

# **Development of structural condition thresholds for TSD measurements**

By

Shivesh Shrestha

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Gerardo W. Flintsch

Linbing Wang

Samer W. Katicha

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## **ACADEMIC ABSTRACT**

*Shivesh Shrestha*

This thesis presents (a) results of a field evaluation of the Traffic Speed Deflectometer (TSD) in the United States (b) deflection thresholds to classify the pavement structural condition obtained from the TSD for a small subset of the Pennsylvania secondary road network. The results of the field evaluation included: (1) repeatability of the TSD, (2) ability of the TSD to identify pavement sections with varying structural conditions, and (3) consistency between the structural number (S<sub>Neff</sub>) calculated from the TSD and S<sub>Neff</sub> calculated by the Pennsylvania Department of Transportation (PennDOT). The results showed consistent error standard deviation in the TSD measurements and that the TSD was able to identify pavement sections that varied in structural condition. Comparison of the S<sub>Neff</sub> calculated with TSD measurements, using an empirically developed equation by Rohde, with the S<sub>Neff</sub> calculated by PennDOT's Pavement Management System based on construction history showed similar trends, although the TSD-calculated S<sub>Neff</sub> was higher.

In order to develop deflection thresholds, a model that related the pavement surface condition to pavement surface age and structural condition was developed. Structural condition thresholds were then selected so that the pavement surface condition predicted from the model for a 10-year-old pavement surface fell within one of the three condition categories (Good, Fair, and Poor), to identify pavements in good, fair and poor condition. With Overall Pavement Index(OPI) characterizing the surface condition and Deflection Slope Index(DSI) characterizing the structural condition, the DSI threshold that separates structurally good from structurally fair pavements was determined as follows: (1) the OPI threshold that separates pavements with good surface condition from those with fair surface condition was obtained from the Pennsylvania Pavement Management System (PMS) and (2) the DSI thresholds were calculated using the determined OPI value and the model equation.

# **Development of structural condition thresholds for TSD measurements**

## **GENERAL AUDIENCE ABSTRACT**

*Shivesh Shrestha*

This thesis presents (a) some of the results of a field evaluation of the Traffic Speed Deflectometer (TSD) in the United States (b) deflection thresholds to classify the pavement structural condition obtained from the TSD for a small subset of the Pennsylvania secondary road network. The results of the field evaluation included: (1) repeatability of the TSD: which is the variation in repeated TSD measurements on the same section of the road, (2) ability of the TSD to identify pavement sections with varying structural conditions, and (3) consistency between the structural number (S<sub>Neff</sub>) calculated from the TSD and S<sub>Neff</sub> calculated by the Pennsylvania Department of Transportation (PennDOT). The pavement structural number is an abstract number expressing the structural strength of the pavement. The results showed that the TSD measurements were repeatable and that the TSD was able to identify pavement sections that varied in structural condition. Comparison of the S<sub>Neff</sub> calculated with TSD measurements, using an empirically developed equation by Rohde, with the S<sub>Neff</sub> calculated by PennDOT Pavement Management System based on construction history showed similar trends, although the TSD-calculated S<sub>Neff</sub> was higher.

In order to develop deflection thresholds to categorize pavements in different condition: good, fair and poor, a model that related the pavement surface condition to pavement surface age and structural condition was developed. Structural condition thresholds were then selected so that the pavement surface condition predicted from the model for a 10-year-old pavement surface fell within one of the three condition categories (Good, Fair, and Poor), to identify pavements in good, fair and poor condition. With Overall Pavement Index(OPI) characterizing the surface condition and Deflection Slope Index(DSI) characterizing the structural condition, the DSI threshold that separates structurally good from structurally fair pavements was determined as follows: (1) the OPI threshold that separates pavements with good surface condition from those with fair surface condition was obtained from the Pennsylvania Pavement Management System (PMS) and (2) the DSI thresholds were calculated using the determined OPI value and the model equation.

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# 1 INTRODUCTION

## 1.1 Background

Pavements are one of the largest assets of the transportation system. State Highway Agencies (SHAs) spend a large amount of money to meet the demands of expanding and maintaining the existing infrastructure and providing better facilities to the users. The American Society of Civil Engineers (ASCE)'s 2013 Infrastructure report card graded the road infrastructure with a rating of "D" stating that about 32% of America's major roads are in poor or mediocre condition (ASCE, 2013). With a large network of pavements coming to the end of their service life, it is important to implement a systematic process to improve the condition of the road infrastructure. This can be achieved through more effective pavement management practices.

The first pavement management system (PMS) was born after a number of prominent civil engineers involved in the US space program came together as they felt the need to integrate planning, design, construction, maintenance and rehabilitation together into a systematic method for providing the required pavement performance over a period of time (Haas et al., 2015). The early pavement management systems were based on parameters such as costs, distress measured, ride quality and traffic. With the development of different technologies over time, it was realized that surface condition (functional condition) measures were not sufficient to represent the overall pavement condition. To get a better picture of the overall pavement condition, the structural condition is also needed. If new surface treatments were applied to a pavement in bad condition, the surface condition measures would become not representative of the true condition of the existing pavement. A study conducted by Zaghoul et al. concluded that the network level decisions based on the functional condition of the pavement varied when parameters representing the structural condition of the pavement such as deflection were taken into account (Zaghoul et al., 1998).

Most of the State Highway Agencies (SHAs) Pavement Management Systems are based on surface condition data and do not consider the structural condition of the pavement. However, some State Department of Transportation (DOTs) have started to use deflection measurements from the

Falling Weight Deflectometer (FWD) to enhance their network-level pavement management processes (Flintsch & McGhee, 2009; Katicha et al., 2013). The FWD is a stationary deflection measuring device which imparts a load pulse to a pavement by dropping a weight on the circular load plate placed on the surface of the pavement. It simulates the loading produced by a rolling wheel and can only take stationary measurements at discrete points, limiting the density of points where data is collected. The FWD has to stop while taking the measurements, which poses potential safety hazards to the personnel as well as to the public and requires traffic control. This is where continuous deflection devices come into perspective, eliminating most of the limitation of working with the stationary measurement devices.

The Strategic Highway Research Program 2 (SHRP2) Project R06F evaluated various continuous deflection measuring devices that were available and identified the Traffic Speed Deflectometer (TSD) as one of the promising equipment to measure the pavement structural condition at traffic speed for potential applications to support network-level pavement management (Flintsch et al., 2013). The TSD measures the deflection slope at up to 60 mph using a set of velocity sensing lasers based on the Doppler's principle. The TSD uses Doppler lasers mounted at a small angle to measure the pavement deflection velocity. To remove the measurement dependence on vehicle speed, the deflection velocity is divided by the instantaneous survey speed to provide a measurement of deflection slope. The pavement deflection is obtained by integrating the deflection slope measurements. A detailed description on the calculation of the deflection measurements from the TSD has been presented by (Katicha & Flintsch, 2014). Furthermore, several deflection indices can then be derived from the deflection measurements. Although most of them have been developed using FWD measurements, they can also be computed using deflection from the TSD.

## **1.2 Problem Statement**

Although TSD measurements have been shown to be sensitive to the pavement structural condition there is still no clear guidelines on how these measurements can be used in a pavement management system. Some important questions that remain unanswered are: (1) what index should be calculated from TSD measurements and used in the pavement management system? (2) what thresholds should be used with the derived index to categorize the structural condition (e.g. good,

fair, poor)? and (3) how should the structural condition derived from the TSD be combined with other pavement management system data?

Answering these questions is a challenging task. Very few SHAs in the US have incorporated pavement structural condition into their network-level PMS and those that have done it, have used structural information obtained with the FWD. The TSD and FWD operate differently and it is not fully understood how the analysis methods developed for FWD data would perform with TSD data.

### **1.3 Objective**

The main objective of this research was to:

- 1) Evaluate repeatability of the TSD, its ability to identify pavements with varying structural condition.
- 2) Determine the effect of pavement structural condition as measured by the TSD, on the deterioration of the pavement sections using a specific case study.

In addition, the thesis also compares effective structural numbers (S<sub>Neff</sub>) calculated from the TSD and S<sub>Neff</sub> calculated by Pennsylvania Department of Transportation (PennDOT). The performance analysis was done using the pavement condition measurements from PennDOT, which uses a surface condition index called Overall Pavement Index (OPI).

### **1.4 Significance**

Most of the pavement management systems are based on the functional condition of the pavement and do not take into account the pavement structural condition in their decision-making process. The pavement surface distresses alone are not capable of representing the exact pavement condition. In order to make effective pavement management decisions and strategies, both the functional and the structural pavement condition data should be incorporated into the decision-making process. The deflection measurements currently remain the only reliable non-destructive method for determining the structural strength of flexible pavements (Ferne et al., 2013). Various studies have shown that incorporating deflection measurements along with the pavement functional condition data into the pavement management system can identify more cost effective pavement rehabilitation and preservation strategies reducing the average annual cost of maintenance significantly (Lister et al., 1982; Steele et al., 2015). Thus, in order to make more accurate and cost-effective pavement management decisions, the structural condition of the

pavements should be taken into consideration in the pavement management system. The deflections values can be used to categorize the pavements based on their structural health and this information can be incorporated into the pavement management system to make more accurate and cost-efficient pavement management decisions.

## 1.5 Scope

The thesis is organized into 5 chapters. Chapter 1 consists of the general background, problem statement, the objective of this thesis, its significance and the methodology used.

Chapter 2 consists of Literature Review which covered: (a) continuous deflection measuring devices; (b) indices that were used to represent the pavement structural condition at the network level; and (c) examples of implementation of deflection measurements for network-level pavement management applications.

Chapter 3 presents a paper that discusses some of the results of a field evaluation of the Traffic Speed Deflectometer (TSD). It presents measurements of deflection slope directly obtained from the TSD, pavement deflections calculated from the measured deflection slopes, and structural indices such as the structural curvature index (SCI) and the effective structural number ( $SN_{eff}$ ). This paper has been accepted for presentation and publication in the peer-reviewed proceedings of the 2017 World Congress on Pavement Asset Management (WPAM2017).

Chapter 4 presents a second paper that presents a novel approach to develop thresholds to classify the pavement structural condition obtained from the TSD. These thresholds were based on deterioration modeling which was performed for a small subset of the Pennsylvania secondary network that was tested with the TSD.

Chapter 5 presents the main findings and conclusions of the analysis and some recommendations for future research.

## 1.6 Methodology

The approach to meet the proposed research objective was based on (1) a critical analysis of previous documented work in the literature, and (2) analysis of data collected in Pennsylvania as part of a network-level TSD demonstration project.

**Literature Review:** The review included implementations of FWD indices. Although the FWD and TSD operate differently, it has been shown that measurements from both devices have good

correlation (e.g. Flintsch et al. 2013) and as such procedures developed with FWD data could potentially also be applicable with TSD data. Examples of recent FWD derived indices include the work of Bryce et al. (2013) and Gedafa et al. (2014). More recently, work with continuous deflection devices has been performed such as Elseifi et al. (2011) and Elseifi et al. (2012) with the RWD and Rada et al. (2015) with the TSD and RWD. Finally, significant work with the TSD has been performed in Europe (most prominently the UK), Australia, and South Africa.

**Analysis of the data collected as part of the network-level TSD demonstration project:** The analysis was based on PMS data from the state of Pennsylvania and TSD data collected as part of the demonstration project. The first part of the thesis reviewed (a) repeatability of the TSD, (b) ability of the TSD to identify pavement sections with varying structural conditions, and (c) consistency between the structural number (S<sub>Neff</sub>) calculated from the TSD and S<sub>Neff</sub> calculated by PennDOT. The second part of the thesis, the PMS and the TSD data was used to develop a model that relates the pavement surface condition to pavement surface age and structural condition. The pavement surface condition is summarized by Overall Pavement Index (OPI), which is used by Pennsylvania to combine all distresses into a single index that ranges from 0 to 100. The structural condition parameter used was the deflection slope index (DSI), which is the difference between the measured deflection 100 mm from the applied wheel load and the measured deflection 300 mm from the applied wheel load. Using this relationship, appropriate thresholds for the pavement structural condition index was developed based on the respective SHA pavement condition categories.

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## **2 LITERATURE REVIEW**

The American Association of State Highway and Transportation Officials (AASHTO) defined pavement management system as “a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating and maintaining pavements in a serviceable condition over a period of time” (AASHTO, 1993). A pavement management system performs analysis of the collected pavement condition data to support the necessary pavement maintenance and rehabilitation actions. This analysis is also used to identify and prioritize maintenance and rehabilitation needs and assist the agencies in determining cost-effective treatment strategies.

Different pavement quality parameters such as rutting, cracking, raveling and roughness are used to identify the functional condition of the pavement. The structural condition of the pavement is manifested in the pavement’s ability to resist deformation caused by heavy vehicles. Traditionally, this has been measured using FWD testing which applies a pulse load on the pavement and measures the resulting surface deflections at pre-selected locations. However, recent technological advancements have resulted in high-speed continuous deflection measuring devices, such as the TSD. Studies have shown that TSD has the potential of being used for the Pavement Management System at least at the network level (Ferne et al., 2009; Rada & Nazarian, 2011; Rada et al., 2015). However, there is still a need to develop methodologies to practically incorporate testing results from the TSD into a pavement management system.

### **2.1 Continuous Deflection Measuring Devices.**

Jitin et al. (2006) conducted a research for Texas Department of Transportation to summarize the state-of-the-art of continuous deflection measurement systems. The study looked into various deflection measuring devices available that could operate at a traffic speed including Quest ARWD, Swedish Road Deflection Tester, Texas Rolling Dynamic Deflectometer and Danish High Speed Deflectograph (later renamed to TSD). Methods for pavement structural evaluation using resilient modulus, deflection ratios, structural number (SN), and modified modulus were also summarized along with an alternative method for determining SN from FWD data and a simple approach to estimate the SN of pavements, which was originally presented by Zhang et al.,(2003). The study concluded that the TSD was the only device that had the possibility of being implemented into the pavement management system of various agencies, as it was the only device that was commercially available. The study also pointed out that it was likely that more than one

deflection value from the measuring instrument may be needed to confirm the existing structural capacity of the pavements. As the initial model of the TSD incorporated only 4 sensors, the study also suggested that if the TSD could be procured with seven sensors, that the data can be analyzed using Method IV proposed by Zhang et al., (2003) for pavement management (Jitin et al., 2006).

In 2010, the Virginia Department of Transportation (VDOT) conducted a study on the Rolling Wheel Deflectometer (RWD) as a network level structural evaluation tool. The study included RWD testing on three Virginia routes and also a comparison of the deflection measurements obtained with the RWD and FWD for sections on I-64 and I-84. The report recommended VDOT to continue using the FWD deflection testing to characterize the pavement network structurally and mentioned that it was not recommended to use RWD on low deflection pavements. The report concluded that the RWD deflections results were statistically different when repeated on certain sites (interstate pavements) and that it did not correlate well to the FWD measurements. Thus RWD was not a suitable tool to pre-screen the pavement network, as compared to the traditional FWD deflection testing (Diefenderfer, 2010). However, some other studies have shown that RWD does indeed have a reasonably good repeatability and there are no significant differences between the mean center deflections and corresponding computed effective structural numbers from RWD and FWD deflection data. (Gedafa et al., 2008) in their study found that there was a good correlation between FWD and RWD results for non-interstate pavements. Thus RWD could be used to do deflection surveys at the network level on certain type of pavements (Elseifi et al., 2011; Gedafa et al., 2008).

The Second Strategic Highway Research Program Project (SHRP2) evaluated the various continuous deflection measuring devices to support pavement management decisions and identified the most prominent ones. The devices that were looked into were the Portancemetre, Measuring Ball, Rolling Dynamic Deflectometer, Traffic Speed Deflectometer, Rolling Wheel Deflectometer, Airfield Rolling Weight Deflectometer and the Road Deflection Tester. The project identified 2 devices TSD and RWD capable of providing: adequate repeatability for network-level data collection, collecting deflection measurements and indices that are broadly comparable to those collected by traditional measurement devices such as the FWD, and providing measurements that can be used for supporting some of the network level pavement management

decisions. The capabilities of the TSD were confirmed in a second phase of the project; however, due to the unavailability of the RWD for detailed evaluation, the capabilities of the RWD were not confirmed (Katicha et al., 2013).

