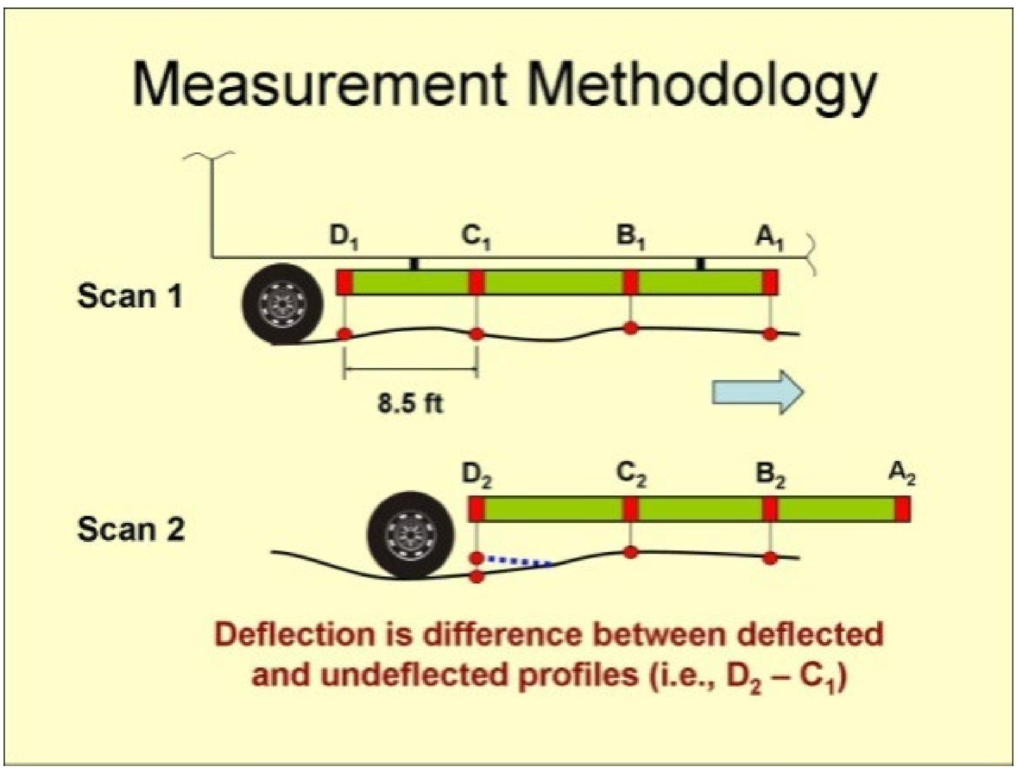

Figure 2. Schematic illustrating "spatially coincident methodology" to determine pavement deflection (from Steele et al., 2002).

Rapid Pavement Tester (RAPTOR)

The RAPTOR (Figure 3) was developed jointly by Dynatest and the Technical University of Denmark. It is an RWD device that uses an array of line lasers to scan a strip of the pavement (Andersen et al., 2017; Deep et al., 2020). The use of line lasers reduces the effect of texture by averaging the scans; however, this leads to the measurements being obtained at an offset from the wheel load (see Figure 4). The sensing system consists of an array of 12 4-kHz line lasers mounted on a beam that is located inside the right wheel path (see Figure 4). Gyroscopes and accelerometers are mounted on the support beam to measure the changes in its horizontal and vertical alignments. The trailer unit that encases the RAPTOR is custom built to accommodate the instrumentation, the independent wheels with their corresponding suspension system, and additional weight units that can adjust the load to 11.2 kips (50 kN) on each rear wheel (Andersen et al., 2017; Athanasiadis and Zoulis, 2019; Skar et al., 2020).

Figure 3. Dynatest RAPTOR.

The measurement principle of the RAPTOR is illustrated in Figure 5. From two sets of laser measurements at times *t* and *t'*, the RAPTOR Displacement Index (RDI) can be obtained from (Athanasiadis and Zoulis, 2019):

$$RDI = z_0' - z_1 - z_1' + z_2 = u_0 - 2u_1 + u_2 \qquad (2)$$

where z_i is the vertical distance obtained from the RAPTOR, and u_i is the pavement deflection. Because of the beam movement during testing, the angle of the lasers with the vertical is not the same at *t* and *t'*. The difference in angles can be determined and corrected using the gyroscope readings applied to the laser measurements (for the case of small angles) using (Athanasiadis and Zoulis 2019):

$$RDI = z_0' - z_1 - z_1' + z_2 L\Delta\theta = u_0 - 2u_1 + u_2 \qquad (3)$$

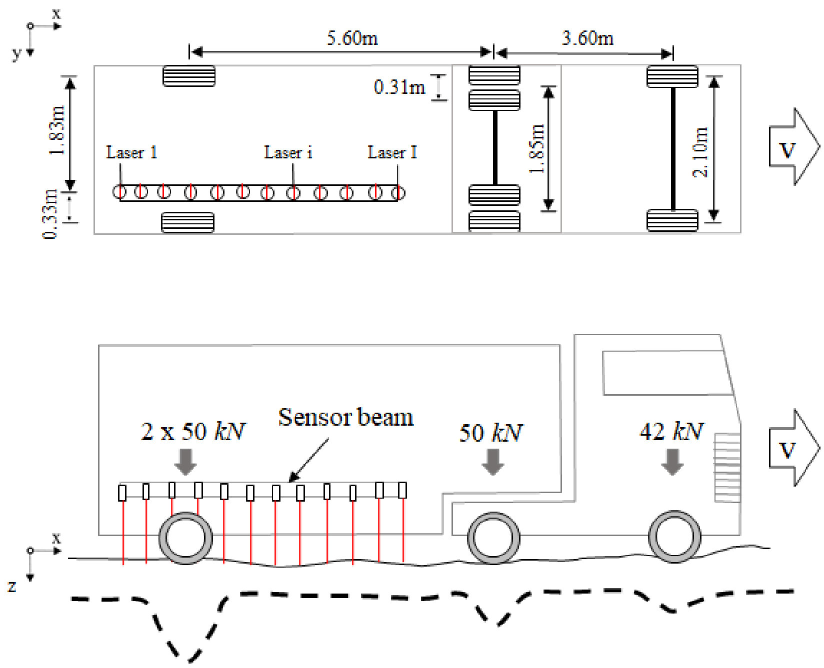

Figure 4. Schematic of RAPTOR.

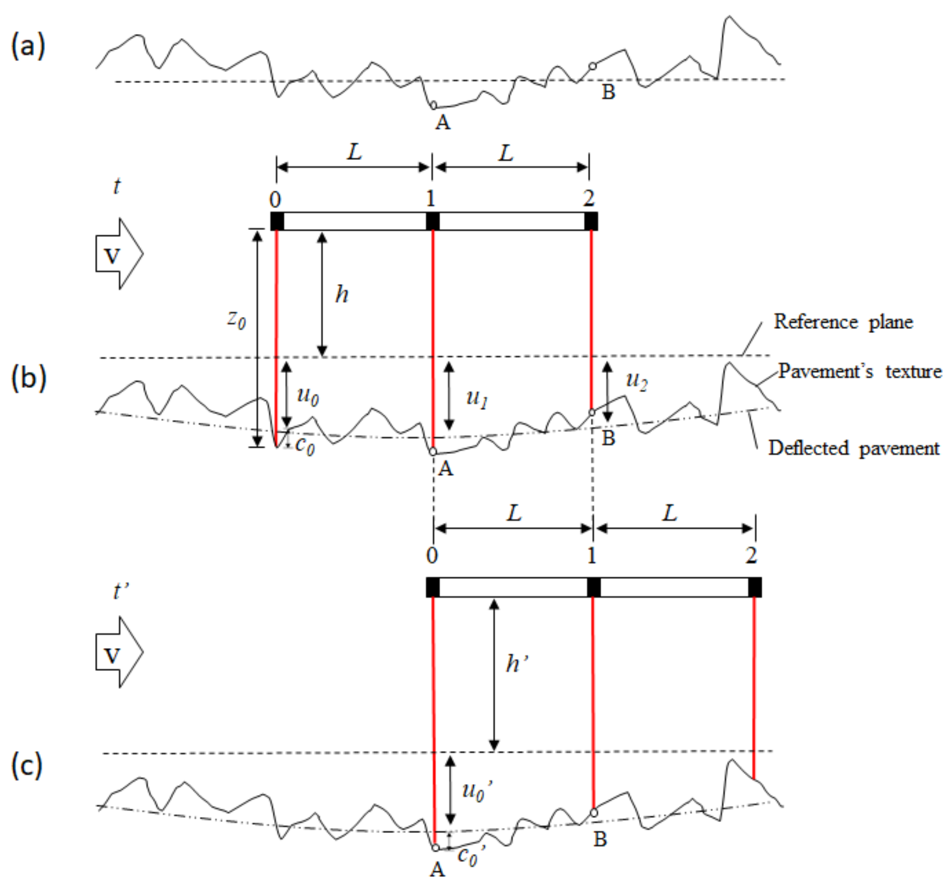

Figure 5. Measurement principle of RAPTOR to calculate curvature.

Traffic Speed Deflectometer

The TSD, shown in Figure 6, is an articulated truck with a rear-axle load that can be varied from 13.4 kips to 29.2 kips (60 kN to 130 kN) by using sealed lead loads. The TSD has up to a dozen Doppler lasers mounted on a servo-hydraulic beam to measure the deflection velocity of a loaded pavement. Until 2020, the TSDs that have been operated in the United States have used six Doppler lasers positioned such that they estimate the pavement deflection velocity at nominal distances of 4 in., 8 in., 12 in., 24 in., and 60 in. (100 mm, 200 mm, 300 mm, 600 mm, 900 mm, and 1,500 mm) in front of the loading axle. A seventh sensor is positioned 11.5 ft (3,500 mm) in front of the rear axle, largely outside the deflection bowl, to act as a reference laser. In 2021, a new TSD that uses 12 Doppler lasers became available in the United States. The beam on which the lasers are mounted moves up and down in opposition to the movement of the trailer 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 68 °F (20 °C). Data are recorded at a survey speed of up to 60 mph (100 km/h) at a sampling rate of 1 kHz (250 kHz in newer devices).

