VIRGINIA TECH

PAVEMENT STRUCTURAL EVALUATION WITH TRAFFIC SPEED DEFLECTION DEVICES

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

FINAL REPORT

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Resilient Infrastructure

Pavement Structural Evaluation with Traffic Speed Deflection Devices

CONTENTS

ABSTRACT

The Pooled Fund study TPF-5(385) Pavement Structural Evaluation with Traffic Speed Deflection Devices was active between October 2018 and September 2023. A total of 26 State highway agencies, along with the Federal Highway Administration (FHWA), participated in the study. These agencies collected a total of 33,495 lane-miles of network-level structural data using the iPAVE traffic speed deflectometer (TSD) at a 0.1-mile resolution. The Pooled Fund produced (1) a report on available traffic speed deflection devices (TSDD) technologies, (2) guidelines for network-level TSDD data collection, (3) a guide for network-level implementation of structural condition data, (4) a report on the use of TSD data for the evaluation of joints in jointed concrete pavements, (5) two reports demonstrating the application of TSD measurement in pavement management, (6) a circular on conducted instructional webinars, and (7) a circular of presentations given in a Pooled Fund organized symposium meeting. The Pooled Fund study directly supported the work performed in two PhD dissertations and 17 publications. It also indirectly supported two reports and at least three publications.

The Pooled Fund made significant practical and theoretical contributions to network-level structural evaluation with TSDDs. The nine conducted webinars and two organized symposiums resulted in a crucial exchange between government agencies, academia, and the private sector on how to implement and benefit from network-level structural information. Research on joints in jointed concrete pavement led to a better understanding of the data collected by the TSD. Guidelines for data collection and pavement management system implementation provide a starting point for highway agencies on how to practically implement a network-level structural evaluation program.

The Pooled Fund also identified areas that still need to be addressed. First among these is the need to develop a reliable device calibration procedure. This is of paramount importance because there can be no confidence in the collected data without such a procedure and no significant advancement in other areas can be achieved without confidence in the collected data. Therefore, four experiments were performed at the Virginia Smart Roads facility to advance the efforts to develop a procedure to calibrate and verify the TSD.

CHAPTER 1: INTRODUCTION

An important indicator of the health of the pavement network is its structural condition. Knowledge of the pavement's structural condition can help select more cost-effective maintenance and rehabilitation treatments (Zaghlou et al., 1998; Bryce et al., 2013; Katicha et al., 2020; Maser et al., 2017; Shrestha et al., 2019; Zhang et al., 2016; Elseifi et al., 2011, 2019; Thyagarajan et al., 2019; Steele et al., 2015). Most transportation agencies have experience evaluating the pavement structural condition using the falling weight deflectometer (FWD). However, the FWD is a stationary device that is not well-suited for network-level structural evaluation. This drawback of the FWD is the main factor that has led to the development of traffic speed deflection devices (TSDDs). Although TSDDs have extensively been tested, with the results demonstrating their ability to provide valuable structural information, effective use of that information by transportation agencies can still be a challenge. TSDDs are not quite the same as FWDs, and the empirical or mechanistic-empirical methods used to analyze FWD measurements are not optimized for analyzing TSDD measurements. Furthermore, calibration procedures for TSDDs have not been established, and their accuracy and precision are not well documented, which makes their use at the project level still difficult. Finally, there are no readily available guidelines on how to use structural information for network-level pavement management.

The Transportation Pooled Fund (TPF) study TPF-5(385) was specifically established to address these broad challenges. It consists of 26 State highway agencies, along with the FHWA, that see the potential benefits of TSDDs and seek to find practical solutions to their effective use. The study's stated objective is to "establish a research consortium focused on providing participating agencies guidelines on how to specify collection and use data collected with TSDDs for network- and project-level (if feasible) pavement management applications… [and] provide participating agencies with a mechanism to conduct pilot demonstration testing in their respective networks." The Pooled Fund study targeted the following seven tasks to support achieving the objective:

1. Develop a list of available devices and their characteristics. The result of this task is a document which lists (potentially) available devices, their characteristics, and the methodologies that have been used to analyze the data from these devices.
2. Develop data collection guidelines and specifications for agencies. The result of this task is a guide for data collection of TSDD measurements.
3. Develop guidelines on how to incorporate pavement structural condition data into agency network-level pavement business processes. The result of this task is a guide for implementing structural condition assessment results into the pavement management system.
4. Demonstrate how structural condition collected from TSDDs can be used for supporting project-level decision-making based on case studies. This task has been challenging, as the use of TSDDs for project-level applications requires proper understanding of calibration procedures and of the accuracy and precision measures of TSDDs. However, four network-level implementation reports have been developed based on testing performed in this study. Also, data delivery and examples of how the collected data can be used by participating agencies were given for each set of collected data.