## **2.2 Network level deflection performance measures.**

Some of the deflection performance measures that have been used on a network level are as follow:

1. Surface Curvature Index (SCI)
2. Structural Number
  - a. Structural Number from FWD – Rohde, 1994
  - b. Structural Number from RWD – Elsefi, 2011
3. Structural Capacity Index – Rhode, 1994
4. Structural Condition Index – Zhang, 2003
5. Structural Strength Indicator – Flora, 2009
6. Remaining Service Life – Gedafa, 2010
7. Modified Structural Index – Bryce, 2013

Bryce et al., conducted an in-depth review of some of these deflection measures. A brief review of the most relevant for network-level deflection performance measurement is presented in the following sections.

### **2.2.1 Surface Curvature Index (SCI)**

Surface Curvature Index is expressed as the difference between the deflection from the first sensor ( $W_1$ ) and the second sensor ( $W_2$ ) from the FWD (Zhang et al., 2003). It has been found to correlate well with the Asphalt Concrete modulus (Xu et al., 2002). The following equation represents the Surface Curvature Index.

$$\text{Surface Curvature Index}(SCI) = W_1 - W_2 \quad (1)$$

### **2.2.2 Structural Condition Index (SCI)**

Zhang et al., (2003) proposed a structural index based on the FWD data, that was able to discriminate between pavements sections requiring additional structural capacity and sections for which surface treatments would be sufficient. This index provided a general indication of the structural adequacy of a pavement based on the estimated total thickness of pavement, as the actual layer-by-layer thickness of pavements was not available at the Texas Department of Transportation

(TxDOT). The research also presented the steps required for determining the required structural number ( $SN_{eff}$ ) to calculate the structural condition index.

The Structural Condition Index (SCI) is defined as the ratio of the existing SN and the required SN of a pavement:

$$SCI = \frac{SN_{eff}}{SN_{req}} \quad (2)$$

where, SCI = the Structural Condition Index,

$SN_{eff}$  = the existing (estimated) Structural Number, and

$SN_{req}$  = the required Structural Number.

### 2.2.3 Structural Strength Indicator (SSI)

(Flora et al., 2010) developed an index called the Structural Strength Index scaled from 0 to 100 based on the FWD measurements. A structural strength index of 0 represented that the pavement section was in the worst structural condition whereas a structural strength index of 100 represented that the pavement section was in the best structural condition. The Structural Capacity Index was defined as follows:

$$SSI_{jk} = 100(1 - \alpha e^{-\frac{\beta}{(\delta_1)^{\gamma}}}) \quad (3)$$

where,  $\delta_1$  is the deflection measured at the center sensor (in mils),

$\alpha$  and  $\beta$  are coefficients that has to be determined by performing regression analysis,

$j$  refers to the different pavement types wither asphalt or PCC, and

$k$  refers to different functional classes (interstate, non-interstate NHS and non-interstate non-NHS highways).

### 2.2.4 Modified Structural Index (MSI)

Bryce et al., (2012) developed a structural index which was capable of representing the pavement's structural condition for the use in network level pavement management applications. This index incorporated various parameters such as traffic, resilient modulus of the subgrade and deflections together into one measure. The study chose the Structural Capacity Index (SCI) originally developed by TxDOT to be modified and implemented within the VDOT's pavement management system. The modified index is called Modified Structural Index (MSI). The MSI is represented by the equation presented below (Bryce et al., 2012):

$$MSI = \frac{K1*(D_0 - D_{1.5Hp})^{K2} * Hp^{K3}}{\alpha*(\log(ESAL) - 2.32*\log(M_R) + \beta)^\gamma} \quad (1)$$

Where,  $D_0$  is the FWD center deflection for an equivalent 9000-pound load,

$D_{1.5Hp}$  is the deflection at 1.5 times the pavement thickness,

$H_p$  is the pavement thickness,

ESAL is the calculated traffic,

$M_R$  is subgrade resilient modulus calculated as  $((0.33*9,000*0.24))/(D_{60}*60)$  with  $D_{60}$  as the deflection at 60 inches away from the center of the load, and

$K_1$ ,  $K_2$ ,  $K_3$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$  are constants that depend on the different types of roads: Interstates, Primary and Secondary.

An enhanced decision matrix, which could be used to select different types of treatments to be applied on the pavement based on the initial decision and MSI values (Table 1) was also developed.

**Table 1: Enhanced decision matrix based on Initial decision (Bryce et al., 2012)**

Initial Decision		DN		PM		CM		RM		RC	
Pavement Surface Age (Years)		≤6	>6	≤6	>6	≤6	>6	≤6	>6	≤6	>6
MSI	≥1	DN	PM	PM	PM	CM	CM	RM	RM	RC	RM
	<1 and ≥0.9	CM	RM	CM	RM	RM	RM	RC	RC	RC	RC
	<0.9	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC

The study found a weak correlation between the various distress based-condition indicators and the structural condition indicators of the pavement. This supported the hypothesis that the functional characteristics of a pavement network alone are not sufficient to describe the overall condition of the pavement. The network-level pavement management decisions that incorporated the structural conditions were closer to the decisions made during the project level assessment than the ones based only on functional condition and surface distress. Furthermore, the study also presented a pilot application of the developed MSI for flexible pavements as a structural screening tool, a performance indicator and also a tool in scoping projects at network level and estimating the overlay thickness.

## 2.2.5 Structural Number

### *Structural Number from FWD Data*

The pavement's structural number can be computed using nondestructive deflection testing based on the techniques presented in the 1986 AASHTO guide design for pavement. But the techniques proposed by in the AASHTO guide caused problems in characterizing the structural strength of the pavement at the network level (Rohde, 1994). Thus, Rhode proposed a method to calculate the structural number of the pavement from its total thickness and the shape of the deflection bowl. The Structural number of a pavement as proposed by Rhode's method can be calculated by using the equations presented below:

$$SIP = D_0 - D_{1.5Hp} \quad (2)$$

where,

$D_0$  = Peak deflection measured under a standard 9000lb FWD load,

$D_{1.5Hp}$  = deflection measured at an offset of 1.5times  $H_p$  under standard 9000lb FWD load,

SIP = Structural Index of pavement, and

$H_p$  = total pavement thickness.

Once the structural index of the pavement was calculated the equation presented below was used to calculate the structural number of the pavement.

$$SN = k_1 SIP^{k_2} H_p^{k_3} \quad (3)$$

where,

SN = Structural number,

$H_p$  = total pavement thickness (mm),

$k_1, k_2, k_3$  = coefficients for different surface types.

The approach presented was verified and compared with other techniques that were available on 62 pavement structures. The procedure gave similar results to those obtained by backcalculation using AASHTO NDT Method I, but the results were not similar to AASHTO NDT Method II. AASHTO NDT Method I involves the mechanistic analysis of measured deflections using two backcalculation programs MODULUS and ELMOD. The layer moduli are translated to layer coefficients which are used along with the recorded layer thickness to determine the structural number. The following equation is then used to calculate the structural number. (Rohde, 1994)

$$SN = \sum_{i=1}^n h_i a_g \left( \frac{E_i}{E_g} \right)^{1/3} \quad (4)$$

Where,  $a_g$  = the layer coefficients of standard materials,  $E_g$  = the resilient modulus of standard materials,  $h_i$  = the layer thickness and SN = the structural number.

AASHTO NDT Method II uses outer deflection sensors to determine the subgrade stiffness and then the structural number is calculated by the following equation (Rohde, 1994):

$$D_0 = \frac{1.5P}{\pi a} \left\{ \frac{(0.0045h)^3}{SN^3} \left[ 1 - \frac{1}{(1+(h/a)^2)^{1/2}} \right] + \frac{1}{E_s \left( 1 + \frac{40000SN^2}{a^2 E_s^{2/3}} \right)^{1/2}} \right\} \quad (5)$$

where,  $D_0$  = peak FWD deflection,

$P$  = FWD load (lb),

$h$  = pavement layer thickness,

$a$  = load radius,

$E_s$  = subgrade modulus,

SN = structural number.

a. Structural Number from RWD data

Based on a testing program in Louisiana, Elseifi et al., (2011) developed a simple regression model to estimate pavement structural number at the network level using RWD data. During this study, for the initial pavement structural evaluation, the structural number of the pavement was calculated from the RWD deflection measurements using the 1993 AASHTO design guide for FWD. The purpose of the developed model was to serve as a quick and simple screening tool at network level to identify pavement sections that were structurally deficient from the ones that were not. The model that was developed is presented below:

$$SN_{RWD} = -6.37 + \frac{150.69 * RI^{-0.81}}{RI + 19.04} + 23.52 * RWD^{-0.24} - 1.39 * \ln(SD) \quad (6)$$

where, RI = RWD index (mils<sup>2</sup>) = RWD deflection × SD of RWD deflection;

RWD = average RWD deflection measured on a road segment (mils)

SD = standard deviation of RWD deflection on a road segment (mils)

$SN_{RWD}$  = pavement structural number predicted from RWD measurements.

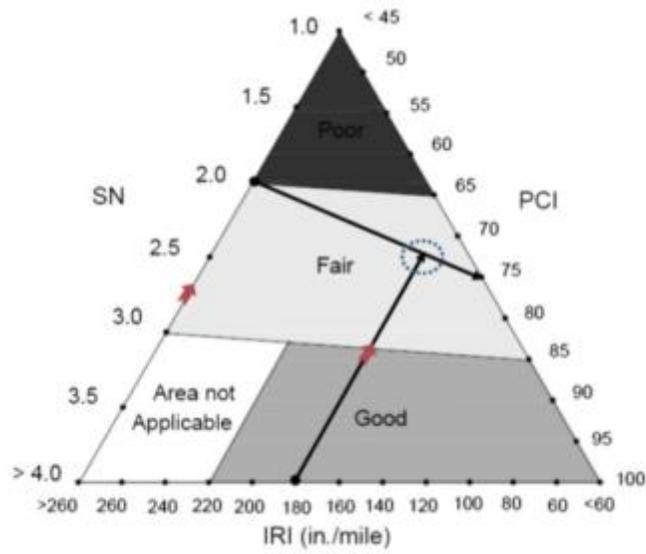
The model was applied at 52 in-service pavements in Louisiana as a part of the testing program. The RMS error of the model indicated that the average deviation between the model and the FWD-calculated SN was 0.63, and the coefficient of determination ( $R^2$ ) was 0.77 (Elseifi et al., 2011).

## **2.3 Use of Deflection Measurements for Pavement Management**

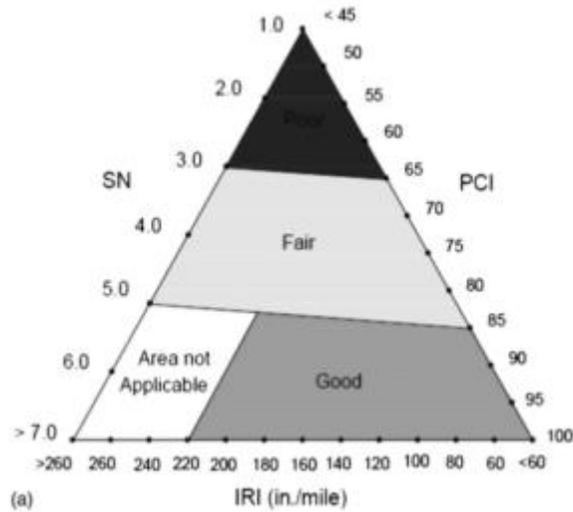
This section presents a few examples of uses of continuous deflection measurements for supporting network-level pavement management decisions.

### **2.3.1 Louisiana DOT**

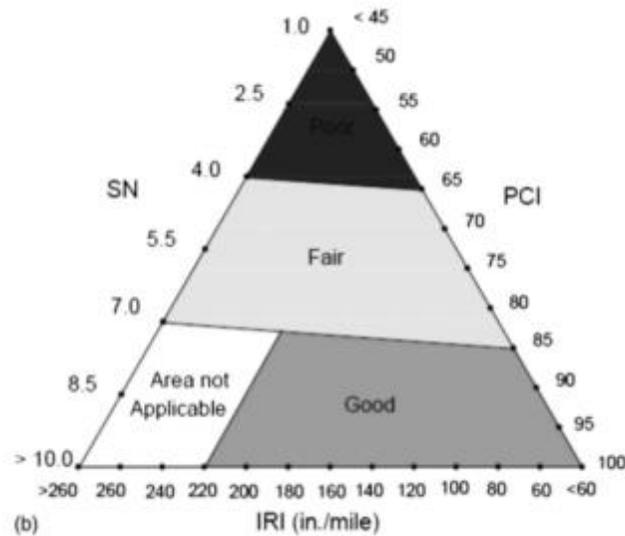
Based on the findings presented in the study by Elseifi et al., (2011), a triangular model to predict overall pavement conditions on the basis of RWD deflection, roughness measurements and surface conditions described by Pavement Condition Index (PCI) was proposed by Elseifi et al., (2012). The triangular model utilized the screening tool proposed during the previous study to calculate the SN of the pavement using the RWD parameters. The pavements were divided into three categories based on their thickness: Thin pavements (<3 in. of AC), Medium pavements (3–6 in. of AC), and Thick pavements (> 6 in. of AC). A threshold value was then set for the SN, IRI and PCI. Based on this threshold a graphical pavement assessment tool was developed that defined the overall condition of the pavement based on the three parameters. This triangular model was applied to 220 sections tested in Louisiana. The results showed there was a difference in the results obtained from the assessment based only on the SN and the results obtained from the assessment based on the triangular model, which takes into consideration both the structural and functional condition of the pavement. The study concluded that an increase in the pavement IRI and decrease in PCI was associated to the decrease in the FWD calculated SN and the RWD deflection, and also the surface roughness had a significant influence on both FWD and RWD measurements. (Elseifi et al., 2012)



**Figure 1: Pavement assessment triangular model for thin pavements (Elseifi et al., 2012)**



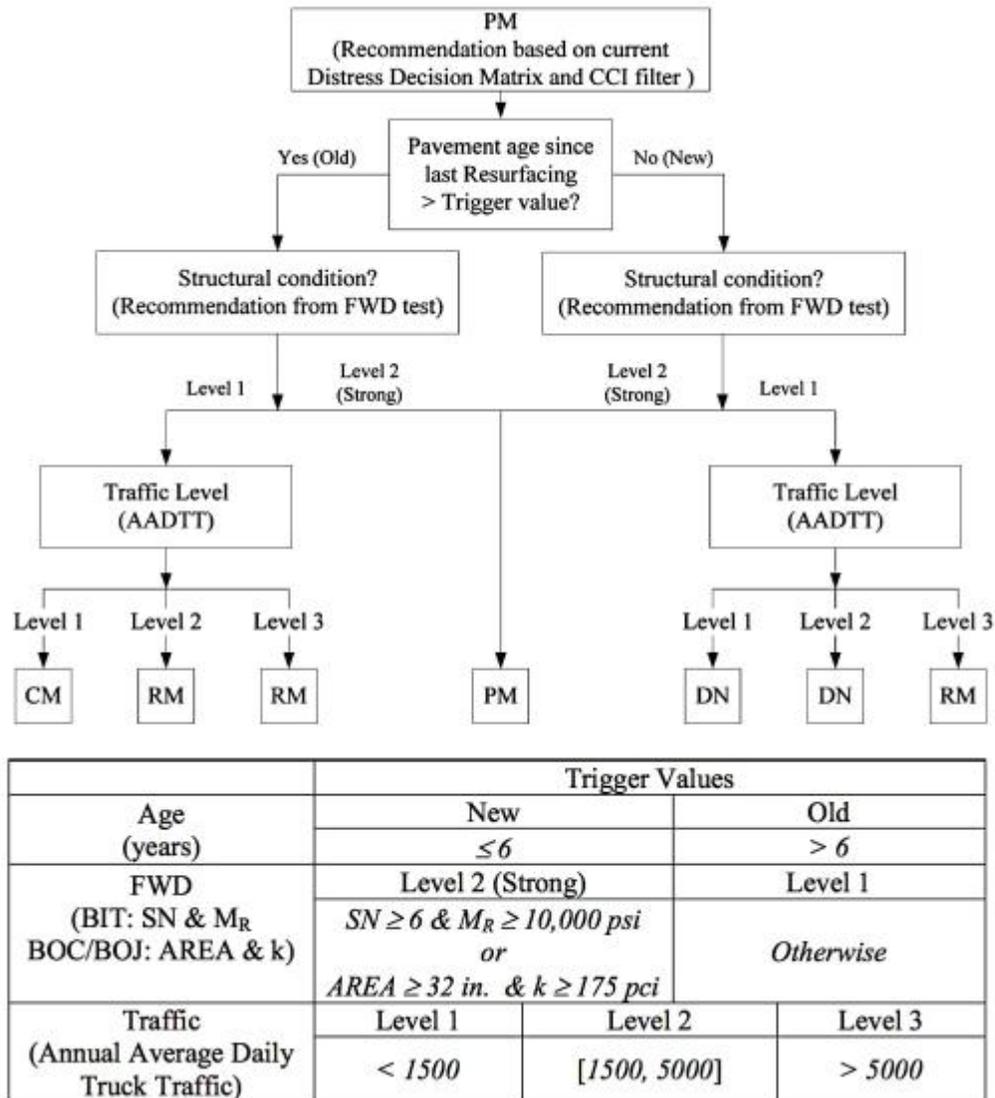
**Figure 2: Pavement assessment triangular model for medium pavements (Elseifi et al., 2012)**