Figure 6. Picture of TSD (second generation) and computer-generated schematic (first generation).

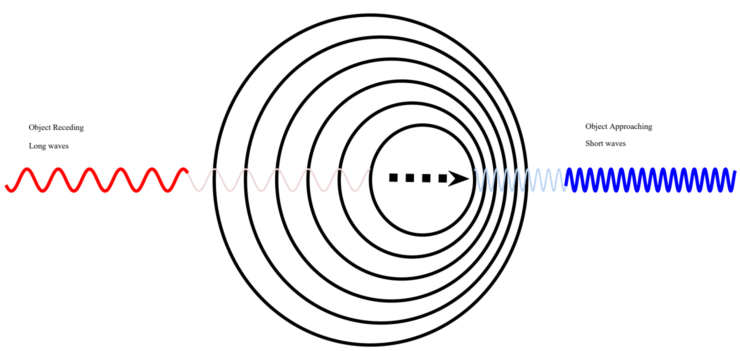

Figure 7. Illustration of the Doppler effect after Hildebrand and Rasmussen (2002; taken from Wright 2021).

The TSD differs from other TSDDs in that it uses Doppler lasers that measure the velocities rather than distance-measuring lasers that measure deflections (velocities are the time derivatives of deflection). The Doppler lasers rely on the Doppler effect (illustrated in Figure 7). Objects moving relative to the lasers alter the laser signal frequency in a way that is proportional to relative velocity. This allows the relative velocity to be determined in terms of the change in frequency.

The TSD Doppler lasers are mounted at a small angle to the vertical to measure the vertical pavement deflection velocity together with components of the horizontal vehicle speed and the vertical and horizontal vehicle suspension velocities. The pavement deflection velocity is divided by the instantaneous vehicle speed to obtain the deflection slope as follows:

$$S = \frac{V_v}{V_h} \tag{4}$$

where S = deflection slope, V_v = vertical pavement deflection velocity, and V_h = vehicle horizontal velocity.

Typically, the deflection velocity is measured in inches/s (mm/s), and the vehicle speed is measured in feet per second (m/s); therefore, the deflection slope measurements are output in units of in./ft (mm/m) and generally reported at a 33- to 53-ft (10- to 16-m) interval, although a 3.3-ft (1-m) interval is also possible.

DATA ANALYSIS METHODS

In this section, we discuss data analysis methods developed for TSDDs, with an emphasis on the TSD because it is the only device with a large fleet (18) operating in different countries. Data analysis methods can fall into three broad categories: 1) data processing, 2) evaluation of the devices, and 3) calculation of structural parameters. Each of these categories encompasses a large number of activities:

1. Data processing: In this report, we investigate data averaging and calculating the deflections from the raw data. Denoising also falls under data processing but is not discussed in this document (see Katicha et al., 2013, 2014, 2017).
2. Evaluation of devices: We discuss measures of variance (precision) and bias (accuracy) in the measurements, short- and long-term repeatability during production testing, comparison with FWD measurements, and comparison between surface condition indicators and structural indicators.
3. Calculation of structural parameters: We discuss temperature-correction procedures, calculation of indices generally used for network-level applications such as SCI300, and backcalculation procedures that are generally used at the project level. Depending on context, the effective structural number (SN_{eff}) is used for network- or project-level applications.

Data Processing

Averaging Length

The amount of data collected by TSDDs depends on the laser frequencies, which have traditionally been in the range of 1000 to 2000 Hz (although the new TSD laser frequency is 250 kHz). At 100 km/h, these frequencies result in a measurement every 14 to 28 mm. However, the data is reported at much larger distances, ranging from 1 m to 160 m (3.3 ft to 0.1-mi). During the Second Strategic Highway Research Program (SHRP 2) R06(F) project, TSD data was evaluated at 1-m, 10-m, and 100-m averaging, while RWD data was only available for 160-m averaging (Flintsch et al. 2013). In the most detailed evaluation of TSDD accuracy and precision performed in the United States, Rada et al. (2016) had access to data averaged over 10 m for the TSD and 15 m for the RWD.

Averaging of the measurements is a compromise between reducing the variance (accuracy) of the measurements and increasing bias (reducing precision) (Flintsch et al., 2013; Rada et al., 2016). Measurements obtained at longer averaging lengths cannot capture structural variations that occur at a spatial length smaller than the averaging length. An example of important structural variations that occur at a length smaller than the typical 10-m averaging length is joint strength in jointed concrete pavements. The recent interest of highway agencies and practitioners in evaluating the strength of the joints has led to efforts to improve TSDDs so that good measurements can be obtained at 1-m averaging.

Katicha et al. (2013) found that the optimal (in terms of the accuracy-precision tradeoff) averaging length is dependent on the structural condition; relatively homogenous sections can have longer averaging lengths, while sections with highly variable structural condition over short distances require shorter averaging lengths. Furthermore, the structural condition variability can be different at different locations along a tested road. Therefore, the optimal averaging length can be different within the same tested road (see Katicha et al., 2014, 2017).

Calculation of Deflections

Most TSDD research regarding the calculation of the deflections has been performed with TSD data. For the Raptor and the RWD, calculation of the deflection is done by the manufacturers of the devices, and researchers have not investigated alternative methods. One thread common to all devices is that to determine the pavement deflection from the raw measurements, an assumption of the location of the "zero" pavement deflection has to be made. Even the RWD and the RAPTOR, which use distance-measuring lasers, make an implicit assumption of the location of zero deflection.

The TSD measures the pavement deflection velocity, which is converted to deflection slope (Equation 4). To determine the pavement deflection, the deflection slope is integrated. Therefore, an assumption about the constant of integration is made either explicitly or implicitly (equivalent to an assumption of the location of zero pavement deflection). Nasimifar et al. (2018a) evaluated the different methods that have been proposed to calculate the pavement deflection from the TSD deflection slope measurements. The methods evaluated are Greenwood's algorithm (Pedersen, 2012), numerical integration based on Hermite cubic splines (called AUTC; Muller and Roberts, 2013), and the Weibull approach (Zofka et al., 2014). Deflections obtained with a viscoelastic modeling scheme (3D-Move software) were used as the reference deflections to which the other methods were compared. The authors found that the methods used to calculate the deflections did not have a significant effect on the results of deflection indices used for network-level evaluation. For more detailed analysis, the authors recommended the use of a filtering method to identify and address anomalous deflection slope measurements, especially when numerical integration is used to determine the deflection basin.

Calculation of Structural Parameters

Structural parameters calculated from TSDD measurements can be targeted for network-level or project-level application. However, the separation is not clear cut, and some parameters can be used for both types of applications. In general, as more parameters other than the TSDD measurements and more mechanistic calculation methods are used, the calculated structural parameter becomes more adequate for project-level application. This section is divided into four subsections: 1) calculation of deflection bowl indices (i.e., indices based solely on deflections), 2) calculation of structural number indices, 3) calculation of layer moduli, and 4) temperature-correction methods. All of the presented indices are for flexible pavements, as use of TSDDs to evaluate rigid and composite pavements is still at the early research stages.

Calculation of Deflection Bowl Indices

Deflection bowl indices originated from structural evaluation with the FWD. These indices have naturally been adopted for TSDDs, although the measurement principles of TSDDs and FWDs are different. Nevertheless, both devices measure the structural capacity, and indices obtained from TSDDs and FWDs generally have a good correlation. With a good correlation, most of the identified strong, fair, and weak sections identified by TSDDs are also identified by the FWD. This general agreement makes these indices well-suited for network-level applications.

Some of the earliest work on deflection bowl indices calculated from FWD measurements is that of Thompson and Hoffman (1983), who introduced the AREA method and the Shape factors (F1 and F2). Horak (1988) presented indices for the different pavement layers: the Base Layer Index (currently known as Surface Curvature Index, SCI300 or SCI12, defined as D0 – D300) for the topmost asphalt layers, the Middle Layer Index (also known as Base Damage Index, BDI, equal to D300 – D600) for the middle base layer, and Lower Layer Index (also known as Base Curvature Index, BCI, equal to D600 – D900) for the lower base layer and subgrade (see Horak, 1988; Kim et al., 2000; Horak and Emery, 2009; Talvik and Aavik, 2009).

Rada et al. (2016) evaluated 77 indices, including those mentioned in the paragraph above, that can be calculated from TSDD measurements to find which best correlate with the tensile strain at the bottom of the asphalt layer and the compressive strain at the top of the subgrade using simulated deflection bowls. These indices can be calculated using the following equations:

$$R1_r = \frac{r^2}{2D_0\left(1 - {D_r}/{D_0}\right)} \tag{5}$$

$$R2_r = \frac{r^2}{2D_0\left({D_0}/{D_r} - 1\right)} \tag{6}$$

$$F1 = \frac{D_0 - D_{24}}{D_{12}} \tag{7}$$

$$F2 = \frac{D_{12} - D_{36}}{D_{24}} \tag{8}$$

$$SCI_r = D_0 - D_r \tag{9}$$

$$SCIm_r = D_{\max} - D_r \tag{10}$$

$$DSI_{s-r} = D_s - D_r \quad (11)$$

$$SD_r = \frac{\tan^{-1}(D_0 - D_r)}{r} \quad (12)$$

$$AUPP = \frac{5D_0 - 2D_{12} - 2D_{24} - D_{36}}{2} \quad (13)$$

$$TS_r = \frac{dD}{dr} \quad (14)$$

where
r, s = distance from applied load in inches ($s > r$),
D_x = deflection at distance x from the load, and
d = differential operator.