5. Demonstrate the cost-effectiveness of collecting structural condition data, both at the network and project levels, through case studies. The result of this task is four network-level implementation reports. However, the cost-effectiveness of collecting structural condition data was not documented.
6. Collect data on at least 100 miles of interstate or primary type pavements for each year of participation (additional data can be collected with additional commitment levels). This task was achieved with more than 200 miles (close to 300 miles) collected for each year of participation.
7. Organize and deliver workshops and training material for the consortium members. This task was achieved by conducting nine webinars and organizing two symposiums.

The advancements to the state of practice achieved as part of these seven tasks highlighted (1) the need for verification procedures for TSDDs to ensure devices are calibrated and provide high-quality data, and (2) the need to perform repeated testing on select road sections to investigate the rate of structural deterioration and ascertain an appropriate frequency of network-level data collection. Therefore, two additional tasks were initiated. The first task consisted of the development of verification procedures for TSDDs with four verification experiments conducted at the Virginia Smart Roads testing facility. The second task consisted of performing repeated testing on road sections in Virginia.

CHAPTER 2: PARTICIPATING STATES AND COLLECTED DATA

Collected Data

Because ARRB Systems was the only TSDD service provider operating in the United States, all data was collected with the ARRB System's intelligent Pavement Assessment Vehicle (iPAVE), shown in Figure 1. The iPAVE uses the traffic speed deflectometer (TSD) to collect structural data. At the start of the Pooled Fund study, the iPAVE version in the United States was a modified version of TSD9. At the end of 2021, the TSD9 iPAVE was replaced with a new iPAVE built on TSD17. TSD17 included improvements in the number of Doppler lasers measuring the pavement deflection velocity and the capability of providing measurements at a resolution as high as 5 cm. In late 2022 to early 2023, the TSD17 iPAVE was further modified to incorporate a 3D ground penetrating radar (GPR) antenna to collect subsurface scans during data collection (Figure 2).

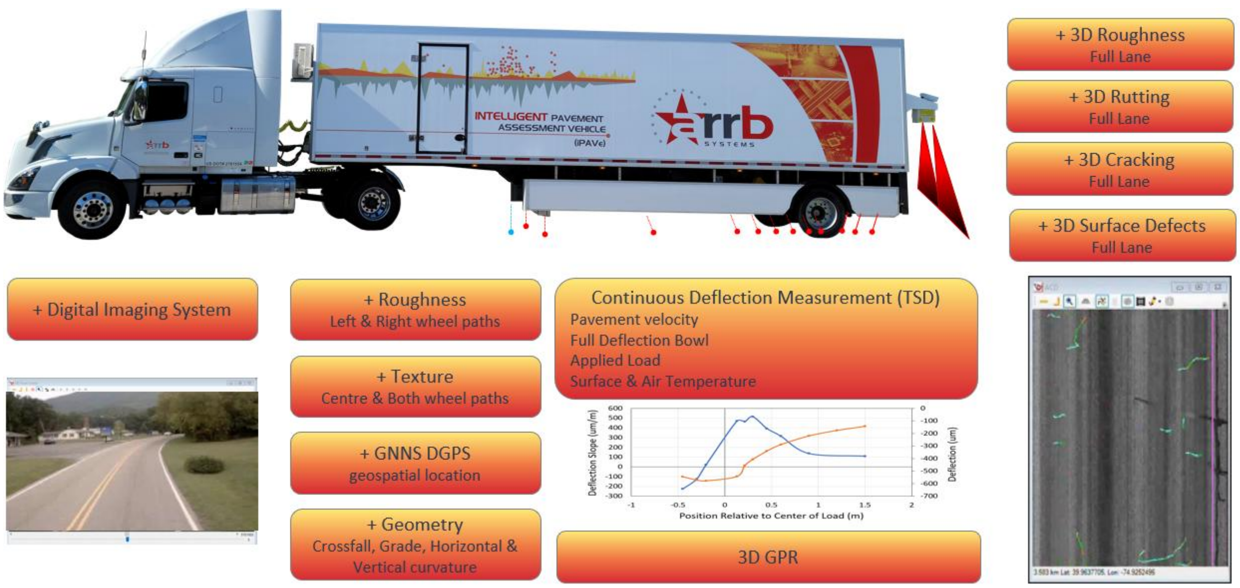

Figure 1. ARRB Systems iPAVE and its capabilities.