**Figure 3: Pavement assessment triangular model for thick pavements (Elseifi et al., 2012)**

### 2.3.2 Virginia DOT

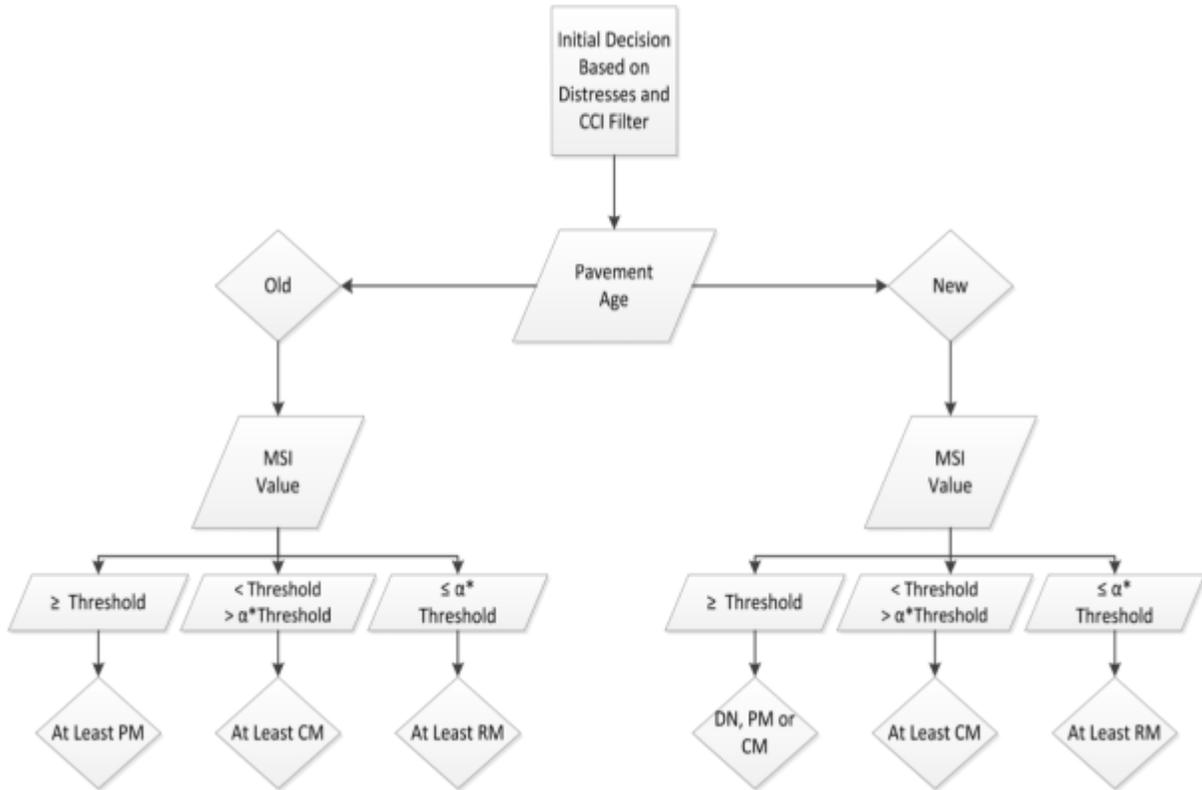
Chowdhury et al., (2012) presented results of their study in which the data obtained from FWD testing was implemented on the decision tree structure for network level pavement evaluation. In this study, the structural capacity of flexible pavements was represented by effective structural number ( $SN_{eff}$ ) and resilient modulus ( $M_R$ ), whereas for rigid and composite pavements the structural capacity was represented by deflection under the load plate and the deflection basin area. Different threshold values were developed to indicate the structural adequacy of the pavements. The existing decision tree model was then updated to include the age of the pavement, traffic level and the structural adequacy required. A sensitivity analysis showed that the variation in area under the deflection basin had the highest effect in the percentage of lane miles affected followed by the structural number. Also “approximately 10.6% of the interstate lane mileage was recommended to have a less severe treatment, whereas approximately 3.4% of the interstate lane mileage was recommended to have a more severe treatment” when compared with the decisions without considering the structural capacity (Chowdhury et al., 2012). Figure 4 shows an example of the decision tree structure presented by Chowdhury in his study.



**Figure 4: Enhanced decision tree for interstate full-depth flexible pavement with a recommendation for preventive maintenance (Chowdhury et al., 2012)**

This decision matrix was then modified by Bryce et al., (2012) which incorporated MSI into the VDOT decision process as shown in Figure 5. As mentioned earlier the MSI incorporates the traffic levels, structural number of the pavement and resilient modulus of the pavement into one measure. Thus, the modified decision tree incorporates all these parameters into the decision-making process. Based on the MSI threshold values the pavement treatment categories have been classified into 3 categories. Each of these categories suggests a particular type of pavement treatment depending upon their level of structural inadequacy. The first category in which the pavement

exceeds the MSI threshold values representing the pavement that is structurally adequate. The second category in which the pavement MSI values fall below the selected threshold but above the threshold value of  $\alpha$  represents a pavement that is structurally deficient. The parameter  $\alpha$  is used to differentiate whether a pavement section is deficient or severely deficient. The third category in which the pavement falls below both the selected threshold and the threshold  $\alpha$  represents a pavement that is severely deficient. (Bryce et al., 2012)



**Figure 5: Decision Process Based on MSI for Bituminous Pavements (Bryce et al., 2012)**

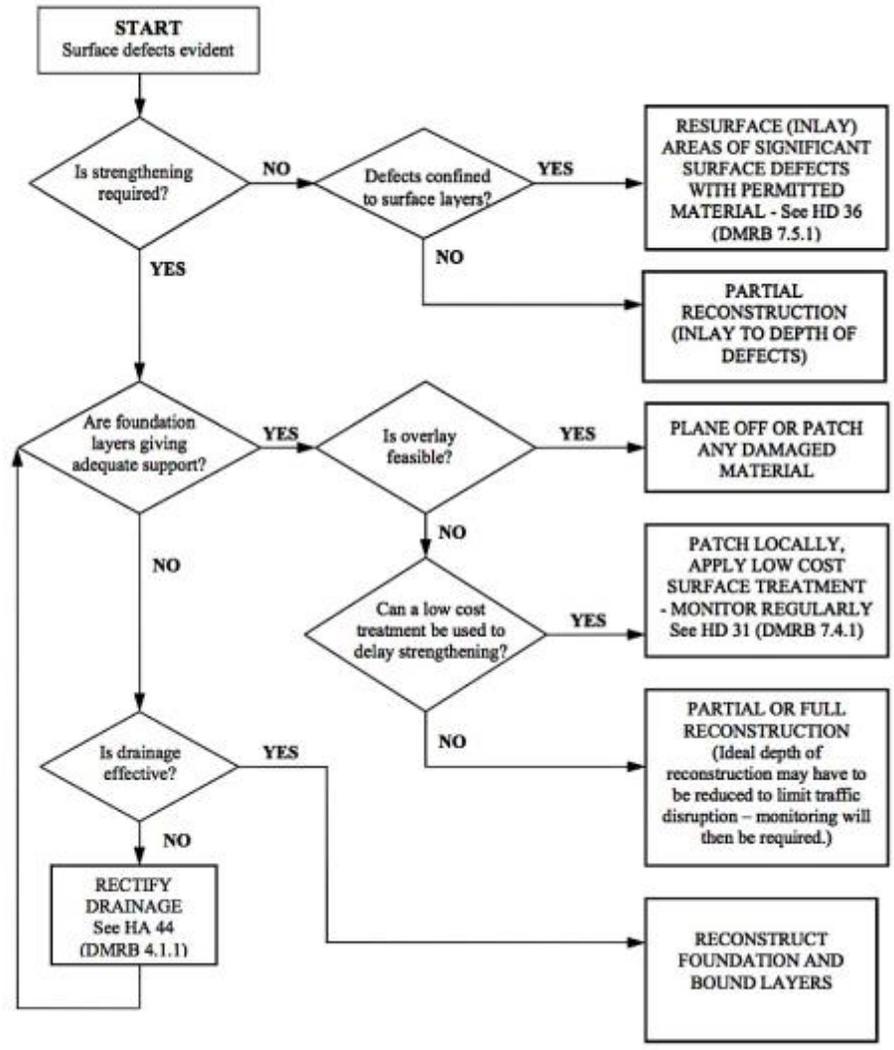
### 2.3.3 UK Highway Agency

A similar approach has been adopted by Transport Research Laboratory (TRL) to incorporate the deflection values obtained from TSD into their network level pavement management decision making process. The UK Highway Agency has used Deflectograph and Falling Weight Deflectometer (FWD) for many years in order to evaluate pavement deflection measurements. In 2010, they implemented a methodology for assessing the structural strength of the pavement network based on traffic speed structural condition surveys. They developed an algorithm that

converted the TSD measurements to an estimated peak deflectograph value. The algorithm incorporated the pavement construction and traffic data obtained from the UK Highway Agency Pavement Management System (HAPMS) to identify homogeneous pavement sections for each 100m length. Each of these sections were then categorized into one of the four Network Structural Category (NSC). The definition of the Network Structural Categories has been presented in Table 2. The appropriate treatments are selected based on the decision-making process mentioned in the “HD30/08-Design Manual for Roads and Bridges (DMRB), Maintenance assessment procedure. London, UK.”. The flowchart presented in the Figure 6 represents the decision-making process used by the UK Highway Agency (Ferne et al., 2013).

**Table 2: UK Network Structural Condition categories (Ferne et al., 2013).**

<b>Category</b>	<b>Description</b>
1	Flexible pavements without any need for structural maintenance
2	Flexible pavements unlikely to need structural maintenance
3	Flexible pavements likely to need structural maintenance
4	Flexible pavements very likely to need structural maintenance



**Figure 6: Maintenance Treatment Options for Flexible Pavements with Asphalt Base (Ferne et al., 2013).**

### 2.3.4 Other Recent Studies

Muller & Roberts (2013) showed that the deflection parameters: maximum deflection ( $d_0$ ) and  $SCI_{300}$  calculated from the TSD have shown to correlate well with the traditionally used FWD. They concluded in their study that there was a good correlation between the shape and magnitude of the TSD deflection bowls based on the approach proposed in their study. The TSD predictions of  $d_0$  and  $SCI_{300}$  based on the measured deflection bowl were on average 6.4% and 16.6% higher than the corresponding FWD measurements respectively (Muller & Roberts, 2013). Rada et al., (2015)

also recommended deflection slope index  $DSI_{4-12}$  (difference between deflections at 4 and 12 inches from the applied load) as the most appropriate index along with  $SCI_{12}$  (also known as  $SCI_{300}$ ) for use in network level pavement management system decision making process.

In 2014, Applied Research Associates, Inc. (ARA) collaborated together with Oklahoma Department of Transportation (ODOT) to study the potential benefits of integrating the pavement structural data obtained from RWD into their pavement management decision process. The pavement structural data obtained from the RWD was used to obtain a pavement condition index called the Pavement Quality Index (PQI). The PQI being a function of four indices: ride quality, rutting, surface distresses and structural condition. Replacing the structural condition used by ODOT (base condition rating) to calculate the PQI with the RWD data decreased the annual average budget by 2.7% and 21.6 % for the Target PQI analysis and the unconstrained analysis respectively. The study also analyzed different modified scenarios that included expanding the pavement preservation and changing the pavement trigger values. By incorporating the deflection data and expanding the pavement preservation to moderate the annual cost was significantly reduced by 25.4%. Lowering the trigger for pavement preservation from a PQI of 88 to a PQI of 85 resulted to a savings of 38.2 % compared to the PQI only strategy which did not take account any deflection measurements. The study concluded that significant cost savings can be realized by using the network-level deflection data to optimize the pavement treatment selection and timing. (Steele et al., 2015)

## **2.4 Summary of the Literature Review**

The literature review shows sufficient evidence to conclude that:

1. The structural condition of the pavement is one of the important measure to determine the overall condition of the pavement. It should be used along with the distress data to achieve more accurate information about the existing pavement condition.
2. There is a need for traffic speed survey vehicles that can evaluate the pavement structural condition. TSD is one of the devices capable of evaluating the structural condition of the pavements at the network level.
3. In the past, different structural indices obtained from the FWD and RWD measurements have been used to represent the structural condition of the pavement and assist in network level decision making process.

4. Some of the few indices obtained from the TSD are reliable and can be used for network level structural evaluation of the pavements. Thus, it is necessary to develop a method to understand and represent these indices to identify the pavements according to their existing structural health and use this information to assist in the network level pavement management decision making process.

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# 3 FIELD DEMONSTRATION OF THE TRAFFIC SPEED DEFLECTOMETER

Shivesh Shrestha, Samer W. Katicha, and Gerardo W. Flintsch

*Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute,  
3500 Transportation Research Plaza (0536), Blacksburg, VA, 24061, USA*

*Corresponding Author:*

Shivesh Shrestha

Charles E. Via, Jr. Department of Civil & Environmental Engineering, Virginia Tech, Blacksburg,  
VA, 24061, USA

Email: Shivesh@vt.edu

## 3.1 Abstract

This paper presents the results of a field evaluation of the Traffic Speed Deflectometer (TSD) in the United States. The evaluation was performed with the participation of nine state highway agencies that are members of a national pooled fund project. The paper presents several methods used to analyse pavement structural conditions using data obtained from the TSD, including (1) measurements of deflection slope directly obtained from the TSD, (2) pavement deflections calculated from the measured deflection slopes, and (3) structural indices such as the structural curvature index (SCI) and the effective structural number ( $SN_{\text{eff}}$ ). The results show consistent error standard deviation in the TSD measurements and that the TSD was able to identify pavement sections that varied in structural condition. Comparison of the  $SN_{\text{eff}}$  calculated with TSD measurements, using an empirically developed equation by Rohde, with the  $SN_{\text{eff}}$  calculated by the Pennsylvania Department of Transportation (PennDOT) Pavement Management System based on construction history showed similar trends, although the TSD-calculated  $SN_{\text{eff}}$  was higher.

Keywords: Pavements, Deflection, Traffic Speed Deflectometer, Pavement Management System, Structural Number

## **3.2 Introduction**

In September 2013, the Traffic Speed Deflectometer (TSD) was brought to the U.S. to perform field testing demonstration trials for interested state departments of transportation participating in a national pooled fund project managed by the Federal Highway Administration (FHWA). The project concluded the first set of TSD testing in seven participating states in July 2014. Two more states joined the pooled fund in 2015.

As part of the demonstration project, data analysis methods that can be used with the TSD measurements were assessed. This included evaluation of the operational accuracy of the TSD, calculation of engineering parameters that characterize the pavement structural condition, comparison with falling weight deflectometer (FWD) measurements where available, and methods to incorporate TSD measurements into a pavement management system. The results presented in this paper was obtained during the data analysis in the project.

## **3.3 Objective**

The objective of this paper is to evaluate structural condition measures collected by the TSD, including the following: (1) repeatability of the TSD, (2) ability of the TSD to identify pavement sections with varying structural conditions, and (3) consistency between the structural number ( $SN_{\text{eff}}$ ) calculated from the TSD and  $SN_{\text{eff}}$  calculated by the Pennsylvania Department of Transportation (PennDOT).

## **3.4 Methodology**

### **3.4.1 Traffic speed deflectometer (TSD)**

The TSD, shown in Figure 7, is an articulated truck with a rear-axle load of 100 kN (22 kips), which, in the model evaluated, uses seven Doppler lasers mounted on a servo-hydraulic beam to record the deflection velocity of a loaded pavement. Six Doppler lasers are positioned such that they measure deflection velocity at a range of distances in front of the rear axle: 100, 200, 300, 600, 900, and 1,500 mm (3.9, 7.9, 11.8, 23.6, and 59 inches). The seventh sensor is positioned 3,500 mm (11.5 ft) in front of the rear axle, largely outside the deflection bowl, acting 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 1,000 Hz.