Table 1. Most Appropriate Indices Using TSD Data Related to Maximum Horizontal Strain at Bottom of Asphalt Layer (from Rada et al., 2016)

Best Indices with TSD Loading	Index	R^2
R1[a]	$R1_{12}$	0.94
	$R1_{18}$	0.92
R2[b]	$R2_{18}$	0.92
	$R2_{24}$	0.94
	$R2_{36}$	0.90
SCI[c]	SCI_{12} = SCI300	0.94
	SCI_{18}	0.92
	$SCIm_{12}$	0.92
	$SCIm_{18}$	0.91
DSI[d]	$DSI_{4\text{–}8}$	0.90
	$DSI_{4\text{–}12}$	0.91
	$DSI_{4\text{–}18}$	0.90
SD[e]	SD_{12}	0.93
	SD_{18}	0.92
TS[f]	TS_8	0.93
	TS_{24}	0.91
AUPP[g]		0.90

a: radius of curvature 1; b: radius of curvature 2; c: surface curvature index; d: deflection slope index; e: slope of deflection; f: tangent slope; g: area under pavement profile

Some of the indices given in the equations above are well known. For example, SCI300 (or SCI12) is obtained from Equation 5 with r set at 300 mm (12 inches). Similarly, the BDI and BCI of Horak (1988) correspond to $DSI_{12\text{-}24}$ and $DSI_{24\text{-}36}$, respectively (as defined in Equation 11, the DSI is the deflection slope index). From the 77 indicators investigated (generated from the above equations by changing r and s), Rada et al. (2016) identified the most appropriate indices for the maximum horizontal tensile strain at the bottom of the asphalt layer (Table 1) and maximum vertical strain at the top of the subgrade layer (Table 2). The R^2 values for the indices were obtained by modeling a wide range of simulated pavement cross-sections with ranging material properties. In both tables, R^2 values of the listed indices are relatively close and, therefore, any of the listed indices would be appropriate for network-level structural evaluation.

Table 2. Most Appropriate Indices Using the TSD Data Related to Maximum Vertical Strain at Top of Subgrade (from Rada et al., 2016)

Best Indices with TSD Loading	Index	R^2
R2[a]	$R2_{60}$	0.92
DSI[b]	DSI_{4-48}	0.90
	DSI_{4-60}	0.90
	DSI_{8-23}	0.92
	DSI_{8-48}	0.93
	DSI_{8-60}	0.93
	DSI_{12-18}	0.90
	DSI_{12-24}	0.94
	DSI_{12-36}	0.95
	DSI_{12-48}	0.95
	DSI_{12-60}	0.95
	DSI_{18-24}	0.97
	DSI_{18-36}	0.97
	DSI_{18-48}	0.97
	DSI_{18-60}	0.97
	DSI_{24-36}	0.97
	DSI_{24-48}	0.97
	DSI_{24-60}	0.97
TS[c]	TS_{12}	0.90
	TS_{18}	0.92
	TS_{36}	0.95
F2[d]	F_2	0.91

a: radius of curvature 2; b: deflection slope index; c: tangent slope; d: shape factor 2

Calculation of Effective Structural Number (SN_{eff})

The effective structural number (SN_{eff}) is a structural parameter linked to the structural number (*SN*) used in the American Association of State Highway and Transportation Officials (AASHTO) 1993 design method. The *SN* is determined by the pavement layer thickness and layer coefficient and is used to determine the pavement layers' thicknesses based mainly on the expected truck traffic (and other parameters). The SN_{eff} uses measured deflections and the pavement thickness to determine the structural condition of the pavement and can be used for both network-level and, when combined with other project-level information, project-level applications. Elseifi et al. (2015, 2017, 2018) proposed two equations to calculate the SN_{eff} for the RWD and TSD. However, their equations use the average annual daily traffic as an input parameter, which is not compatible with the idea that the *SN* is an indicator of the load carrying capacity of the pavement (the SN_{eff} in the equations changes if the traffic is changed, which should not be the case). For this reason, the equations are not presented.

Two main approaches have been proposed to calculate SN_{eff} from TSD measurements. The first is based on the AASHTO 1993 method for overlay design, and the second is based on the Rohde equation (Rohde, 1994). The Rohde equation approach has been used by Flintsch et al. (2013), Katicha et al. (2014, 2017), and Nasimifar et al. (2019a,b). The first three references used the original equation developed for FWD measurements, while Nasimifar et al. (2019a,b) used the same equation but with recalibrated constants to reflect TSD loading conditions. The recalibration was based on 429 pavement structures simulated with 3-D MOVE. The Rohde (1994) equation to calculate SN_{eff} is given by:

$$SN_{eff} = C_1 SIP^{C_2} Hp^{C_3} \quad (15)$$

where
SIP = structural index of pavement (µm),
Hp = total pavement thickness (mm), and
C_1, C_2, and C_3 = coefficients for different surface types; for AC pavement: 0.4728, -0.4810, and 0.7581, respectively, for the FWD and 0.4369, -0.4768, and 0.8182, respectively, for the TSD (Nasimifar et al. 2019a).

SIP is calculated as follows:

$$SIP = D_0 - D_{1.5Hp} \quad (16)$$

where
D_0 = temperature-corrected peak deflection (see Nasimifar et al. 2019a) measured under a standard 9000-lb load,
$D_{1.5Hp}$= deflection measured at an offset of 1.5 times Hp under a standard 9000-lb load, and

Hp = total pavement thickness in inches.

Calculation of the SN_{eff} based on the AASHTO method for overlay design using TSD data has been used by Schmaltzer and Weitzel (2017). In this approach, SN_{eff} is calculated as follows:

$$SN_{eff} = 0.0045 H_p \sqrt[3]{E_p} \quad (17)$$

where E_p is the effective modulus of pavement layers determined from the following:

$$D_{max} = 1.5 \times p \times a \left\{ \frac{1}{M_r \sqrt{1 + \left(\frac{H_p}{a} \sqrt[3]{\frac{E_p}{M_r}} \right)^2}} + \frac{\left[1 - \frac{1}{\sqrt{1 + \left(\frac{H_p}{a} \right)^2}} \right]}{E_p} \right\} \quad (18)$$

where
p = contact pressure (psi),
a = circular load radius (inches),
H_p = total pavement layer thickness (inches), and
D_{max} = maximum deflection in (inches).

The subgrade modulus used in Equation 2 is determined as follows:

$$M_r = \frac{P(1-\mu^2)}{r \times \pi \ \times d_r} \approx \frac{0.24P}{r \times d_r} \tag{19}$$

where
P = applied load (lb),
d_r = measured deflection (inches),
r = distance between the load center and the point where deflection is measured (inches), and
μ = Poisson's ratio (generally assumed to be 0.5).

To determine M_r, Schmaltzer and Weitzel (2017) used the TSD deflection d_r and corresponding distance r that resulted in the lowest calculated M_r. The AASHTO method implements a more elaborate iterative approach. We note that Schmaltzer and Weitzel (2017) also used an alternative approach to determine the TSD deflections from the deflection slopes.

Backcalculation of Layer Moduli

In pavement structural evaluation, backcalculation of layer moduli is used for project-level applications (e.g., overlay design). Backcalculation using TSDD measurements is still in the early research stages. One approach proposed is to convert TSDD measurements into equivalent FWD measurements and then perform a "regular" backcalculation, as is done with FWD measurements (Elseifi et al., 2019). The conversion is done using an artificial neural network (ANN) calibrated with 3D-Move examples of pavement responses from FWD and TSD loading.

Nasimifar et al. (2017b) compared the results of a simple linear elastic backcalculation approach based on WESLEA and a viscoelastic backcalculation approach using 3D-Move. For the linear elastic approach, they recommended the use of dual uniform circular loads rather than the conventional single circular plate used with FWD testing. The viscoelastic approach based on 3D-Move has the advantage of accounting for the viscoelastic nature of the pavement response and can be performed using the deflection velocities measured by the TSD; that is, there is no need to determine the deflection slopes and then deflections to perform the backcalculation. Rather, the pavement deflection slopes and deflections are obtained as part of the backcalculation. With all these advantages, the approach still has the significant drawback of being computationally very intensive compared to the linear elastic approach. This makes the approach currently impractical for network-level applications and restricted to project level-analysis. Figure 8 shows calculated deflection slopes and deflections from the measured deflection velocities using 3D-Move backcalculation. Viscoelastic backcalculation was also performed by Nielsen (2020).

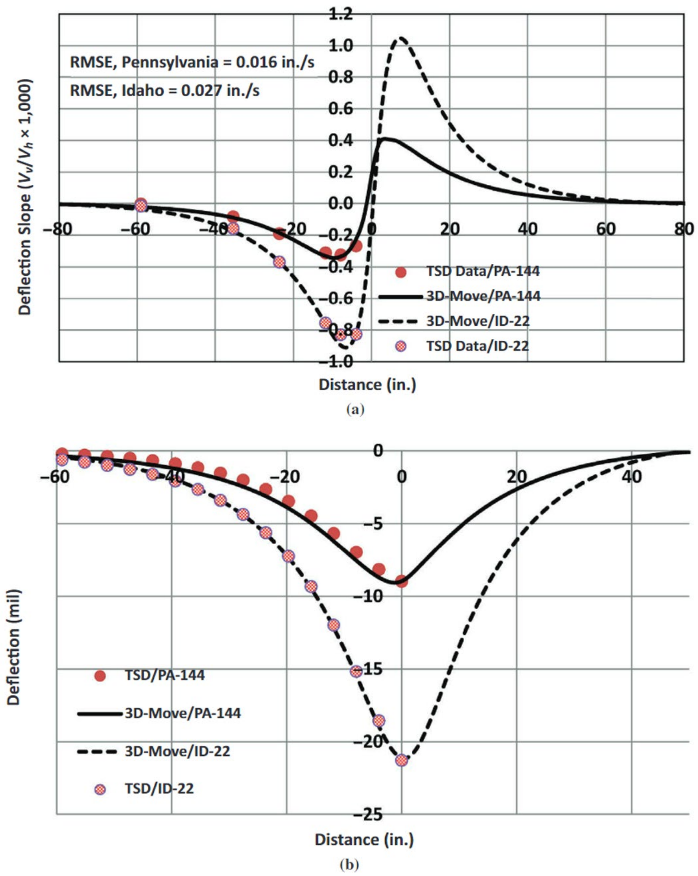

Figure 8. TSD collected data; a) measured and calculated deflection slopes, b) calculated deflections from 3D-Move and from TSD algorithm.

Temperature Correction

Temperature correction of TSDD measurements has not been extensively investigated. In some cases, temperature-correction methods developed for the FWD have been used. For example, Katicha et al. (2020) used the temperature-correction approach in the AASHTO pavement design guide (AASHTO, 1993) to correct D_0 for the calculation of *SNeff*.

Nasimifar et al. (2018b) developed an approach to temperature correct SCI300 calculated from TSD measurements. The model is an improvement to the Stiffness Adjustment Model (SAM) developed by Rada et al. (2016) that it takes into account viscoelastic considerations as well as the asphalt layer thickness. The model improvements in Nasimifar et al. (2018b) were performed because the SAM model was found to be inaccurate for thin pavements (Katicha et al., 2017). In the SAM, the temperature adjustment factor is based on the relationship between 1) SCI300 and the tensile strain at the bottom of the asphalt layer, and 2) the tensile strain at the bottom of the asphalt layer and the dynamic modulus of the asphalt layer. Nasimafar et al. (2018) added the asphalt layer thickness and the latitude of the tested location to the temperature adjustment factor. The temperature-correction factor is calculated as follows:

$$\lambda = \frac{SCI_{Ref}}{SCI_T} = \frac{10^{-0.05014T_{Ref}+0.019049T_{Ref}\log(h_{AC})\log(\varphi)}}{10^{-0.05014T+0.019049T\log(h_{AC})\log(\varphi)}} \tag{20}$$

where
λ = temperature adjustment factor,
SCI_{Ref} = adjusted SCI300 at reference temperature,
T_{Ref} = reference temperature in °C,
h_{AC} = asphalt layer thickness, mm,
T = mid-depth asphalt concrete layer temperature at the time of measurement in °C, and
φ = latitude of the location of measurement (within 30 to 50 degrees).

The temperature at the mid-depth of the asphalt concrete layer is estimated using the BELLS3 equation (Lukanen et al., 2000) as follows:

$$T_d = 0.95 + 0.892IR + \{\log(d) - 1.25\}\{-0.448IR + 0.621T_p + 1.83\sin(hr_{18} - 15.5) + 0.042IR\sin(hr_{18} - 13.5)\} \quad (21)$$

where
T_d = pavement temperature at depth d, ºC,
IR = pavement surface temperature, ºC,
log = Base 10 logarithm,
d = depth at which temperature is to be predicted, mm,
T_p = average air temperature the day before testing, ºC,
sin = sine function on an 18-hr clock system, with 2π radians equal to one 18-hr cycle, and
hr_{18}= time of the day in a 24-hr clock system but calculated using an 18-hr asphalt concrete temperature rise and fall time cycle.

National Oceanic and Atmospheric land-based weather station data can be used to obtain the average temperature on the day before testing.

For the calculation of SN_{eff}, only D_0 needs to be corrected for temperature. Currently, the approach used is the same one used to correct D_0 obtained from the FWD, which is based on the AASHTO temperature adjustment charts (AASHTO 1993).

EVALUATION OF DEVICES

Device Precision/Repeatability/Standard Error

Rada et al. (2016) performed the most thorough evaluation to date of the accuracy and precision of the TSD and RWD. The evaluation was performed on pavement sections instrumented with geophones. For the TSD, the standard error of deflection slope measurements averaged over 10 m was estimated to be between 0.05 mm/m and 0.0767 mm/m (0.9 to 2.3 mm/s deflection velocity with speeds from 30 to 60 mph). The slope of a regression model between the TSD measurements and the geophones was mostly very close to 1 (average of 1.01 and a standard deviation of 0.01). For the RWD, they found a standard error for the measured deflection averaged over 16 m ranging from 15 to 58 µm. The slope of a regression model between the RWD measurements and the geophones was more variable with an average of 1.31 and a standard deviation of 0.59. Pavement stiffness was found to have an important effect on accuracy but the two devices were deemed adequate for network-level applications.

Flintsch et al. (2013) also evaluated the TSD and RWD standard errors using repeated measurements. For the TSD, the standard error of deflection slope measurements averaged over 10 m was evaluated between 0.037 and 0.105 mm/m, which is close to what was found by Rada et al. (2016) and shows that good estimates of the standard error can be obtained from repeatability tests without the need for data collection on instrumented pavement sections. For measurements averaged over 1 m, the standard error was about three times larger, while for measurements averaged over 100 m it was about three times smaller (following the statistical behavior that when measurements are averaged, the standard deviation decreases in proportion to the square root of the number of measurements being averaged).

Short- and Long-term Repeatability During Routine Testing

Flintsch et al. (2013) and Katicha et al. (2017) reported on the long-term and short-term repeatability of the TSD. The testing reported in Katicha et al. (2017) was done as part of the pooled fund TPF-5(282), *Demonstration of Network Level Pavement Structural Evaluation with Traffic Speed Deflectometer*, reflecting how the device performs in routine testing conditions (rather than in an experimental setting). Figure 9 and Figure 10 show two examples of short-term SCI300 (D0 – D300) repeatability of measurements at a 10-m resolution (corrected to a reference temperature of 70 °F) performed on consecutive days in New York and Virginia, respectively. Although not reported by Katicha et al. (2017), the standard error of the difference between the two sets of measurements was observed to be of the same order as the one reported in Flintsch et al. (2013). Figure 11 and Figure 12 show two examples of long-term repeatability (1-year interval) of measurements at a 10-m resolution (corrected to a reference temperature of 70 °F). In the first example of a road tested in Pennsylvania (Figure 11), the long-term repeatability is similar to that of the short-term repeatability. In the second example, showing roads tested in South Carolina (Figure 12), the overall trends are similar, but there is notable difference that is larger than what is expected based on the short-term repeatability (most obvious with I-85 Northbound). This example reinforces the need to develop verification and validation protocols for TSDDs in general and the TSD in particular.

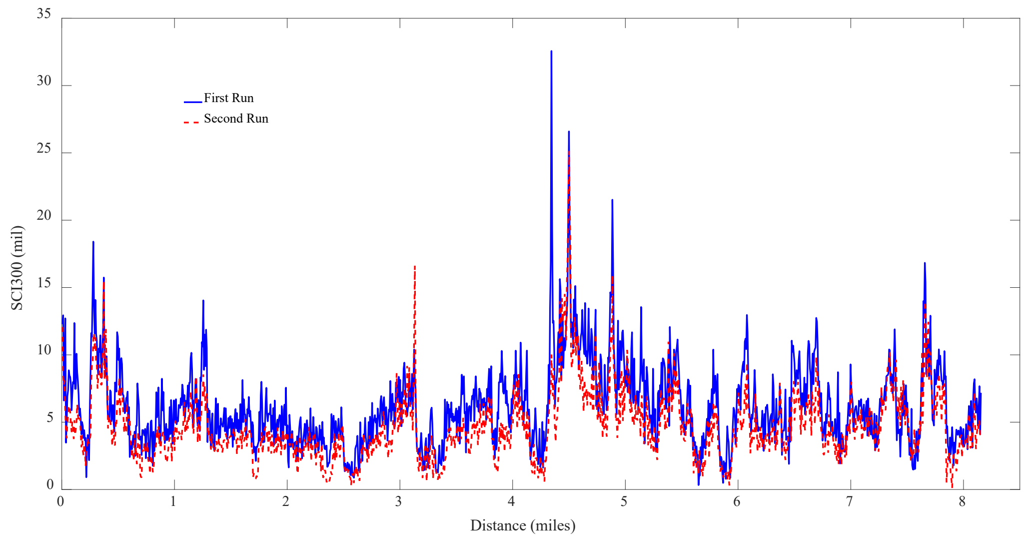

Figure 9. Short-term repeatability on SR 417 west in New York with tests performed on consecutive days in November 2013.

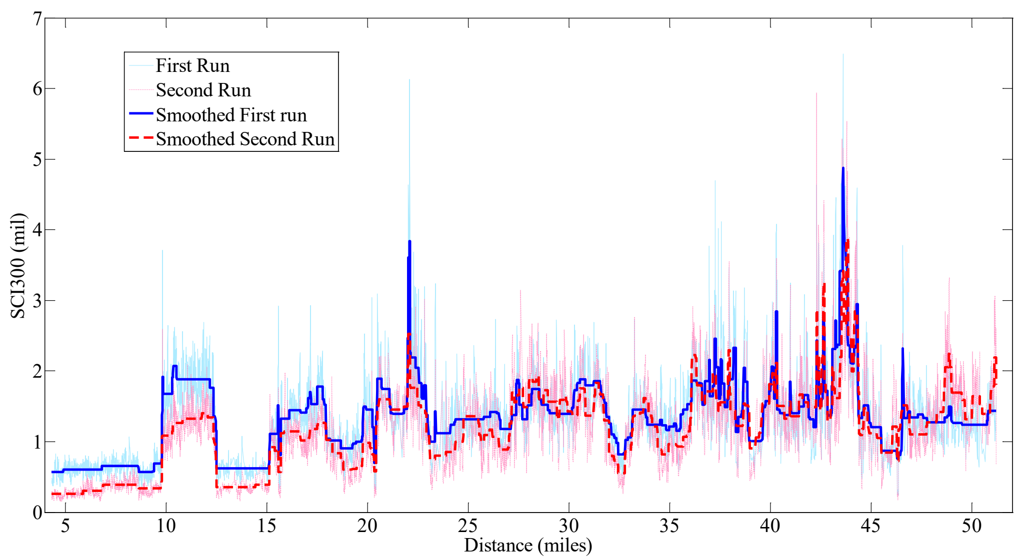

Figure 10. Short-term repeatability on US 29 south in Virginia performed on two consecutive days in June 2015. The smoothed lines are given to help visual comparison of the measurements

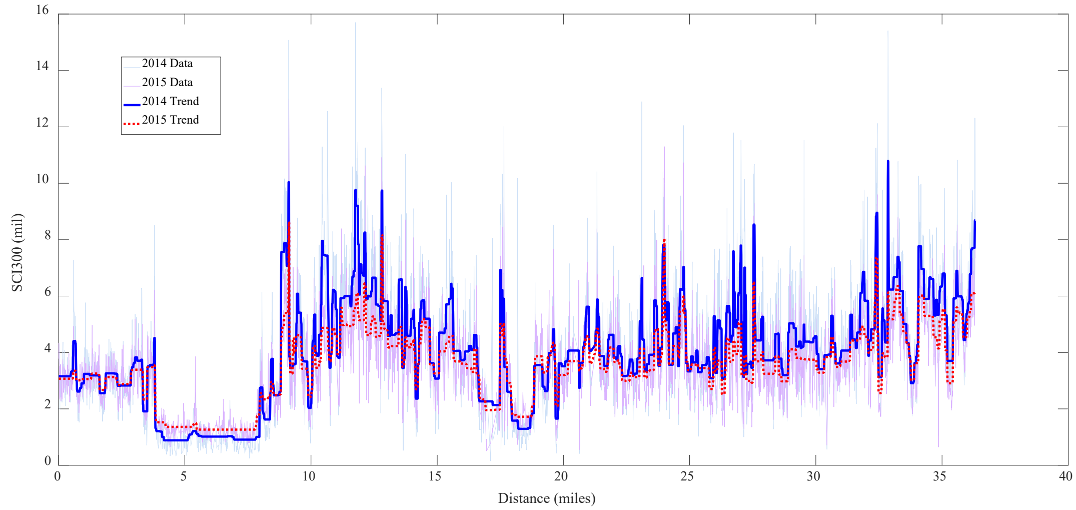

Figure 11. Long-term repeatability on Route 144 in Pennsylvania.