**Figure 7. Picture of TSD used during testing and computer generated-schematic**

The TSD uses Doppler lasers mounted at a small angle to measure the pavement deflection velocity. Due to its location, midway between the loaded trailer axle and the rear axle of the tractor unit, the reference laser is expected to measure very little vertical pavement deflection velocity, and its response can therefore be used to remove unwanted signals from the six measurement lasers. When accurately calibrated, the TSD measures pavement deflection velocities that do not depend on driving speed. To remove this dependence, the deflection velocity is divided by the instantaneous survey speed to give a measurement of deflection slope. Thus, the deflection slope is calculated as follows:

$$S = \frac{V_v}{V_h} \quad (10)$$

where,  $S$  is the deflection slope

$V_v$  is the vertical pavement deflection velocity

$V_h$  is the vehicle horizontal velocity.

Typically, the deflection velocity is measured in mm/s while the survey speed is measured in m/s; therefore, deflection slope measurements are output in units of mm/m. At a speed of 80 km/h (50 mph) and a data collection frequency of 1,000 Hz, measurements are collected at 22.4-mm (0.88-inch) intervals, resulting in an average of 446 individual measurements for a 10-m (33-ft) section of pavement.

### 3.4.2 Data analysis methods

#### 3.4.2.1 Noise standard deviation of deflection slope measurements

Noise standard deviation can be calculated from a single test run measurement using the difference sequence method (Katicha et al., 2012; Katicha et al., 2013; Katicha et al., 2014; Hall et al., 1990; Brown and Levine, 2007). The simplest of the difference sequence methods consists of taking the difference between two consecutive measurements. If  $\hat{d}$  refers to the TSD-measured deflection slope, which can be decomposed into true deflection slope  $d$  and measurement error  $\varepsilon$ , then the difference sequence calculates the pseudo-residuals,  $DS$ , as follows:

$$DS_i = \frac{\hat{d}_i - \hat{d}_{i+1}}{\sqrt{2}} = \frac{d_i - d_{i+1}}{\sqrt{2}} + \frac{\varepsilon_i - \varepsilon_{i+1}}{\sqrt{2}} \quad (11)$$

The error standard deviation is then estimated using the robust median absolute deviation (Katicha et al., 2016; Xu et al., 2002):

$$S = 1.4826 \times \mathbf{median}(|DS_i - \mathbf{median}(DS_i)|) \quad (12)$$

Equation 11 is a consistent estimate of the standard deviation of a normally distributed variable, which was verified for the TSD in Katicha et al. (2014). A simple explanation to confirm that the measurement error is normally distributed for the data collected in this pooled fund project is that each TSD measurement is the average of about 450 measurements obtained over a 10-m interval. Even if the error in each of those 450 individual measurements is not normally distributed, by the central limit theorem, the error of the 10-m average tends to the normal distribution.

#### 3.4.2.2 Noise standard deviation using repeated tests

If repeated runs are performed on the same section, then the noise standard deviation can also be estimated by taking the difference between the two repeated runs. Two sets of measurements can be described as follows:  $\hat{d}_{1i} = d_{1i} + \varepsilon_{1i}$  and  $\hat{d}_{2i} = d_{2i} + \varepsilon_{2i}$ , respectively. Here, the subscripts 1 and 2 denote the test number while the subscript 'i' denotes the measurement location. To estimate the TSD measurement noise standard deviation, the difference,  $\hat{d}_{2i} - \hat{d}_{1i}$ , is calculated as follows:

$$\hat{d}_{2i} - \hat{d}_{1i} = (d_{2i} - d_{1i}) + (\varepsilon_{2i} - \varepsilon_{1i}) \quad (13)$$

Because we are taking repeated measurements at the same location and  $(d_{2i} - d_{1i}) = 0$ , we can

calculate a DS-like quantity by dividing Equation 13 by  $\sqrt{2}$  and determine the error standard deviation using Equation 11.

### 3.4.2.3 Calculation of pavement deflection and structural indices

The most important step in the deflection and structural indices calculation is the calculation of the deflections from the deflection slope measurements. Once the deflections are known, the structural indices are easily obtained as a function of the calculated deflection. The deflection is calculated by integrating the deflection slope as follows:

$$d(x) = \int_x^{\infty} s(y) dy \quad (14)$$

where,  $s(y)$  = slope at location  $y$  measured from the applied load

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

The infinite upper limit of integration is a theoretical bound. In practice, the upper limit of integration should be selected large enough so that the deflection at that location is very small (practically zero). In the calculations performed in this project, the upper limit of integration was set at 3.5 m (11.5 ft). Because the deflection slope is measured at finite discrete locations, the integration is performed numerically using the trapezoidal integration rule.

The structural indices calculated are the Structural Curvature Index 300 (SCI300) and the effective structural number ( $SN_{eff}$ ). The SCI300 is a deflection index that has been shown to relate to asphalt layer modulus and strain levels (Xu et al., 2002), which can be calculated from the TSD deflection slope. It can be calculated using Equation 15:

$$SCI300 = D(0) - D(300) \quad (15)$$

$SN_{eff}$  was calculated using Rohde's method (1994):

(1) Determine the structural index of the pavement (SIP) as follows:

$$SIP = D(0) - D(1.5H_p) \quad (16)$$

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.

(2) Determine the existing pavement  $SN_{eff}$  as

$$SN_{eff} = k_1 SIP^{k_2} H_p^{k_3} \quad (17)$$

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

This method was used to calculate the structural number for the deflection data obtained from the TSD. The results of structural number calculations for Pennsylvania are presented in this paper. The TSD-calculated  $SN_{eff}$  values were compared to  $SN_{eff}$  values estimated by PennDOT based on construction history (Figure 14). The PennDOT method consists of determining  $SN_{eff}$  based on layer thicknesses and layer structural coefficients as follows:

$$SN_{eff} = \sum_{i=1}^n a_i H_i m_i \quad (18)$$

where  $a_i$  is the layer coefficient

$H_i$  is the layer thickness

$m_i$  is the drainage coefficient.

Layer coefficients are based on material used and the age of the layer. As an example, asphalt layers are assigned a layer coefficient of 0.44 for the first 9 years of service and 0.30 after that.

## 3.5 Results

### 3.5.1 Noise standard deviation of deflection slope measurements

Table 3 shows the estimated noise standard deviation on an 8.5-mile pavement section tested in the state of New York. Two runs on consecutive days were performed, and the results of the noise estimation for each day are in good agreement. Using the test results of both runs, the noise standard deviation can also be evaluated using Equation 11 and Equation 12; the results are reported in the “Both Days” row of Table 3. The results are again in agreement with the estimation performed for each individual run (“Day1” and “Day2”). The results of each sensor show that, as the sensors get closer to the applied load, the estimated noise standard deviation increases. This is because the sensors closer to the applied load measure higher deflection slope values, which affects the noise estimation. For example, in Equation 11, when the sensor is close to the applied load (for example, the sensor that is 100 mm from the applied load),  $d_i - d_{i+1}$  is relatively large compared to  $\varepsilon_i - \varepsilon_{i+1}$ . In that case, the estimated noise standard deviation will be larger. On the other hand, when the sensor is far from the applied load,  $d_i - d_{i+1}$  is relatively small compared to  $\varepsilon_i - \varepsilon_{i+1}$ , and the estimated noise standard deviation is not significantly affected by the pavement deflection. Note that this effect is also linked to the data reporting interval, as discussed in Flintsch et al. (2013), Katicha et al. (2012), and Katicha et al. (2014).

**Table 3. Estimated noise standard deviation for two consecutive test runs performed in New York**

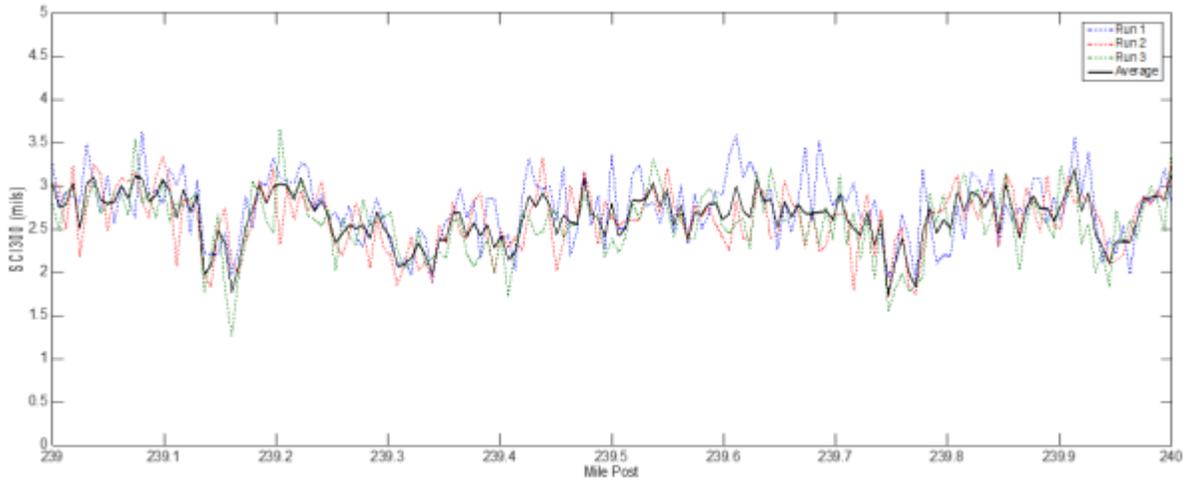
Testing	Sensor Position [mm]					
	1500	900	600	300	200	100
Day1	0.3768	0.3948	0.4428	0.4788	0.4764	0.5460
Day2	0.3948	0.4056	0.4416	0.4764	0.4980	0.5736
Both Days	0.3984	0.4476	0.4548	0.5520	0.4800	0.5988

### 3.5.2 Repeatability

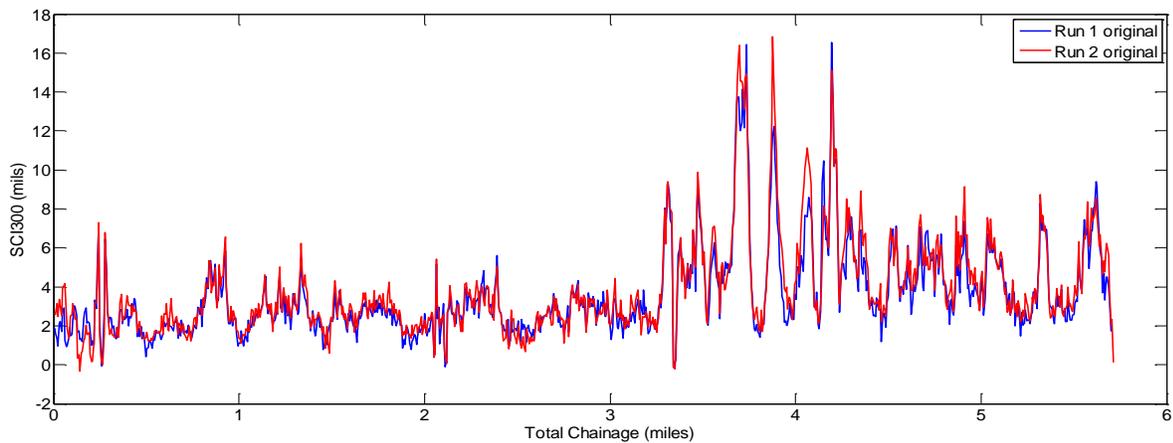
One way to quantify repeatability is to define it as the difference between two measurements obtained at the same location. Given this definition, a perfectly repeatable device is one in which the difference is always equal to zero. The difference between two measurements can be decomposed into systematic and random error (which is the error noise standard deviation). The systematic difference can often, though not always, be corrected through calibration; however, the random difference is unavoidable. Flintsch et al. (2013) showed that, in the TSD’s case, the systematic error is negligible compared to the random error. For this reason, the error noise standard deviation calculated in the previous section can be used as an indicator of repeatability.

Figure 8. Measured SCI300 on 1-mile section of Interstate 57 in Illinois. Figure 8 shows the SCI300 results of a tested 1-mile section of Interstate 57 in Illinois. Three test runs were performed in succession, and the results show that the three runs follow the same trend, which is better represented by the average of the three runs.

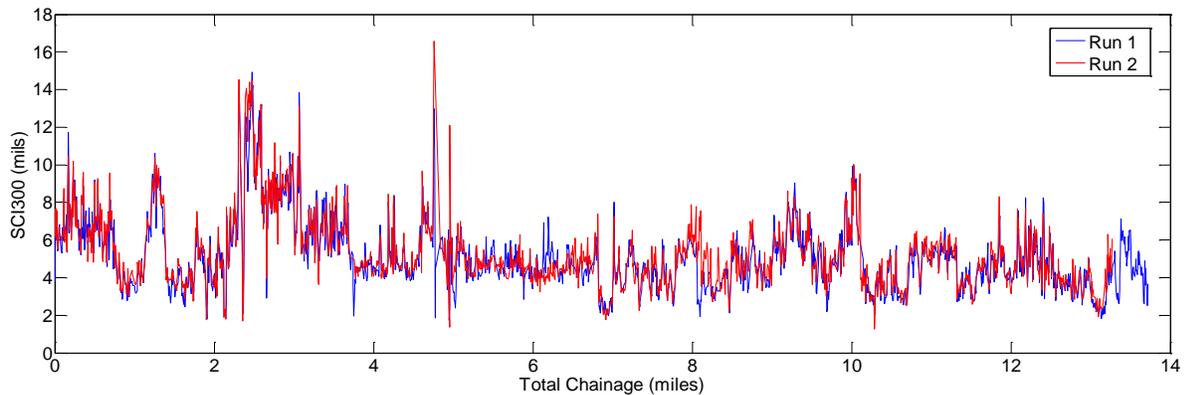
Figure 9 and Figure 10 show the measured SCI300 of the original repeated runs on State Route 26 South in New York and Jackson Road in California, respectively. The repeated runs tested in New York were performed on the same day, as were the repeated runs in California. The results for both New York and California demonstrate good repeatability for the TSD, as the plots for the individual and average runs closely follow each other.