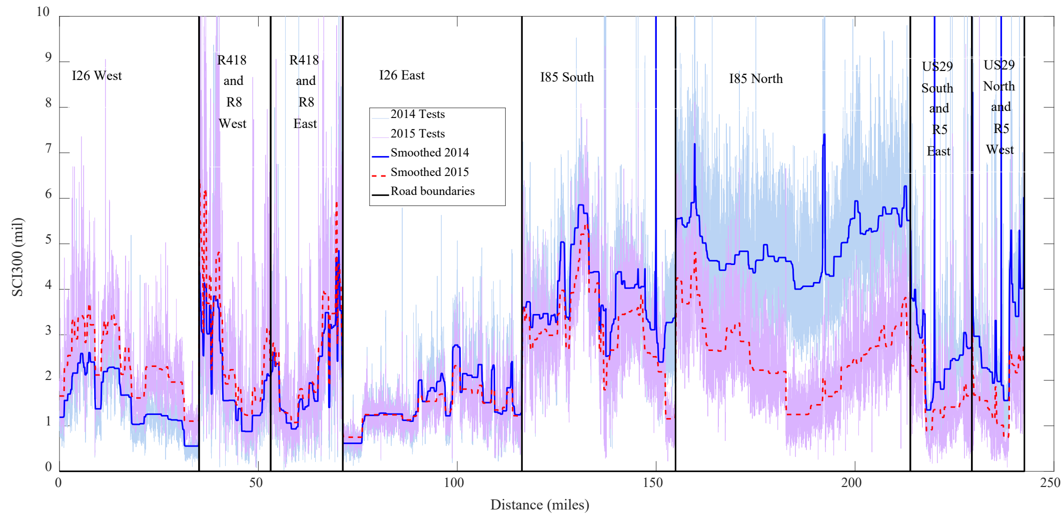

Figure 12. Long-term repeatability of the TSD on roads tested in South Carolina.

Comparison with FWD Measurements

An important aspect to consider when comparing a TSDD with the FWD is that the two devices, while generally measuring the structural response of the pavement, have many significant differences that result in their measurements not being exactly equivalent (Flintsch et al., 2013; Nasimifar et al., 2017b; Katicha et al., 2014b, 2017). TSDDs record the pavement response under the maximum loading for all sensors at a fixed time, whereas the FWD measures the maximum deflection, which occurs at different times for the different sensors, as shown in Figure 13 (the case with the RWD and Raptor is the same) (Shrestha et al., 2018).

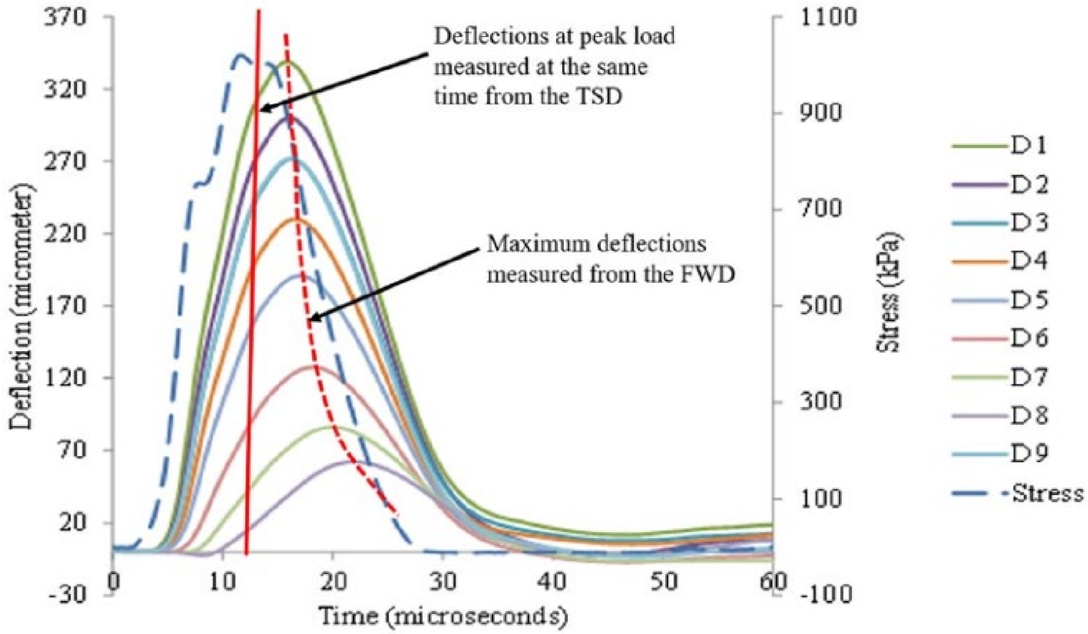

Figure 13. Deflection measurement from FWD and TSD (after Chatti et al., 2017).

Elseifi et al. (2012) found that RWD and FWD measurements were in general agreement with an R^2 of 0.82 for measurements averaged over entire road sections (in total 16 road sections). However, they also reported that the center deflections from the RWD and FWD were statistically significantly different for 15 of the 16 tested sites. Similarly, Elseifi and Zihan (2018) found the measurements from the TSD and FWD to be statistically different. Katicha et al. (2014b) used the Limits of Agreement (LOA) method of Bland and Altman (1983, 1986, 1999) to compare FWD and TSD measurements. The LOA gives the average difference between a measurement obtained with the TSD and a measurement obtained with the FWD and a confidence interval for that difference.

Even if statistical measures show that FWDs and TSDDs produce statistically different measurements, most past studies have shown that from an engineering and practical perspective the FWD and TSDDs show similar trends in the structural variation along a tested road. Figure 14 (Katicha et al., 2014b) and Figure 15 (Katicha et al., 2017b) show that the two devices have similar trends with the same relatively weak and strong sections identified by both devices even when the numerical values of the measured deflections are not the same (Figure 15). In Figure 15, the pavement section around milepost 215 was recycled in 2010 and shows FWD results before and after the recycling was performed. These results suggest that for network-level applications, TSDD measurements can replace FWD measurements (Katicha et al., 2020) and that good empirical models can be developed between TSDD measurements and FWD measurements for network-level applications (Elbagalati et al., 2016, 2017b; Elbagalati et al., 2018; Elseifi and Zihan, 2018; Zihan et al., 2018; Zihan et al., 2020). The drawback of empirical models is that they cannot be generalized to conditions other than those with which the models were developed.

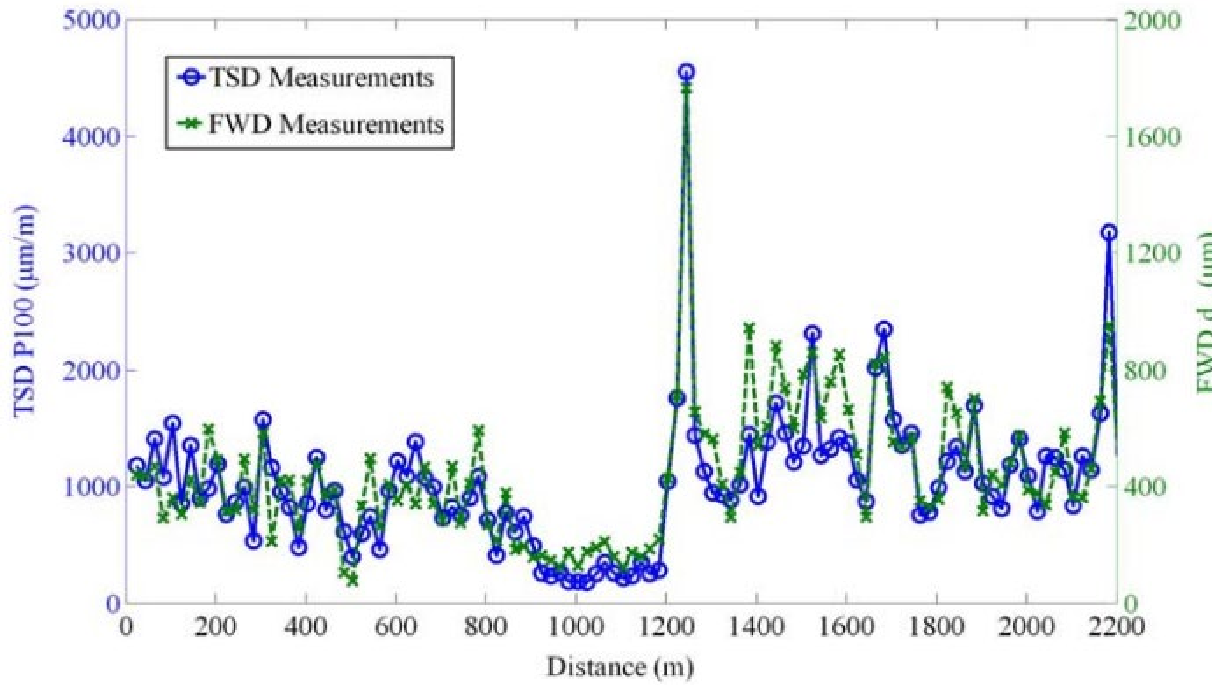

Figure 14. TSD deflection slope at 100 mm from wheel load and FWD D0 measured at a road section in England as part of the SHRP2 R06(F) project.

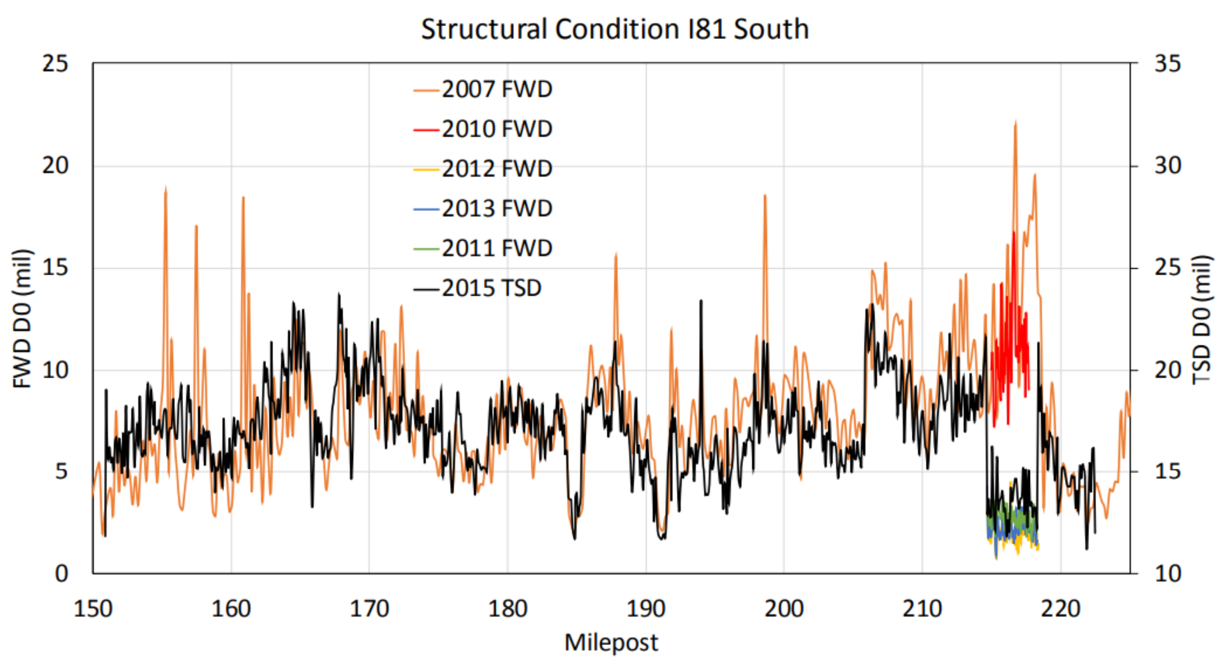

Figure 15. Comparison of TSD and FWD D0 on I-81 South in Virginia.

APPLICATIONS OF TSDDS

A major motivation that led to the development of TSDDs is the limitations of the FWD for network-level pavement structural evaluation. With advances in TSDD technologies and wider acceptance by the pavement engineering community, the use of TSDDs in a project-level setting is gaining wide interest. Therefore, it is expected that in the near future (say 5 years), as the devices are improved and better data analysis methods are developed, TSDDs will be used for both network-level and project-level applications. This section gives examples of current network-level and project-level analysis methods used with TSDDs. The emphasis will again be on the TSD because it is currently the only device widely available, and the only one available in the United States.

Network-level Applications

Flexible Pavements

Early development, assessment, and application of TSDDs focused on network-level structural evaluation. The usefulness of the RWD and the TSD for this purpose has been extensively investigated and confirmed by Rada et al. (2011) and Flintsch et al. (2013). Table 3 lists some of the major national research reports that have investigated the two devices. No comparable national investigation of the Raptor has been performed.

Initial assessments focused on the TSDD's ability to identify relatively weak and strong sections and broad correlations with the FWD (Flintsch et al., 2013). These assessments quickly confirmed the capabilities of the devices, and methods to incorporate the structural condition measured by TSDDs into a pavement management system (PMS) followed (e.g., Elseifi and Elbagalati, 2017; Elseifi and Zihan, 2018; Katicha et al., 2017, 2020). Rada et al. (2016) made an extensive theoretical and experimental evaluation of which indices that can be calculated from TSDDs are most appropriate for implementation in a PMS. Katicha et al. (2017, 2020) proposed a method to incorporate the structural condition into pavement management using structural indices evaluated by Rada et al. (2016). Most of the proposed indices are highly correlated; therefore, from a network-level pavement application perspective there is little practical difference in which set of indices is used as long as indices calculated from the deflections that are closer to the applied load are used to characterize the structural condition of the pavement and indices calculated from the deflections that are farther from the applied load are used to characterize the structural condition of the subgrade.

Because most highway agencies currently implement a pavement management approach based on pavement surface condition, as a first step in the implementation process, Katicha et al. (2017, 2020) proposed an approach similar to the current framework of incorporating the structural condition used by VDOT with network-level FWD data. The framework consists of first determining a preliminary treatment category selected based solely on the surface condition and then modifying that treatment category by further taking into account the structural condition (Figure 16). As a general rule for treatment modification, structurally weak pavement sections could have their initial treatment category (i.e., that based on the surface condition) changed to a heavier treatment category, while structurally strong sections could have their initial treatment category changed to a lighter treatment category; sections that are structurally fair would not undergo modification of the initial treatment category. Of course, different variations around this general approach can be implemented by highway agencies to better fit their overall approach to pavement management. Below, we give an overview of the approaches proposed by Elseifi and Elbagalati (2017), Elseifi and Zihan (2018), Katicha et al. (2017), and Katicha et al. (2020).

Table 3. List of the Major Reports on Network-level Application of TSDDs

Topic	Device	Reference	Summary
Investigation and Evaluation of Devices	**RWD and TSD**	**Rada et al. (2011)**	**Federal Highway Administration (FHWA) report that summarized available TSDDs**
	RWD and TSD	**Flintsch et al. (2013)**	**SHRP 2 report that evaluated potential TSDDs for network-level application. More emphasis on TSD repeatability and comparison with FWD.**
	RWD and TSD	**Rada et al. (2016)**	**FHWA report:** **Devices investigated on instrumented pavement sections at the MnRoad facility, with extensive mechanistic modeling.**
Calculation of Indices from the TSDDs	**RWD**	**Abdel-Khalek et al. (2012)**	**Proposed SN for RWD**
	RWD and TSD	**Rada et al. (2016)**	**FHWA report:** **Investigated 75 TSDD deflection indices and developed relationship to structural parameters**
Implementation at the Network-level PMS	**RWD**	**Elseifi and Elbagalati (2017)**	**Louisiana Transportation Research Center (LTRC) report:** **Proposed improved SN model from RWD to integrate it into Louisiana PMS. Also analyzed the efficiency of RWD in analyzing structurally deficient sections.**
	TSD	**Katicha et al. (2020)**	**Virginia Transportation Research Center (VTRC) report:** **Investigated replacing FWD measurements with TSD in VDOT**
	TSD	**Katicha et al. (2017)**	**Pooled fund study with TSD and nine participating states**
	TSD	**Elseifi and Zihan (2018)**	**LTRC report:** **Zihan et al. (2018) used ANN to incorporate TSD measurements in backcalculation to predict pavement layer moduli**

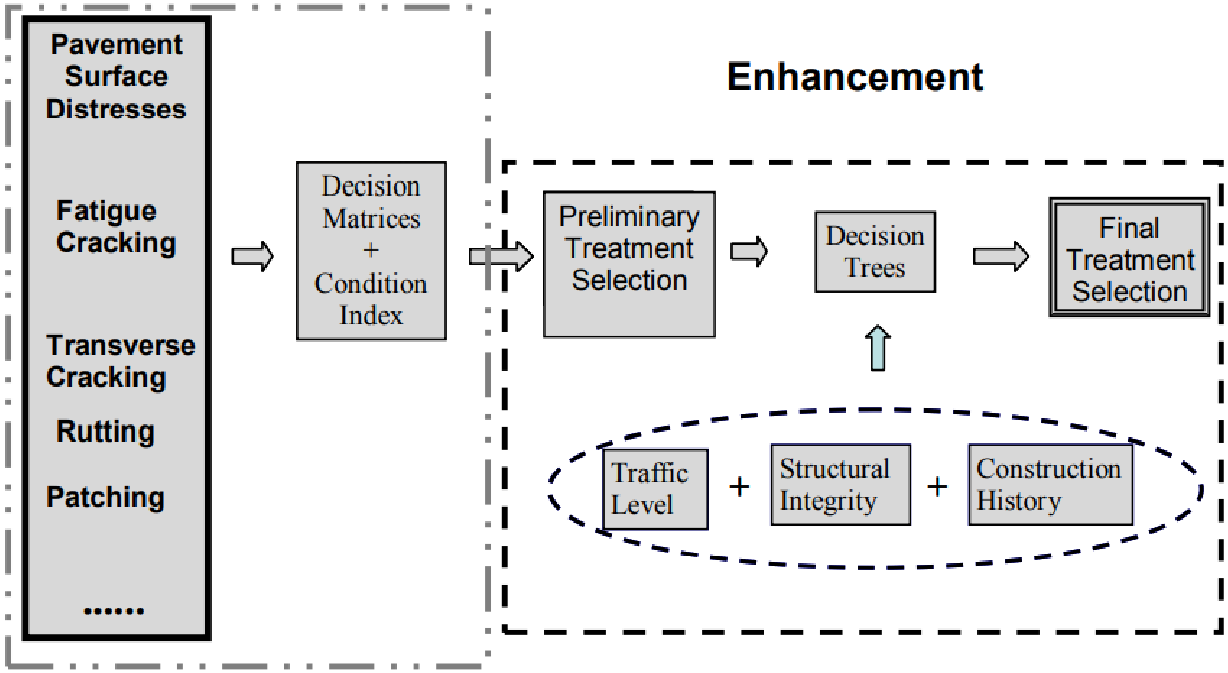

Figure 16. Two-phase PMS decision-making process (Virginia Department of Transportation, 2008).