**Figure 8. Measured SCI300 on 1-mile section of Interstate 57 in Illinois**



**Figure 9. Measured SCI300 on State Route 26 South in New York**

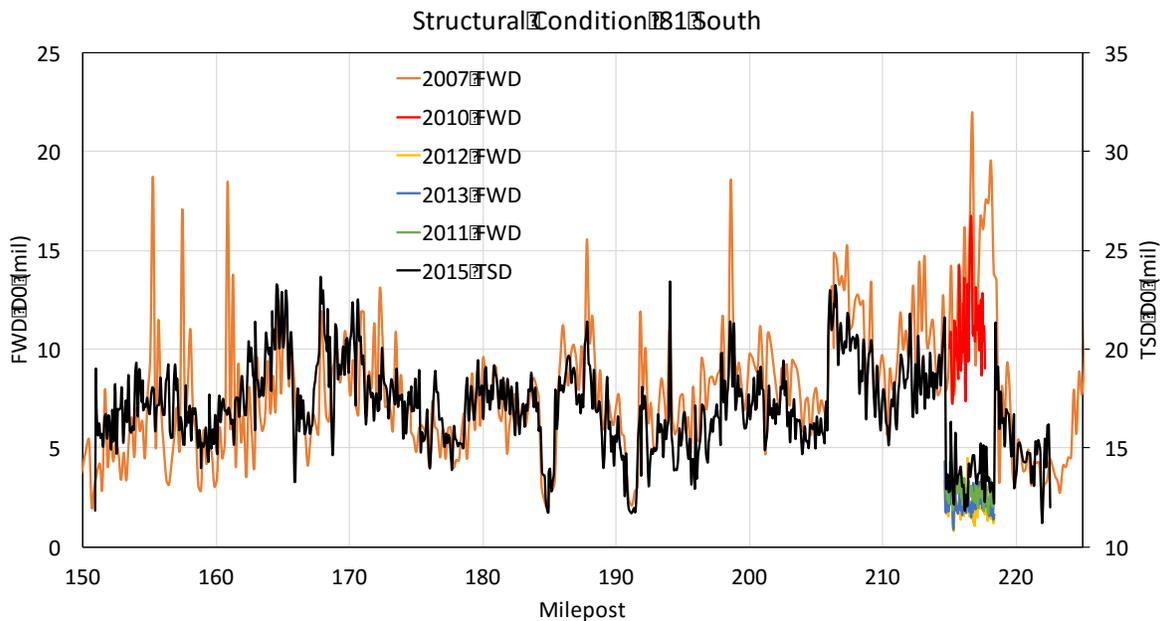


**Figure 10. Measured SCI300 on Jackson Road in California**

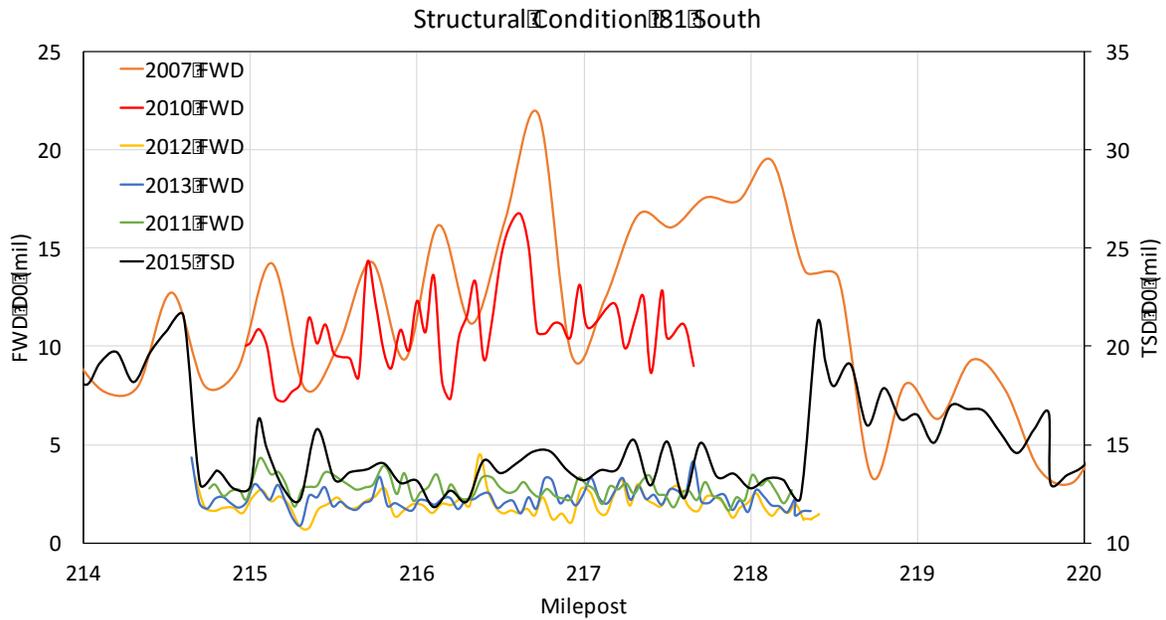
### 3.5.3 Identification of pavement sections with varying structural condition

Figure 11 shows the plot for D0 obtained from the TSD and FWD on Interstate 81 South in Virginia. As the figure illustrates, the D0 measurements obtained from the TSD in 2014 follow

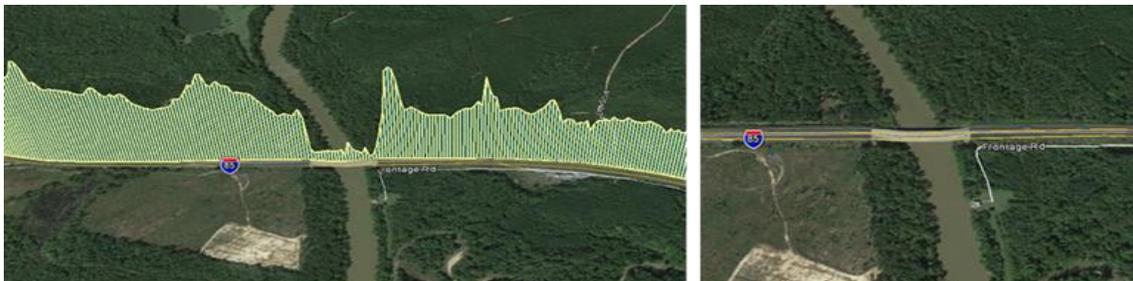
trends similar to the D0 measurements obtained from the FWD in 2007, except for a small segment between mileposts 215 and 218. Figure 12 provides a more detailed view of the plots between mileposts 214 and 220, and illustrates that the D0 measurements from the FWD showed high deflection values for the pavement section in 2007 and 2010. The TSD measurement in 2014 shows that the pavement structural condition improved, as the deflection measurements recorded for that pavement section were comparatively lower. As the pavement section had undergone full depth reclamation in 2011, FWD measurements were available for the following years. The FWD measurement for D0 for the years 2011, 2012 and 2013 confirmed the D0 measurement reported by the TSD. Thus, the TSD seems to be capable of identifying pavements with varying structural condition. Figure 13 shows an example of an SCI300 plot on Google Earth for a test run on Interstate 85 South in South Carolina. The plot shows that the TSD was capable of identifying bridges along the pavement sections, as the bridges were structurally stronger compared to the pavement sections around them.



**Figure 11. Measured D0 with TSD and FWD on Interstate 81 South in Virginia**



**Figure 12. Measured D0 between mileposts 214 and 220 on Interstate 81 South in Virginia**

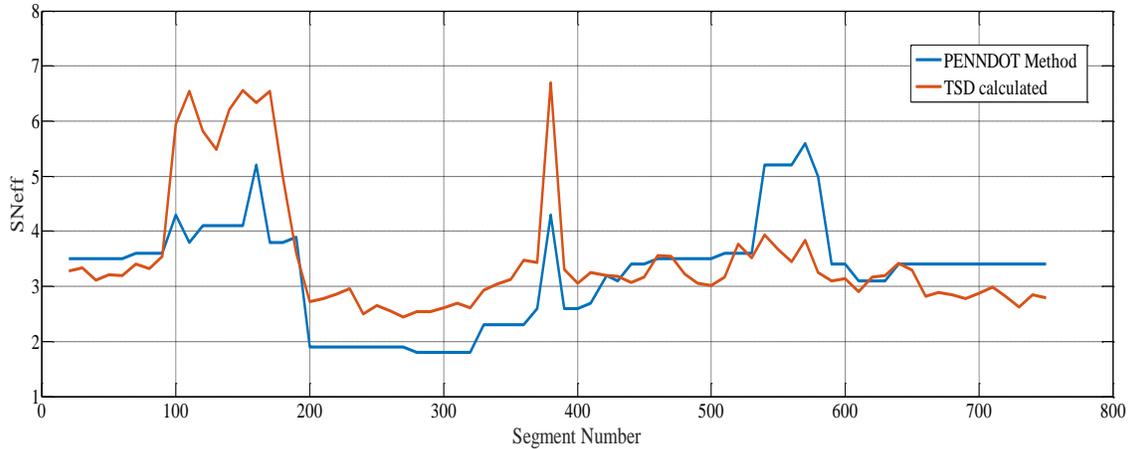


**Figure 13. SCI300 plot in Google Earth for Interstate 85 South in South Carolina**

**3.5.3.1 Comparison of TSD-calculated  $SN_{eff}$  with  $SN_{eff}$  estimated from PennDOT construction records**

PennDOT uses the 1993 American Association of State Highway and Transportation Officials (AASHTO) design guide method to estimate the pavement  $SN_{eff}$  based on construction and maintenance history and a set of predefined layer coefficients that depend on material type and age. Figure 14 shows the  $SN_{eff}$  calculated using the TSD and the approach followed by PennDOT over a stretch of State Route 144. Each segment refers to a pavement section in the PennDOT Pavement Management System. These segments have an average length of 0.4659 miles, with a minimum length of 0.2430 miles and a maximum length of 0.6460 miles; about 75% of the segments measure between 0.4 and 0.5 miles. There are similarities in the trends of the TSD-calculated  $SN_{eff}$  and the  $SN_{eff}$  based on construction data, although the TSD gives significantly larger  $SN_{eff}$  values. Note that no temperature correction, which will be evaluated in the future, was

performed on the TSD measurements (measurements were generally collected at temperatures between 65°F and 80°F). One possible explanation for this discrepancy is that conservative layer coefficients may result in lower  $SN_{eff}$  values.



**Figure 14.  $SN_{eff}$  in Pennsylvania calculated from TSD measurements and by PennDOT based on construction history**

### 3.6 Discussion

Different indices representing pavement structural condition can be calculated from the TSD, but not all of them agree with the measurements from the FWD. A proper index calculated with the TSD can identify pavement sections that vary in structural condition and could provide information on their structural adequacy. This information can be used along with the pavement surface condition information provided by state highway agencies to make better pavement management decisions. Furthermore, deflection thresholds developed for these deflection indices could identify pavement sections in different structural conditions. In various cases, pavement deflection data have already provided insights about pavement structural condition to engineers, enabling them to reconsider their initial pavement treatment strategy and opt for more cost-effective pavement treatment decisions (Lister et al., 1982).

### 3.7 Conclusions

The main conclusions of this study are as follows:

- (1) The TSD shows consistent noise standard deviation in its measurements. As the sensors get closer to the load, the measured noise standard deviation increases. Measurements from the TSD have been found to be repeatable, and measurement error standard deviation was

- found to be similar for all state highway agencies. A known and stable measurement error (that does not change with different tests) provides confidence in the device's capabilities.
- (2) The TSD was found to be capable of identifying pavements with varying structural capacity. On Interstate 81 South in Virginia, the TSD was able to identify a section of the pavement that had undergone full depth reclamation in 2011. The identified pavement section was comparatively stronger than adjacent sections of pavement. During the analysis, the TSD easily identified most of the bridges within the test sections, as they had different structural conditions compared to adjacent pavement sections. In some cases, external factors (such as temperature and pavement moisture condition) may have caused the measurements to vary in terms of their magnitude. The causes of such discrepancies are still under investigation.
  - (3) The calculated  $SN_{eff}$  from the TSD using Rohde's method showed similar trends to the  $SN_{eff}$  calculated using the PennDOT method. Thus, identifying a proper index for TSD can help us establish the relationship and understand the connection between the measurements calculated from the TSD and FWD.

### **3.8 Acknowledgements**

We would like to acknowledge the Federal Highway Administration (FHWA) for all of their support and guidance in this project, Greenwood Engineering for collecting and providing the TSD data, and the following states for participating in the pooled fund project: California, Georgia, Idaho, Illinois, Nevada, New York, Pennsylvania, South Carolina, and Virginia.

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## **4 DEVELOPMENT OF DEFLECTION THRESHOLDS TO CATEGORIZE PAVEMENTS IN DIFFERENT STRUCTURAL CONDITIONS**

Shivesh Shrestha, Samer W. Katicha, and Gerardo W. Flintsch

*Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute, 3500 Transportation Research Plaza (0536), Blacksburg, VA, 24061, USA*

*Corresponding Author:*

Shivesh Shrestha

Charles E. Via, Jr. Department of Civil & Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061, USA

Email: Shivesh@vt.edu

### **4.1 Abstract**

In this paper, thresholds to classify the pavement structural condition obtained from Traffic Speed Deflectometer (TSD) testing were developed for a small subset of the Pennsylvania secondary road network that was tested with the TSD. The approach used consisted of two steps. A model that relates the pavement surface condition to pavement surface age and structural condition was developed. Structural condition thresholds were then selected so that the pavement surface condition predicted from the model for a 10-year-old pavement surface fell within one of the three condition categories (Good, Fair, and Poor). The surface condition is summarized in the Overall Pavement Index (OPI), which is used by Pennsylvania to combine all distresses into a single index that ranges from 0 to 100. The structural condition parameter used was the deflection slope index (DSI), which is the difference between the measured deflection 100 mm from the applied wheel load and the measured deflection 300 mm from the applied wheel load. With OPI characterizing the surface condition and DSI characterizing the structural condition, the DSI threshold that separates structurally good from structurally fair pavements was determined as follows: (1) the OPI threshold that separates pavements with good surface condition from those with fair surface condition was obtained from the Pennsylvania Pavement Management System (PMS) and (2) the

DSI thresholds were calculated using the determined OPI value and the model equation. The determined thresholds were found to be comparable with thresholds developed by Rada et al. (2016) based on fatigue cracking due to strains at the bottom of the asphalt layer. One advantage of the proposed approach is that it links the structural condition to the actual field-observed pavement deterioration rate and therefore should relatively easily integrate into the PMS.

## **4.2 Introduction**

Pavements are one of the biggest assets of the transportation infrastructure. Large sums of money are invested to ensure that pavement assets are well maintained and are rehabilitated in time. An annual investment of \$101 billion is required to maintain the roads at their current level, but only \$91 billion dollars is being invested annually (ASCE, 2013). This unfunded gap in the highway fund is increasing with the decline in overall pavement conditions. Various transportation agencies rely on their PMSs to select different pavement rehabilitation strategies based on the present pavement condition and distresses. The main goal of these strategies is to maximize benefits from these investments and efficiently maintain and repair existing pavements. Pavement condition has a major impact on the agency and the user cost. Thus, it is important to maintain and rehabilitate the pavements on time and prevent further pavement deterioration. Most of the transportation agencies assess the pavement condition solely based upon the pavement surface distresses, which do not necessarily reflect the pavement structural condition (Bryce et al., 2012; Flora, 2009). This results in less-than-optimum decisions, as research has shown that pavement structural condition significantly affects the rate of pavement deterioration (Bryce et al., 2012; Flora, 2009; Katicha et al., 2016; Zaghoul et al., 1998). Thus, incorporating the pavement structural condition into the pavement management decision-making process could result in better-informed decisions (Lister et al., 1982; Zaghoul et al., 1998).

Different devices have been used to carry out structural condition surveys of the pavement, such as the Benkelman beam, Falling Weight Deflectometer (FWD), and Deflectograph. However, these instruments are either stationary or operate below the traffic speed, which makes them unsuitable for network-level data collection. They also have high operation cost as a function of network sampling, disturb the traffic flow, and pose potential risk to the person operating the device. The Second Strategic Highway Research Program 2 (SHRP 2) R06(F) project identified

the TSD as one of the potential devices that can effectively measure the structural condition of the pavements at the network level. The Federal Highway Administration (FHWA) initiated the pooled fund project “Demonstration of Network Level Pavement Structural Evaluation with Traffic Speed Deflectometer” with nine participating State Highway Agencies (SHAs) to evaluate the potential benefits of network-level structural evaluation. This paper describes how structural condition thresholds can be developed so that results from network-level pavement structural condition can be incorporated into an SHA’s PMS. The data used in this paper were taken from the second cycle of data collection in the state of Pennsylvania.

### **4.3 Objective**

The objective of this study is to develop thresholds to categorize the pavement structural condition based on measurements collected by the TSD. These thresholds were determined based on a developed regression model that predicts the pavement surface condition based on pavement age and the deflection index obtained from the TSD. The main benefit of having thresholds to characterize the pavement structural condition is to provide a way to incorporate these thresholds into the PMS decision-making process to come up with better-informed pavement management decisions.

### **4.4 Methodology**

The methodology used in this study is broken down into two main steps.

1. Development of the deterioration model using parameters available from the Pennsylvania Department of Transportation’s (PennDOT’s) PMS and the deflection indices calculated from the TSD. This was achieved following these steps:
  - a. From the PMS, the OPI was obtained along with the Global Positioning System (GPS) coordinates for the sections and other pavement information such as pavement age, Average Annual Daily Traffic (AADT), and total pavement thickness.
  - b. The pavement deflection data were obtained from the TSD. The data included the GPS coordinates of the pavement sections and the pavement deflection data at consecutive 10-m intervals. The GPS coordinates in the PMS were matched to the GPS coordinates from the TSD data.

- c. Determine the distribution of the OPI. During this process, it was discovered that working with the quantity  $100 - \text{OPI}$  is more practical from a mathematical modeling perspective. For this reason, the deterioration index was defined as  $Y = 100 - \text{OPI}$ . The distribution of the deterioration index was found to be best represented by a negative binomial distribution.
  - d. A negative binomial regression was then performed to model the pavement deterioration as a function of the different parameters available. The Akaike Information Criterion (AIC) was used to select the best model.
2. Development of deflection thresholds from the deterioration model.
    - a. The OPI thresholds for pavements in different conditions were used to develop DSI thresholds. This was achieved by determining the DSI values that correspond to each OPI threshold category for a pavement with a 10-year-old surface.