To incorporate the structural condition determined from the RWD into the Louisiana PMS, Abdel-Khalek et al. (2012) developed a regression model that calculates the SN_{eff} of a pavement section as a function of the average and standard deviation of RWD-measured deflection on that pavement section (and what the authors call RWD Index [RI], which is the average times the standard deviation). The pavement section length used in the model is 0.1-mi, and the model was calibrated using the FWD-calculated SN_{eff}. Elbagalati et al. (2018) extended the model to take into account the asphalt layer thickness and traffic, with the final model given as follows:

$$SN_{RWD0.16} = -14.72 + 27.55\left(\frac{AC_{th}}{D_0}\right)^{0.04695} - 2.426\ln(SD) + 0.29\ln(AADTPLN) \qquad (22)$$

where
$SN_{RWD0.16}$ = SN_{eff} from RWD measurements on a 0.1-mi (0.16-km) pavement section,
ACth = asphalt concrete layer(s) thickness in inches,
D_0 = average RWD deflection at 0.1-mi resolution,
SD = standard deviation of RWD-measured deflection at 0.1-mi, and
$ADDTPLN$ = average annual daily traffic per lane (vehicles/day).

The model was verified with cores taken at sections that were identified as structurally weak, showing evidence of asphalt stripping and material distresses. Elseifi and Elbagalati (2018) then proposed comparing SN_{eff} to the required effective structural number (SN_{req}) to determine a structural condition index (SCI = SN_{eff}/SN_{req}) that can be used in a PMS (Elbagalati et al., 2017; Elseifi and Elbagalati, 2017). This approach is similar to the one developed for FWD measurements by Bryce et al. (2013a, 2013b).

A similar approach was proposed by Elseifi and Zihan (2018) for TSD measurements with the SN_{eff} regression model given by the following equation:

$$SN_{TSD} = 18.67 \times e^{-0.013D_0} + 8.65(D_{48})^{0.11} + 0.18(T_{th}) + 0.31\ln(ADT) - 24.28 \qquad (23)$$

where
SN_{TSD} = SN_{eff} from TSD measurements,
D_0 = center deflection under the tire (mils),
D_{48} = deflection 48 inches from center deflection (mils),
Tth = total pavement thickness (inches), and
ADT = average daily traffic (vehicles/day).

Although the two models for RWD and TSD are developed to closely match FWD-calculated SN_{eff}, they have the drawback that the traffic enters the equation of SN_{eff}. This is contrary to the definition of SN as a function of layer thicknesses and layer coefficients. If, as is generally expected, traffic increases, then the model predicts that SN_{eff} increases without any changes to the pavement.

Katicha et al. (2017) proposed using the SN_{eff} calculated using the Rohde equation (Equation 15) or using indices suggested by Rada et al. (2016) as they relate to the tensile strain at the bottom of the asphalt layer (Nasimifar et al., 2016, 2017b). The indices are related to strains in the pavement and therefore can be related to fatigue life or permanent deformation in the subgrade. For example, the tensile strain at the bottom of the asphalt layer can be estimated from SCI_{300} or DSI as follows:

$$\epsilon = a(DSI)^b$$

$$\epsilon = a'(SCI_{300})^{b'}$$

$$SCI_{300} = D_0 - D_{300}$$

$$DSI = D_{100} - D_{300}$$

where the parameters a, b, a', and b' depend on the thickness of the asphalt layer (see Rada et al. 2016). Whether SN_{eff} or tensile strain from deflection indices is used, the parameter can be used to determine the remaining (structural) service life of the pavement. For the SN_{eff}, this can be done by comparing SN_{eff} to SN_{req}, while for the tensile strain, this could be done by using the calculated tensile strain to determine the number of cycles to failure using a fatigue equation. Details of the approach using SN_{eff} are presented in the project-level applications subsection. Another approach followed in Katicha et al. (2020), which is less mechanistic, is to determine thresholds for good, fair, and poor structural condition based on distribution of the selected structural index or based on comparison with FWD data. For example, VDOT uses an FWD-measured SN_{eff} of 6, which corresponds to the 30th percentile of SN_{eff}, as the threshold between structurally fair and structurally poor pavements for interstate roads. Katicha et al. (2020) proposed using that same percentile as a threshold with TSD-calculated SN_{eff}.

The methods presented in the previous paragraph focus on classifying pavement sections into structurally good, fair, and poor conditions to support treatment selection. However, the structural condition can be used to improve pavement deterioration models that are used for long-term planning and budgeting. For example, Katicha et al. (2020) showed, using a large portion of the Virginia interstate and primary network (4,000 mi in total), that observed deterioration recorded in the pavement management system occurred faster for sections that were structurally weaker than for sections that were structurally stronger (Figure 17). Based on this observation, they developed pavement deterioration models that depend on the pavement age and the pavement structural condition. Figure 18 shows deterioration models developed for interstate roads, with red representing the deterioration of weaker pavement sections and green representing the deterioration of stronger pavement sections.

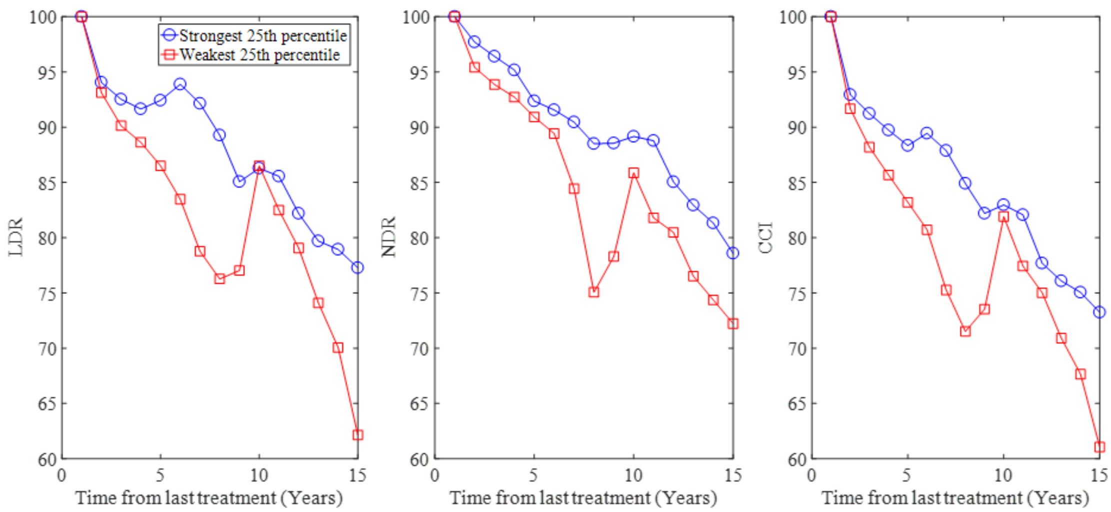

Figure 17. Average condition for tested interstate roads of structurally strongest 25th percentile and structurally weakest 25th percentile of sections as a function of time from last treatment (LDR = Load-related Distress Rating, NDR = Non-load-related Distress Rating, and CCI = Critical Condition Index).

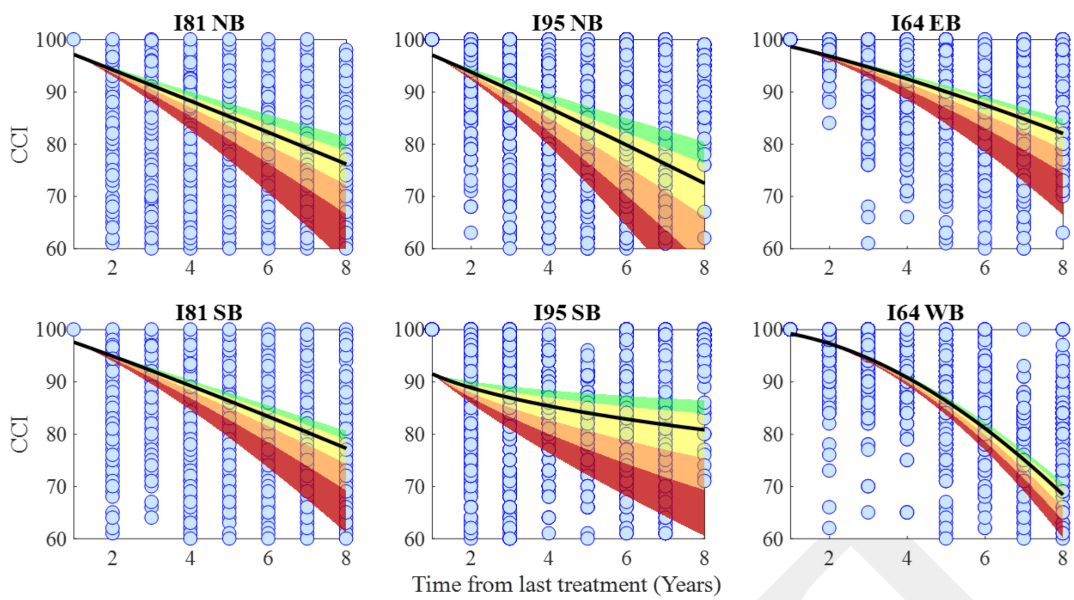

Figure 18. Deterioration models incorporating the structural condition.

Rigid and Composite Pavements

The development of structural capacity indices for network-level evaluation has generally focused on flexible pavement applications (Ali and Tayabji, 1998; Zhang et al., 2003; Chakroborty et al., 2007; Bryce et al., 2013a). For rigid pavements, it has generally been assumed that deflection tests conducted at the network level provide little to no useful information regarding expected performance (Zhang et al., 2003). This is because structural deterioration in rigid pavements is generally spatially localized (joint load transfer efficiency, slab cracking). Therefore, traditional network-level FWD testing performed at 0.1- to 1-mi intervals is not effective in detecting these localized structural deteriorations (Bryce et al., 2016; Carvalho et al., 2012). Because of the relative lack of network-level analysis methods for rigid and composite pavement based on FWD measurements, and because the response of rigid pavements can be close to the accuracy of the devices, efforts to investigate the capabilities of TSDDs on rigid and composite pavements have been very limited.