#### **4.4.1 TSD Equipment Description**

The TSD is a deflection-measuring device that measures the deflection velocity of the pavement at traffic speed. It is an articulated truck with a rear-axle load that can be varied from 58.7 to 127.6 kN. The TSD used in this study has seven Doppler lasers mounted on a servo-hydraulic beam to measure the pavement deflection velocity when the loaded truck with the equipment passes over the pavement. The purpose of the servo-hydraulic beam is to keep the lasers at a constant height from the pavement surface to reduce any disturbance that might occur with the movement of the trailer. Six Doppler lasers are positioned at a distance of 100, 200, 300, 600, 900, and 1,500 mm from the rear axle, which imparts the load to the pavement. The seventh laser, positioned largely outside the deflection bowl at a distance of 3,500 mm from the rear axle, acts as a reference laser. A climate control system maintains the trailer to a constant temperature of 20°C (68°F) and prevents the thermal distortion of the steel measurement beam. The data are recorded at a speed of up to 96 km/h (60 mph) at a rate of 1,000 Hz.

#### **4.4.2 TSD Data Measurement**

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 unwanted signals from the six measurement lasers. When accurately calibrated, the TSD measures pavement deflection velocities that depend on driving speed. To remove this dependence, the deflection velocity is divided by the instantaneous vehicle speed to give a measurement of deflection slope. Therefore, the deflection slope is calculated as follows:

$$S = \frac{V_v}{V_h} \quad (19)$$

where,  $S$  is the deflection slope

$V_v$  is the vertical pavement deflection velocity

$V_h$  is the vehicle horizontal velocity.

The calculated deflection slope is then converted to pavement deflection measurements by integration as shown below:

$$d(x) = \int_x^\infty s(y)dy \quad (20)$$

where,  $s(y)$  = slope at distance  $y$  measured from the center of the rear wheel of the TSD

$d(x)$  = deflection at distance  $y$  measured from the center of the rear wheel of the TSD.

The upper limit of integration of infinity is theoretical. Practically, the upper limit of integration should be large enough so that the deflection at that location is very small (almost zero). Greenwood Engineering, who provided us the TSD measurements, reports the deflection values recorded by the TSD by optimizing the model parameters to fit the deflection slope data. The deflection values are then normalized to a standard axle load of 9,000 lb. Temperature correction is then performed as proposed by Rada et al. (2016). Different deflection indices can then be calculated from the obtained deflection measurements.

The indices that were used for this study are:

$$DSI = D_{100} - D_{300} \quad (21)$$

$$SCI300 = D_0 - D_{300} \quad (22)$$

where,  $D_0$ = deflection at the point of application of the load (i.e., center of the rear wheel)

$D_{100}$ = deflection at 100 mm from the point of application of the load

$D_{300}$ = deflection at 300 mm from the point of application of the load

DSI and SCI300 were selected in this study to represent the pavement structural condition obtained from the TSD, as they were found to be the indices that best correlated to the tensile strain at the bottom of the layer, which is related to fatigue cracking (Rada et al., 2016).

#### 4.4.3 TSD and PMS Data Collection

PennDOT uses the OPI to categorize the condition of their pavements. The OPI ranges from 0–100, 0 representing a completely failed pavement and 100 representing an undamaged pavement with no distress. The OPI for flexible pavements is calculated using the equation:

$$OPI_{ACP} = (0.25 \times RUF) + (0.15 \times FCI) + (0.125 \times TCI) + (0.10 \times MCI) + (0.10 \times EDI) + (0.05 \times BPI) + (0.05 \times RWI) + (0.175 \times RUT) \quad (23)$$

where,  $RUF = \text{Roughness Index} = 100 - ((0.27 \times \text{IRI}) - 11)$

IRI = International Roughness Index

FCI = Fatigue Cracking Index

TCI = Transverse Cracking Index

MCI = Miscellaneous Cracking Index

EDI = Edge Deterioration Index

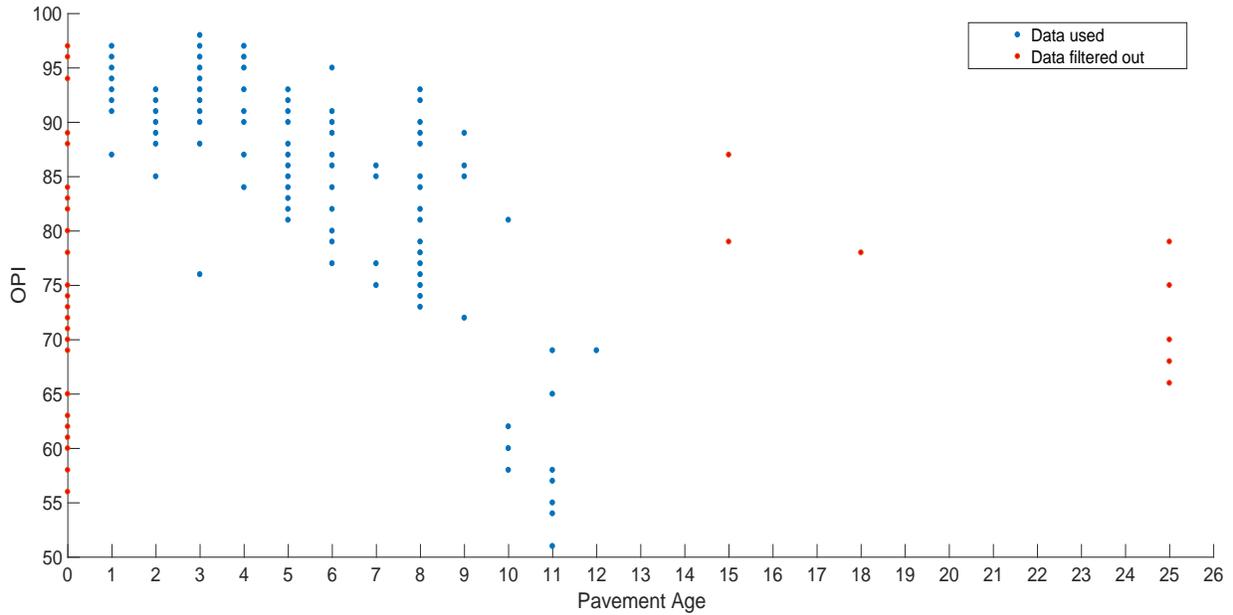
BPI = Bituminous Patching Index

RWI = Raveling/Weathering Index

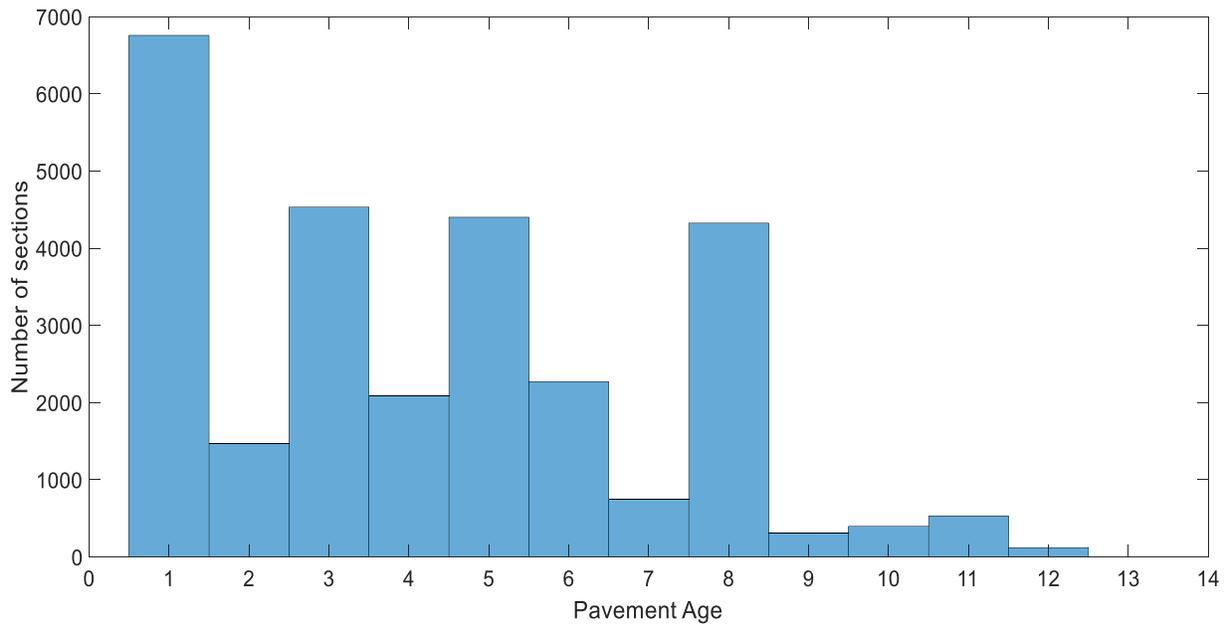
RUT = Rut Depth Index

The pavement condition data used in this study were obtained from PennDOT’s PMS for the year 2013–14. Deflection data were collected from the second round of testing of the TSD in Pennsylvania in 2015. The GPS coordinates of the data from the PMS and TSD were matched with each other. This resulted in a total of 35,775 sections (i.e., 223 miles of data) with both PMS and TSD-measured data and a section length of 10 m (i.e., length of the section measured by the TSD). The pavement age was defined as the difference between the year OPI was measured and the last year of resurfacing applied to the pavement sections. Pavement sections with age 0 and age greater than 12 years were filtered out from the data. For pavement sections with age 0, there were sections with OPI values ranging from 56 to 97. A possible explanation for the low OPI measurements (i.e., less than 85) can be that, for some of these sections, although a pavement treatment was applied, the pavement condition was measured before the treatment was applied. The pavement sections with age greater than 12 years were very strong compared to the rest of the sections. It was not clear whether any treatments were applied to them and not recorded in the PMS or whether they were designed stronger compared to other sections. Thus, they were filtered out as shown in Figure 15. The final dataset comprised of 27,949 pavement sections (10-m long) with a total length of

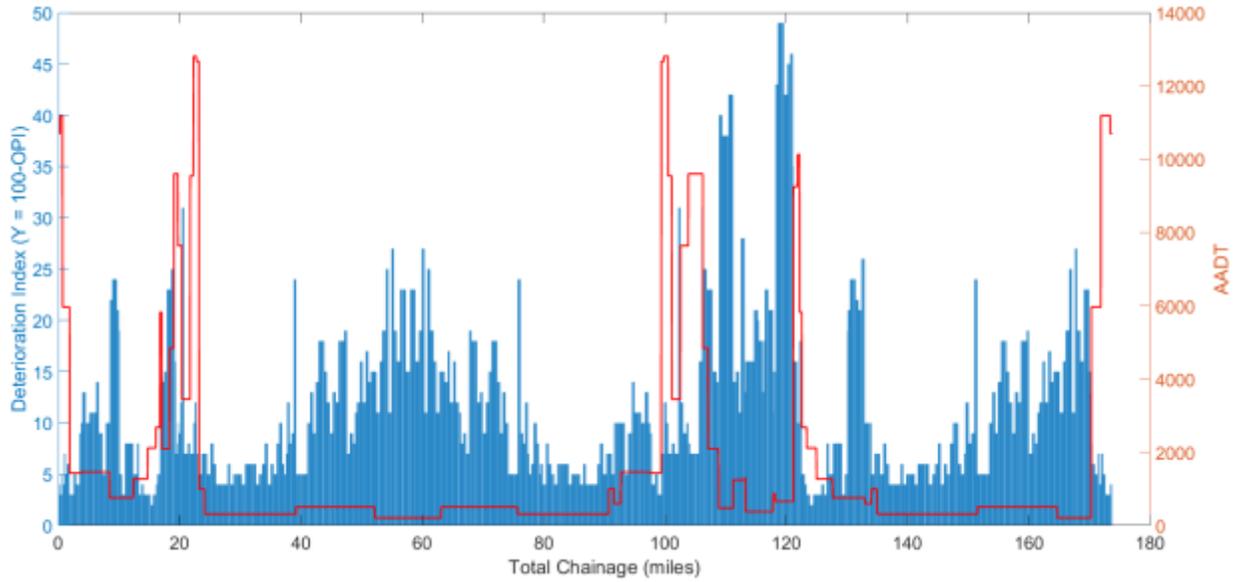
173 miles. Figure 16 shows the distribution of the pavement age of the tested sections. Figure 17 shows the deterioration index of the pavement sections and the AADT along the total chainage. Table 4 shows the list of the tested roads and their respective lengths.



**Figure 15. OPI for pavement sections with different age.**



**Figure 16. Distribution of pavement age.**



**Figure 17. Pavement deterioration and AADT for the pavement sections along the total chainage.**

**Table 4. Total length of each road section (in miles)**

<b>Road Name</b>	<b>Length of the section (miles)</b>
SR230 West	1.85
SR17 West	6.59
SR53	8.63
SR453	1.98
SR879	4.11
SR144 North 1	12.85
SR144 North 2	21.58
SR144 South 2	21.65
SR144 South 1	13.47
SR17 East	6.63
SR879 - SR153	18.83
SR2027 - SR970	3.99

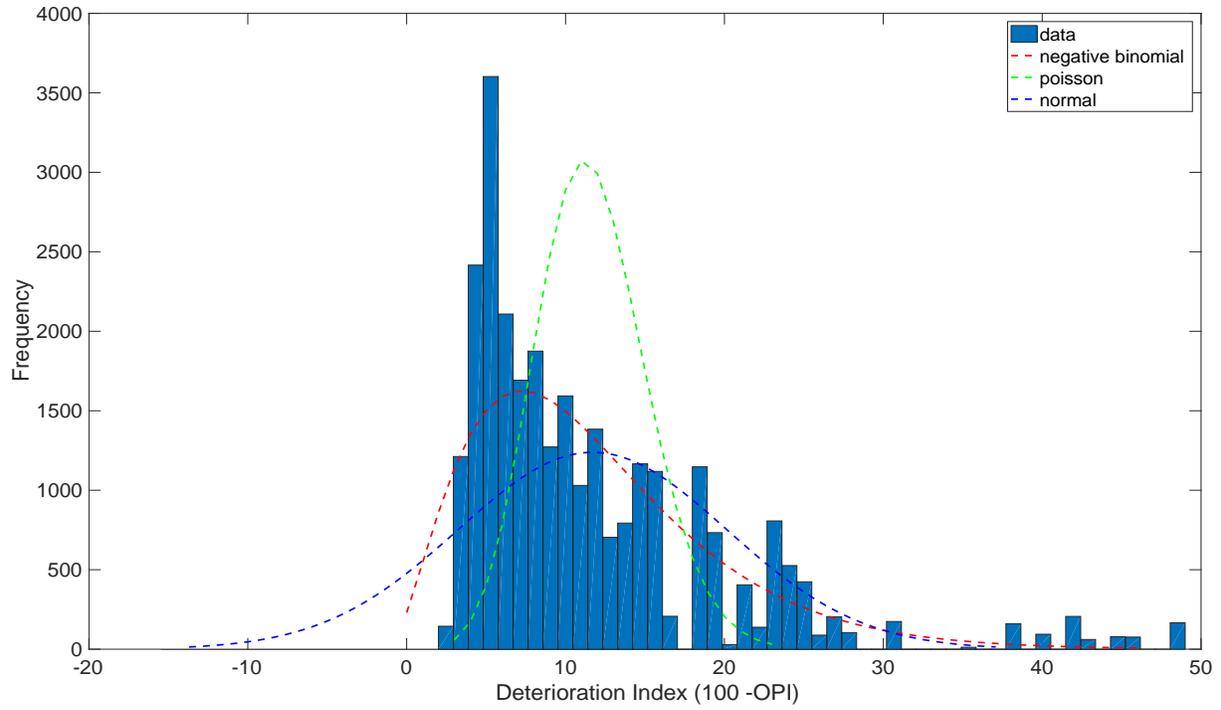
<b>Road Name</b>	<b>Length of the section (miles)</b>
SR53 - SR144	48.07
SR230 East	3.40
<b>Total</b>	<b>173.63</b>

## 4.5 Analysis

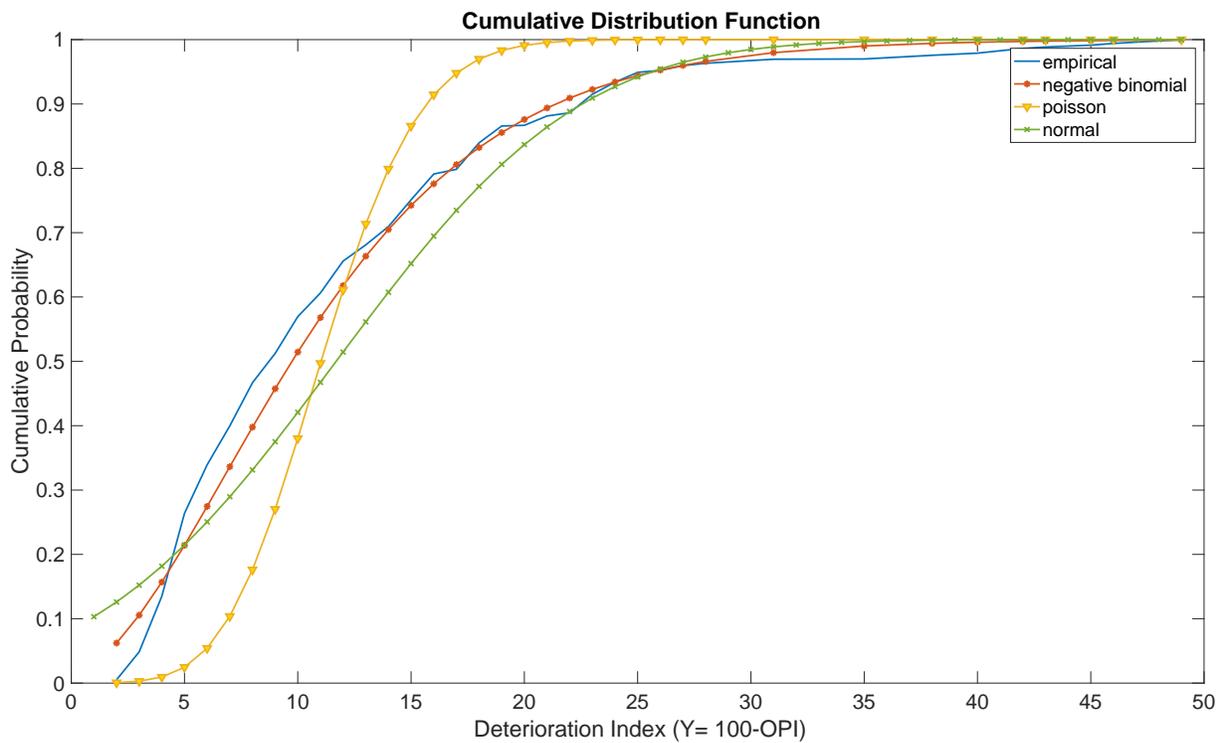
The pavement deterioration index was calculated by subtracting the OPI value for each individual section from a full condition rating score of 100 (i.e.,  $Y = 100 - \text{OPI}$ ). Figure 18 shows the distribution of the pavement deterioration index with different fitted distributions, including negative binomial, Poisson, and normal distributions. Figure 19 shows a cumulative distribution function plot of the deterioration index along with negative binomial, Poisson, and normal distributions. The fit using the negative binomial distribution maximized the likelihood function (maximum negative log-likelihood value) and minimized the AIC value as presented in Table 5. Katicha et al. (2016) also found that the negative binomial distribution was the most appropriate fit to the pavement deterioration data in Virginia. Thus, negative binomial regression was used to determine the best model to use to predict the OPI. The different parameters investigated were pavement thickness, age, AADT, and pavement structural condition obtained from the TSD. The pavement structural condition was represented by deflection measurements and the deflection indices DSI and SCI300. During the deterioration modeling, it was observed that the DSI from the TSD represented the pavement deterioration better than individual deflection measurements and SCI300.

**Table 5. Results for best distribution fit**

<b>Distribution Name</b>	<b>Negative Log-likelihood</b>	<b>AIC</b>
Negative binomial	92481	184966
Poisson	129126	258253



**Figure 18. Distribution of pavement deterioration index.**



**Figure 19. Cumulative distribution lot for pavement deterioration (i.e., 100 – OPI).**

#### 4.5.1 Model selection

Different models were tested using available parameters (i.e., pavement age, AADT, total pavement thickness, OPI, DSI, and SCI300) to represent the pavement deterioration (i.e., 100 – OPI). Forward stepwise regression was used to determine the final model. In this approach, variables enter the model sequentially one at a time. At each step, the variable that results in the largest reduction in the AIC is entered into the model. In the end, the model that yields the smallest value of AIC is selected. The AIC is a measure of the relative quality of the fitted models that is a trade-off between goodness of fit measured by the log-likelihood and model complexity measured by the number of parameters used (Mazerolle, 2004):

$$AIC = -2L + 2k \tag{24}$$

where,  $L$  = log-likelihood

$k$  = the number of estimated parameters included in the model (i.e., number of variables + the intercept)

#### 4.5.2 Development of deflection thresholds

PennDOT uses the OPI to summarize the surface condition of their pavements. The condition categories of the pavement as a function of OPI are shown in Table 6 (Morian, 2011):

**Table 6. Pavement condition category based on OPI**

OPI Value	Network Category			
	Interstate	Other NHS	Non-NHS ≥ 2000	Non-NHS < 2000
<95	Excellent	Excellent	Excellent	Excellent
91–95	Good	Good		
86–90			Fair	Fair
81–85	Poor	Poor		
75–80			Fair	Fair
70–74	Poor	Poor		
65–69			Poor	Poor
60–65	Fair	Fair		
<60			Poor	Poor

## 4.6 Results

Table 7 presents the correlation between the different parameters evaluated in this study. Age had the highest correlation with the OPI, while DSI and SCI300 came in a close second and third. AADT and Total Pavement Depth had a relatively low correlation with OPI.

**Table 7. Correlation between different parameters**

	<b>AADT</b>	<b>Age</b>	<b>OPI</b>	<b>Total Pavement Depth</b>	<b>DSI</b>	<b>SCI300</b>
<b>AADT</b>	1.00	0.18	0.09	0.27	-0.34	-0.32
<b>Age</b>	0.18	1.00	-0.76	-0.04	0.20	0.21
<b>OPI</b>	0.09	-0.76	1.00	0.13	-0.38	-0.37
<b>Total Pavement Depth</b>	0.27	-0.04	0.13	1.00	-0.13	-0.12
<b>DSI</b>	-0.34	0.20	-0.38	-0.13	1.00	0.98
<b>SCI300</b>	-0.32	0.21	-0.37	-0.12	0.98	1.00

Various models were taken into consideration to study the influence of different parameters available on pavement deterioration. Six of the models, discussed below, were as follows:

1. Intercept + Age
2. Intercept + AADT
3. Intercept + Age + AADT
4. Intercept + Total Pavement Depth
5. Intercept + Age + Total Pavement Depth
6. Intercept + Age + DSI

**Model 1:** Age was the most significant parameter in the deterioration modeling compared to other parameters. Two age parameters,  $\ln(\text{Age})$  and Age, were taken into account during the model development. The first parameter, the natural log of Age, was selected so that the model-calculated deterioration is zero when the pavement is new (Age = 0). The second parameter, Age, was selected so that the general pattern of the pavement deterioration curve was obtained. Age also had the strongest correlation with the OPI, with a correlation coefficient of -0.76. All the other models had at least two age parameters including the intercept in the model.

**Model 2 and Model 3:** AADT was one of the parameters considered for the deterioration modeling. Traffic has an adverse effect on the pavement condition and is one of the main reasons for pavement deterioration. With an increase in traffic, pavement experiences more distresses, leading to a higher rate of pavement deterioration. During deterioration modeling, models with AADT resulted in a negative coefficient for the parameter. This means that AADT had an inverse relationship with the pavement deterioration: with an increase in AADT, the rate of pavement deterioration would decrease. As we had limited pavement sections available for this study, the inverse relation we observed in our dataset could be related to the following reasons: (1) pavements with higher traffic level are kept in better condition than those with less traffic (American Association of State Highway and Transportation & Pavements, 2001; Bryce et al., 2014); (2) pavements designed for higher traffic are designed better to withstand the higher traffic. Since these are external factors and they do not accurately represent actual pavement deterioration behavior, AADT was not considered in the final model.

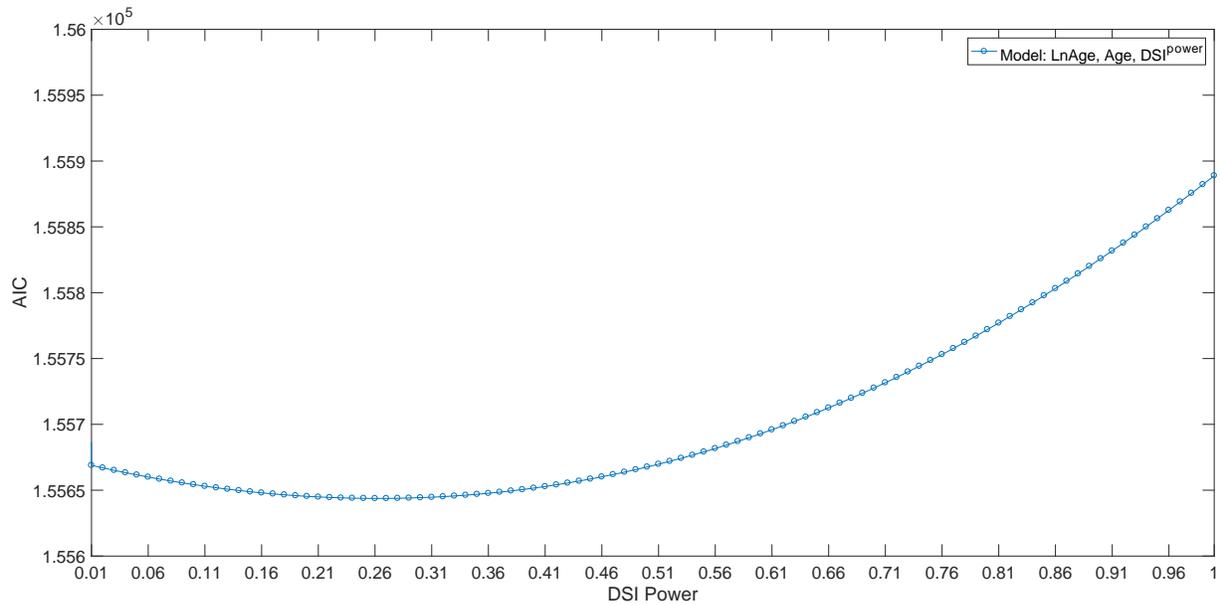
**Model 4 and Model 5:** The total depth of the pavement was considered for model development. Model 4 was developed with two parameters: the intercept and the total pavement depth. The total pavement depth had a negative coefficient; i.e., an increase in total depth would result in a decrease of pavement deterioration. This is an accurate representation of the theoretical relationship between these two parameters. But, since the model with pavement age was the most significant model, all the models selected for further development were age dependent (i.e., intercept and pavement age were the parameters selected for the models). Model 5 was one of the age-dependent models that incorporated the total pavement depth. When total pavement depth was considered as the third parameter in the model, the coefficient for the total pavement depth had a positive intercept. This means that an increase in the total depth of the pavement would result in an increase of pavement deterioration. This does not accurately represent the theoretical relationship between the two parameters: pavement deterioration should perform better with thicker pavements compared to thinner pavements under similar loading conditions. It was assumed that this inverse relationship observed in Model 5 was due to (1) lack of a wide variety of data for different road networks and (2) absence of other significant parameters that could have an impact on the relationship between the total depth of the pavement and the pavement deterioration.

**Model 6:** Among the models developed with the available parameters, the best model to represent the pavement deterioration was determined to be the model with Age and DSI. Other models were also analyzed with deflection measurements obtained from the TSD and with SCI as well. The DSI was selected as the most appropriate index to represent structural condition and model pavement deterioration, which was also confirmed from the study by Rada et al. (2016). The final deterioration model is represented by the equation:

$$Y = e^{(1.096+0.141 \times \ln(\text{Age})+0.138 \times \text{Age}+0.312 \times (\text{DSI})^{0.26})} \quad (25)$$

where,  $Y = 100 - \text{OPI} = \text{pavement deterioration}$

$\text{DSI} = \text{D100} - \text{D300} = \text{deflection slope index}$



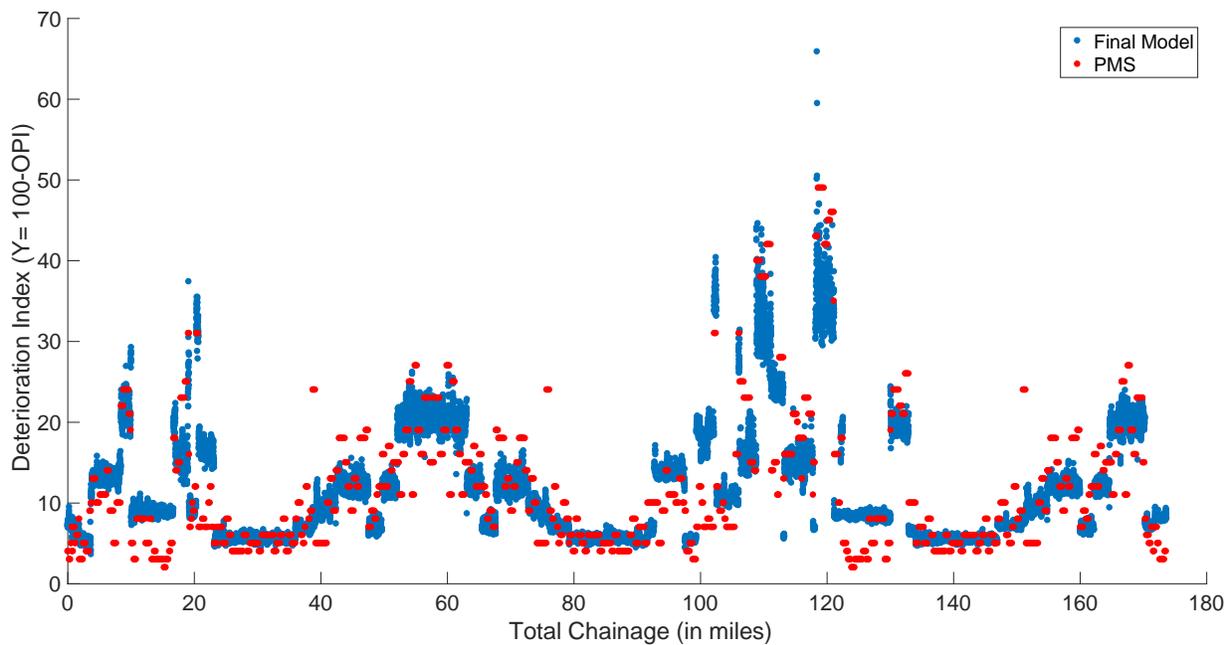
**Figure 20. AIC for different powers of DSI.**

In the final model,  $\text{DSI}^{0.26}$  was selected as final DSI parameter as it resulted in the lowest AIC for the model as shown in Figure 20. Based on this model, thresholds for DSI were developed to classify roads in different structural conditions: Good, Fair, and Poor. Since all the pavement sections available with both the PMS data and TSD measurements were secondary roads, OPI thresholds from the Non-National Highway System (Non-NHS) road category were used. Table 8 shows the calculated DSI thresholds based on the OPI threshold values obtained for pavements in different states of repair. It was observed that pavement sections showed significant deterioration at the age of 10 years (Figure 15). Most of the pavements receive some sort of treatment before 11 years of age (Katicha et al., 2016). Thus, the thresholds were developed for the age of 10 years.