Flintsch et al. (2013) suggested that the TSD may be capable of evaluating the joint condition of rigid pavements based on the results of tests performed at 10 km/h. These tests showed that the raw deflection slopes of the TSD were compatible with the load transfer efficiency (LTE) of joints assessed with the FWD (i.e., significant increases in the slope were observed at the joint that had poor LTE). Although these results are encouraging, they were obtained at a slow speed that allowed averaging a large number of measurements at high resolution to reduce the amount of noise in the measurements. The large number of averaged measurements needed to reduce the amount of noise at high resolution is not available with measurements collected at traffic speed (45 mph or higher). The relatively high noise obtained at high resolution has been a major obstacle that has limited the use of TSDDs on concrete pavements. Nonetheless, Katicha et al. (2017b, 2014, 2013) and Scavone et al. (2021) analyzed TSD measurements at a 1-m resolution collected at traffic speed (45 mph). They found that with the proper use of signal processing denoising methods that the TSD could potentially identify weak spots in jointed concrete pavements that are likely to be weak joints. These results, along with the recent increase in the frequency of the TSD Doppler lasers from 1 kHz to 250 kHz, suggest that evaluation of joint condition in jointed concrete pavements will be practically feasible in the near future. Some results with the new 250-kHz lasers presented at the DaRTS meeting by Greenwood Engineering, the manufacturers of the TSD, show great promise.

Project-level Applications

In a broad sense, what differentiates network-level and project-level applications are 1) the accuracy and precision of the measurements needed, 2) the extent of mechanistic and engineering design principles used in analyzing the data, and 3) the resolution at which the data is analyzed. Therefore, although the topics presented here are under project-level applications, it could be argued that in certain circumstances these same topics could be included under network-level applications. This is especially true for the case of the remaining service life and overlay design approach based on the AASHTO 1993 design method. The two topics presented in this section are 1) overlay design (based on AASHTO 1993), and 2) backcalculation of layer moduli. We point out that some of what is presented here overlaps what has already been presented in the “Calculation of Structural Parameters” subsection.

Overlay Design

The presentation of this topic focuses on the works of Schmalzer and Weitzel (2017) and Nasimifar et al. (2019a). Both the Schmalzer and Weitzel (2017) approach and the Nasimifar et al. (2019) approach are based on the AASHTO 1993 overlay design procedure with the following two modifications:

1. Schmalzer and Weitzel (2017): The approach uses an alternative method to determine the TSD deflections based on the Boussinesq equation.
2. Nasimifar et al. (2019a): the approach recalibrates Rohde equation (Rohde 1994) to calculate SN_{eff} rather than the approach in the 1993 AASHTO overlay design, which is based on the equivalent pavement modulus.

Overlay design in both approaches is done based on the difference between SN_{req} and SN_{eff}; the difference (if positive) called overlay *SN*, SN_o. SN_o combined with the layer coefficient determines the required overlay thickness. SN_{req} is calculated using the AASHTO equation:

$$\log(ESALs) = z_R s_0 + 9.36\log\left(SN_{req} + 1\right) + \frac{\log\left(\frac{\Delta PSI}{2.7}\right)}{0.4 + \frac{1094}{\left(SN_{req} + 1\right)^{5.19}}} + 2.32log(M_r) - 8.27 \quad (24)$$

where
ESALs = number of 18-kip equivalent single-axle loads,
z_R = standard normal z-value (based on functional classification of road),
s_0 = standard deviation (usually 0.45),
ΔPSI = serviceability loss (1.7 for flexible pavements), and
Mr = subgrade modulus

The subgrade modulus is determined using Equation 19. The SN_{req} is determined for a specific design life (typically 20 years) and truck traffic (with possibly traffic growth). To calculate SN_{eff}, Nasimifar et al. (2019a) used Rohde's method (Equation 15 and Equation 16), while Schmaltzer and Weitzel (2017) follow the 1993 AASHTO procedure to calculate SN_{eff}, which is based on Equation 17 and Equation 18 presented earlier.

The overlay thickness (if required) can be calculated as follows:

$$b \times H_o = SN_{req} - SN_{eff} \quad (25)$$

where
b = overlay layer coefficient (0.44 for asphalt overlay), and
H_o = required overlay thickness (inches).

Backcalculation of Layer Moduli

In the mechanistic (empirical) analysis of pavements, critical strains in the pavement layers are evaluated: typically, the tensile strain at the bottom of the asphalt layer and compressive strain at the top of the subgrade. Strains are then used in transfer functions, for example the fatigue equation for the tensile strain, to determine the number of load applications to failure. This is why most indices used for network-level applications are evaluated based on their correlation to strains (e.g., Thyagarajan et al., 2011; Rada et al., 2016). However, at the project-level, strains are more accurately calculated based on the layer moduli.

Deflection data collected from TSDDs can be used to perform backcalculation of layer moduli using linear elastic or linear viscoelastic theory. Lee et al. (2016) used multi-layer elastic analysis to backcalculate the layer moduli of a highway pavement surveyed with a TSD. The backcalculation results obtained from TSD deflections were compared to the results obtained from FWD deflections, with the resulting difference being between 1% and 7%. Because of the familiarity of highway agencies with backcalculation using FWD deflections, some researchers have proposed methods to convert TSDD deflections into FWD deflections and then perform backcalculation using the converted deflections. The proposed conversion methods are usually based on simulated FWD and TSD deflections using viscoelastic multilayer software such as 3D-Move (Saremi, 2018, 2019) or ViscoWave (Steele at al., 2020; Zihan et al., 2020). The conversion of TSDD deflections to FWD deflections addresses the fact that TSDD loadings and measured deflections are not exactly the same as those of the FWD; however, in the long run, it would be better to perform the backcalculation on TSDD measurements directly. One advantage of this approach is that TSDDs are more representative of the actual truck loading, and in some cases backcalculation can be performed using the raw data collected by the device. For example, given that there are different methods that can be used to determine the TSD deflections from the deflection velocities, Nasimifar et al. (2017a) used 3D-Move to backcalculate the pavement layer moduli directly from the TSD deflection velocities, circumventing the need to determine the deflections. Although this approach is much more computationally demanding and time consuming than using a layer linear elastic software, it is feasible for detailed project-level analysis. Also recently, Nielsen (2019) presented a Python-based viscoelastic backcalculation tool for the TSD. This implementation considers the asphalt pavement layers as viscoelastic and the granular layers as linear elastic but with a degree of damping. The backcalculation procedure is reduced to a non-linear optimization problem where the layers' strength parameters (elasticity and viscosity) are the decision variables, and the target is minimizing the difference between predicted slope-deflection values at the locations of the TSD sensors and the actual measurements. This procedure was validated with actual TSD data obtained with the latest version of the TSD that uses a 12-sensor array with sensors in front of and behind the wheel load.

Summary and Conclusions

The push for the development of TSDDs started more than 20 years ago. Over the last 10 years, starting with the review of Rada and Nazarian (2011), TSDDs have been extensively tested, scrutinized, compared to the FWD, and shown to be adequate for network-level pavement management applications. The efforts have shown that TSDDs are ready for implementation. Of course, there are still important gaps that need to be filled; however, most of these gaps cannot be fully addressed without practical implementations by state departments of transportation. Some of the most important gaps are protocols for data collection, standards for calibration, approved guidelines for pavement management implementation, and verification and validation procedures. In terms of project level-applications, researchers have already started developing suitable approaches, and practical implementations should soon become available. However, the applicability of project-level analysis methods also depends on the availability of a calibration standard and verification and validation procedures.

We conclude with an overview of how state departments of transportation have used or plan to use TSDD measurements. This overview was presented at a workshop organized as part of the 2021 Transportation Research Board meeting. A detailed e-circular of this workshop will be published in the future, and we include only a relatively short summary of that workshop. The main activity of the workshop consisted of 10 presentations; seven from state highway agencies that have collected TSD measurements, one academic, one from an FHWA employee, and one from an AASHTO member. The academic presentation highlighted how far along pavement structural evaluation has progressed from the early Benckelman beam through the development of the FWD, which coincided with spread of the personal computer, all the way to the current state of the technology with TSDDs. The spread of the personal computer during the development of the FWD has certainly facilitated the development of backcalculation procedures to obtain pavement layer moduli. This has brought structural evaluation from a mostly qualitative measure with the Benckelman beam to a more mechanistic measure. Will advances in machine learning have a similar effect on how TSDD data is analyzed as the personal computer had on FWD data analysis?

In terms of state highway agencies, experience with TSDDs varies from agencies that have just started collecting their first set of data to agencies that are in the process of incorporating data into their PMS and developing procedures to use that data as part of the decision-making process. Irrespective of the level of experience with the use of TSDD data, there seems to be a relative consensus that TSDDs are “a game changer technology” and can provide better insight and better treatment selection. For example, Idaho has already evaluated the benefits of TSDDs in terms of monetary savings and determined a return on investment of 4 or more. Virginia and Texas are, like Idaho, relatively on their way to fully or partially incorporating TSDD measurements into the PMS and the decision-making process. Other agencies have initiated research projects (often with universities within their state) to find out how to best use TSDD measurements.

The FHWA has extensively supported the development and encouraged testing of TSDDs as a funding agency for different research projects as well as through in-house research. From that perspective, the advantages and usefulness of TSDDs have been well established. There still is a need for guidelines and procedures for data collection and quality assurance as well as calibration, verification, and validation of measurements. There also is a need to continue the development of structural performance models and procedures to evaluate rigid pavements, the foremost of which is the evaluation of joints in jointed concrete slabs.

AASHTO has a significant role to play as an umbrella agency providing the necessary requirements to moving from experimenting with TSDDs to implementing TSDDs. AASHTO can provide standards for test procedures and equipment management (calibration and validation of measurements). There already are AASHTO standards for FWD that can be used as an initial starting point for development of standards for TSDDs. One of the main benefits of these standards will be to harmonize the data across state lines.

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