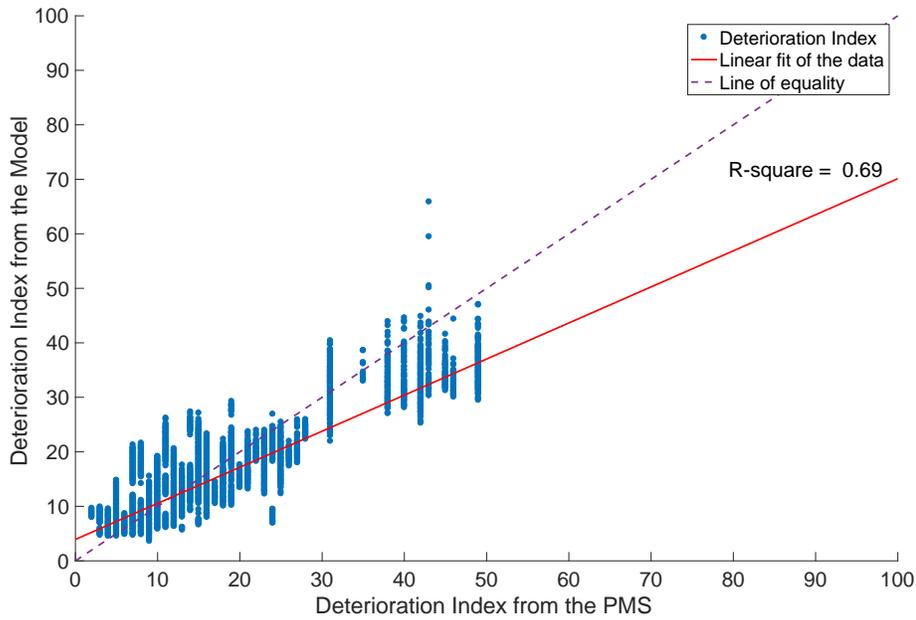
**Table 8. DSI ranges for Non-NHS pavements under different traffic conditions**

Non-NHS: AADT $\geq$ 2000			Non-NHS: AADT $<$ 2000		
OPI	Pavement Condition	DSI	OPI	Pavement Condition	DSI
$> 80$	Good	$< 0.39$	$> 69$	Good	$< 5.90$
65 - 80	Fair	0.39–9.78	60 - 69	Fair	5.90–15.90
$< 65$	Poor	$> 9.78$	$< 60$	Poor	$> 15.90$

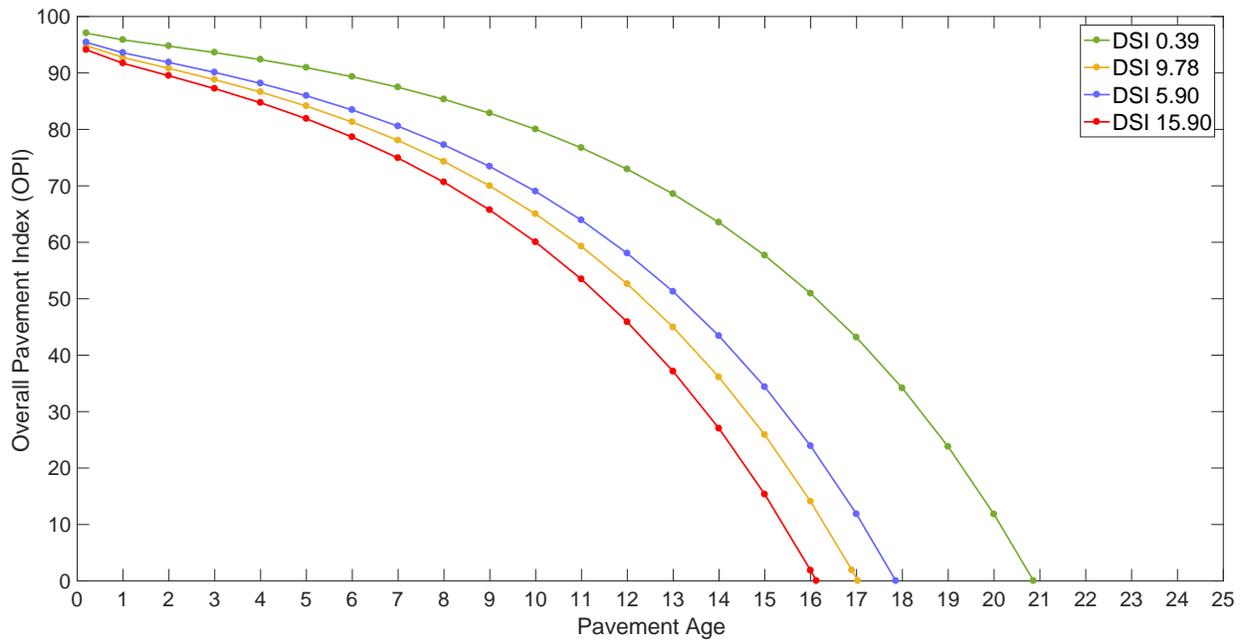
Figure 21 shows the deterioration index from the PMS and the deterioration index from the final model. Both the deterioration index from the PMS and the model follow similar trends. Figure 22 shows the deterioration index from the model against the deterioration from the PMS with a coefficient of determination ( $R^2$ ) of 0.69. Figure 23 shows the pavement deterioration as a function of age calculated from the final model for the four developed thresholds shown in Table 5.



**Figure 21. Deterioration obtained from the model and PennDOT’s PMS.**



**Figure 22. Pavement deterioration index calculated from the PMS and the model.**

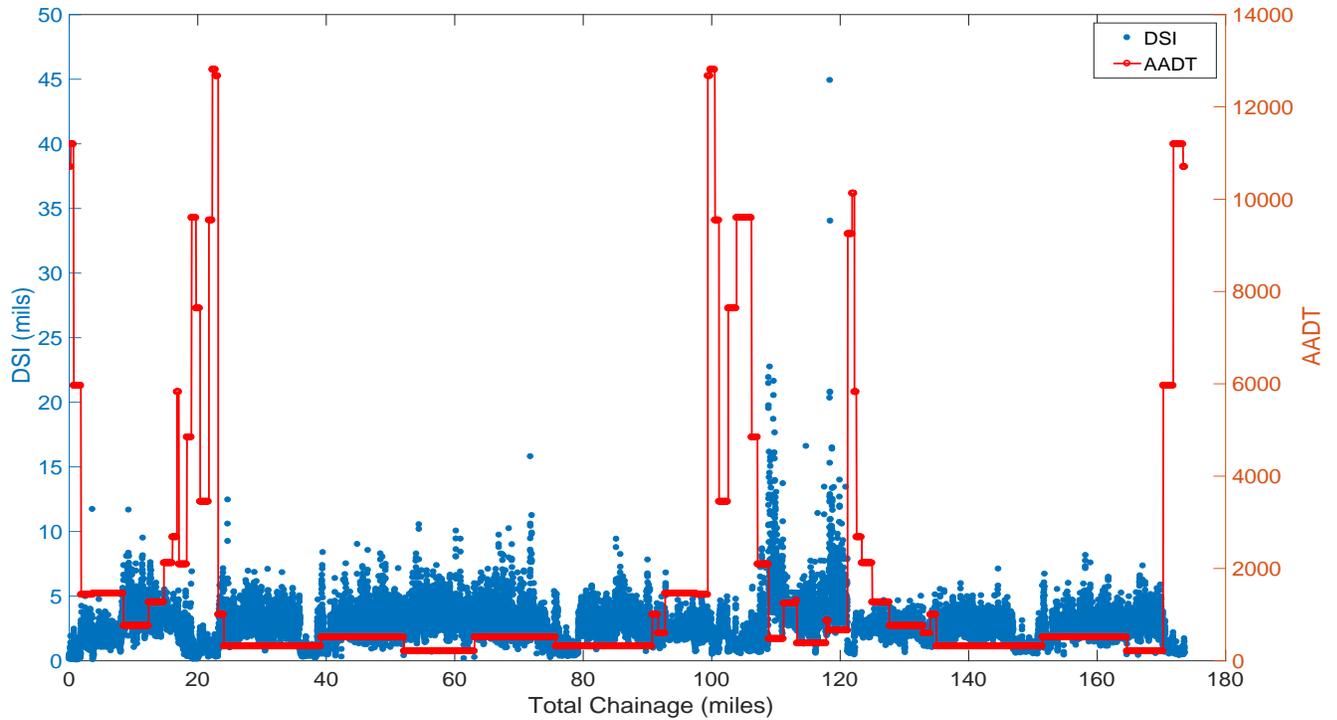


**Figure 23. Pavement deterioration with time for pavements in different structural conditions.**

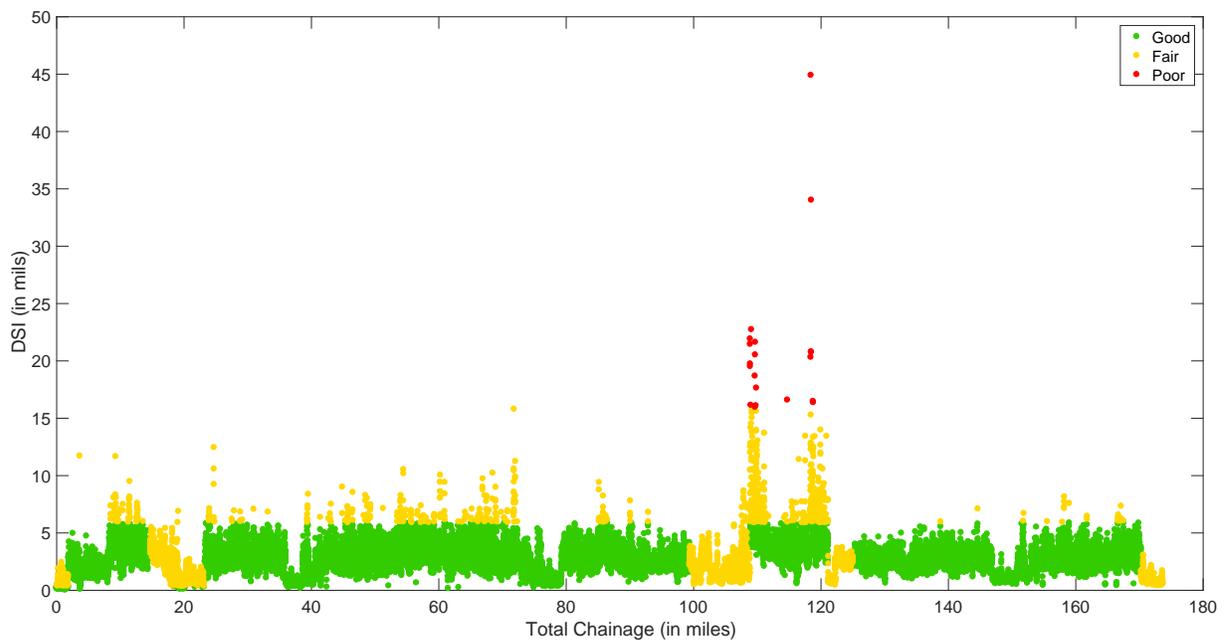
Structural condition of tested sections:

Figure 24 shows the DSI measurements obtained from the TSD along with the AADT data obtained from the PMS. Pavement sections with higher AADT seem to be in better structural

condition. Figure 25 shows the structural condition of the tested pavement sections. The pavement sections were first categorized based on their AADT, and then corresponding deflection thresholds were applied to that measured DSI.



**Figure 24. DSI obtained from the TSD and AADT along the total chainage.**



**Figure 25. DSI measurements obtained from the TSD in terms of the thresholds developed.**

## 4.7 Conclusions

1. The negative binomial distribution seemed to be the most appropriate fit for the pavement deterioration data obtained from PennDOT's PMS. Various other fits were also tested for the data, including Normal and Poisson distributions.
2. Pavement age was the most significant parameter for deterioration modeling. Pavement age had the highest correlation with the OPI within the data, with a correlation coefficient of  $-0.76$ . Age-dependent models had lower AIC compared to other models and were considered to be closer to the true model.
3. Pavements with high AADT were in better condition (both functionally and structurally) compared to pavements with lower AADT. Pavements with high AADT had lower DSI values, meaning they were structurally stronger. During the deterioration modeling, an inverse relationship was observed between the pavement deterioration ( $100 - \text{OPI}$ ) and AADT. This means that the pavements with higher traffic were in better condition (functionally, as represented by OPI). This could be due to the fact that: (a) pavements with higher traffic level are kept in better condition than those with less traffic or (b) pavements designed for higher traffic are designed better to withstand the higher traffic.
4. Structurally weak pavements deteriorated faster compared to pavements that were in better structural condition. As the pavement's structural condition worsened, the rate of pavement deterioration increased.
5. DSI was selected to best represent the pavement deterioration among all the pavement structural condition parameters, such as individual deflection measurements obtained from the TSD at various distances and the deflection index, SCI300.
6. The final model to best represent the pavement deterioration was determined to be the model with Age and DSI. The DSI thresholds developed for non-NHS pavements with  $\text{AADT} \geq 2000$  were 0.39 mils and 9.78 mils, and for pavements with  $\text{AADT} < 2000$  were

5.90 mils and 15.90 mils. These thresholds were used to identify pavements in good, fair, and poor condition respectively.

#### **4.8 Future Work**

The deterioration model developed in this study was based on the data available from the tested TSD routes and PennDOT's PMS. The deflection thresholds were developed only for secondary roads. With the availability of more data, thresholds for interstates and primary roads could also be developed. If more data becomes available with a wider range of AADT data, it might be possible to include AADT into the deterioration model as well. The next step would be to demonstrate the implementation of this pavement structural information into the pavement management decision-making process. Some SHAs have already been looking into these methods. However, most SHAs still do not incorporate the pavement condition data into their PMS and their decision-making process. Incorporating the pavement structural condition data has already shown to be very effective in helping to understand pavement performance and selecting cost-effective treatments for the pavements.

#### **4.9 Acknowledgements**

We would like to acknowledge the Federal Highway (FHWA) for their guidance and support in this study, Greenwood Engineering for collecting and providing the TSD data, and the Pennsylvania Department of Transportation (PennDOT) for providing the data from their pavement management system.

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## 5 FINDINGS, CONCLUSION AND RECOMMENDATIONS

Pavement structural condition is an important measure to determine the overall condition of the pavement. It can be used along with the distress and smoothness data to achieve more accurate information about the existing pavement condition. The literature agrees that the TSD is one of the devices capable of evaluating the structural condition of the pavements at the network level. This thesis presented an evaluation of the TSD capabilities and proposed an approach to incorporate the pavement structural condition into pavement deterioration modeling and to develop deflection thresholds using the deterioration models to classify pavements in different structural condition.

### 5.1 Findings

The analysis conducted in the thesis resulted in the following findings:

1. The TSD showed consistent noise standard deviation in its measurements. Measurements from the TSD were found to be repeatable, and measurement error standard deviation was found to be similar for all state highway agencies.
2. The TSD is capable of identifying pavements with varying structural capacity. For example, the analysis of the TSD data identified most of the bridges within the test sections and also a section of the pavement that had undergone full depth reclamation, as they had different structural conditions compared to the pavement sections around them.
3. The negative binomial distribution was found to be the most appropriate distribution to model pavement deterioration data obtained from the PennDOT's PMS. Pavement age was the most significant parameter for deterioration modeling as age dependent models had the lowest AIC of all the tested models.
4. Pavements with high AADT were in better condition (both functionally and structurally) compared to pavements with lower AADT. This could be due to the fact that: (a) pavements with higher traffic level are kept in better condition than those with less traffic, and/or (b) pavements designed for higher traffic are designed better to withstand the higher traffic.
5. The model that best represents the pavement deterioration included Age and DSI as independent variables. It was possible to use this model to determine DSI threshold for non-NHS pavements with  $AADT \geq 2000$  and  $AADT < 2000$ , which were used to identify pavements in good, fair and poor condition.

## **5.2 Conclusion**

The measurements from the TSD was found to be repeatable and the TSD was able to identify pavements with varying structural capacity. An age-dependent deterioration model was developed that incorporated the pavement structural condition index DSI obtained from the TSD. Using this model DSI thresholds were developed for non-NHS pavements with  $AADT \geq 2000$  and  $AADT < 2000$ , to identify pavements in good, fair and poor condition for a 10-year old pavement surface. Thus, the pavements were able to be categorized in good, fair and poor condition based on their structural condition. Structurally weak pavements deteriorated faster compared to pavements that were in better structural condition

## **5.3 Recommendations**

All the routes used in the study for pavement deterioration modeling were secondary roads; similar methods can be applied to develop deterioration model and thresholds for interstates and primary roads as well. Furthermore, the deterioration model could be modified with the availability of a larger pavement condition database.

AADT was one of the significant parameters for deterioration modeling, but because of the effect of external factors observed in the database the model including AADT was not selected. With the availability of more data, the SHA's could develop their own models with the parameters available and propose different thresholds to identify the pavement structural condition. SHAs can develop their own deflection thresholds based on the available to incorporate the information regarding the pavement structural condition in the pavement management decision making process.

The benefits of incorporating the pavement structural condition information from the TSD into the PMS decision making process can be studied by comparing the long term pavement performance and cost analysis studies between the pavement sections that incorporated the pavement structural condition information from the TSD and the pavement sections that solely rely on the current PMS decision making process that does not take into account the pavement structural condition.