Figure 2. Installed 3D GPR antenna.

Participating States and Amount of Data Collected

A total of 26 State agencies, along with the FHWA, joined the Pooled Fund study. The States that joined are highlighted in Figure 3. A total of 36,650 lane- miles of data was collected. The number of lane-miles collected by each participating agency is shown in Figure 4. Twelve agencies collected more than 1,000 lane miles and among those, four collected more than 2,000 lane-miles. Figure 5 shows the total number of lane-miles collected each year. The Pooled Fund study started in October 2018, and less than 1,000 miles of data was collected that year. Between 8,000 and 9,500 lane-miles of data were collected in each of 2019, 2020, and 2021. By the end of 2021 and into mid-2022, ARRB Systems upgraded the iPAVE in the United States and installed a new 3D GPR system. This transition slowed the rate of data collection to 4,000 miles in 2022 and 4,800 miles in 2023. The network of the data collected is shown in Figure 6.

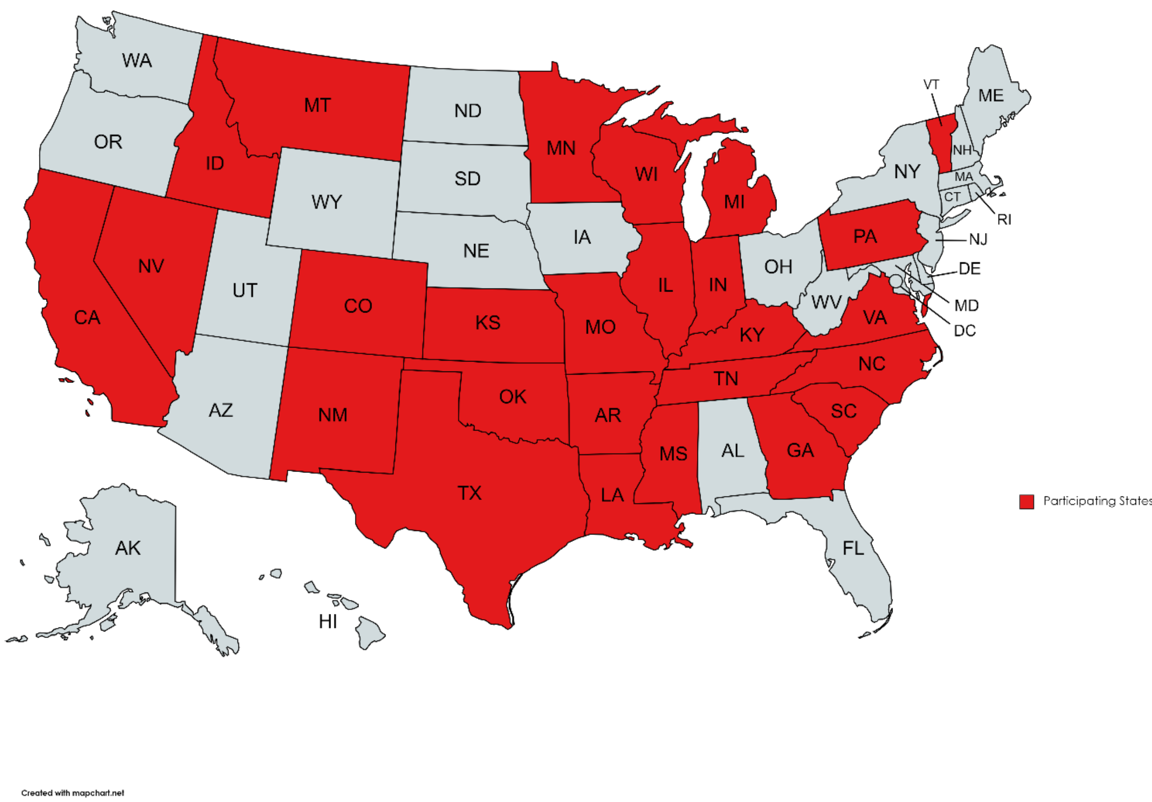

Figure 3. Pooled Fund member States.

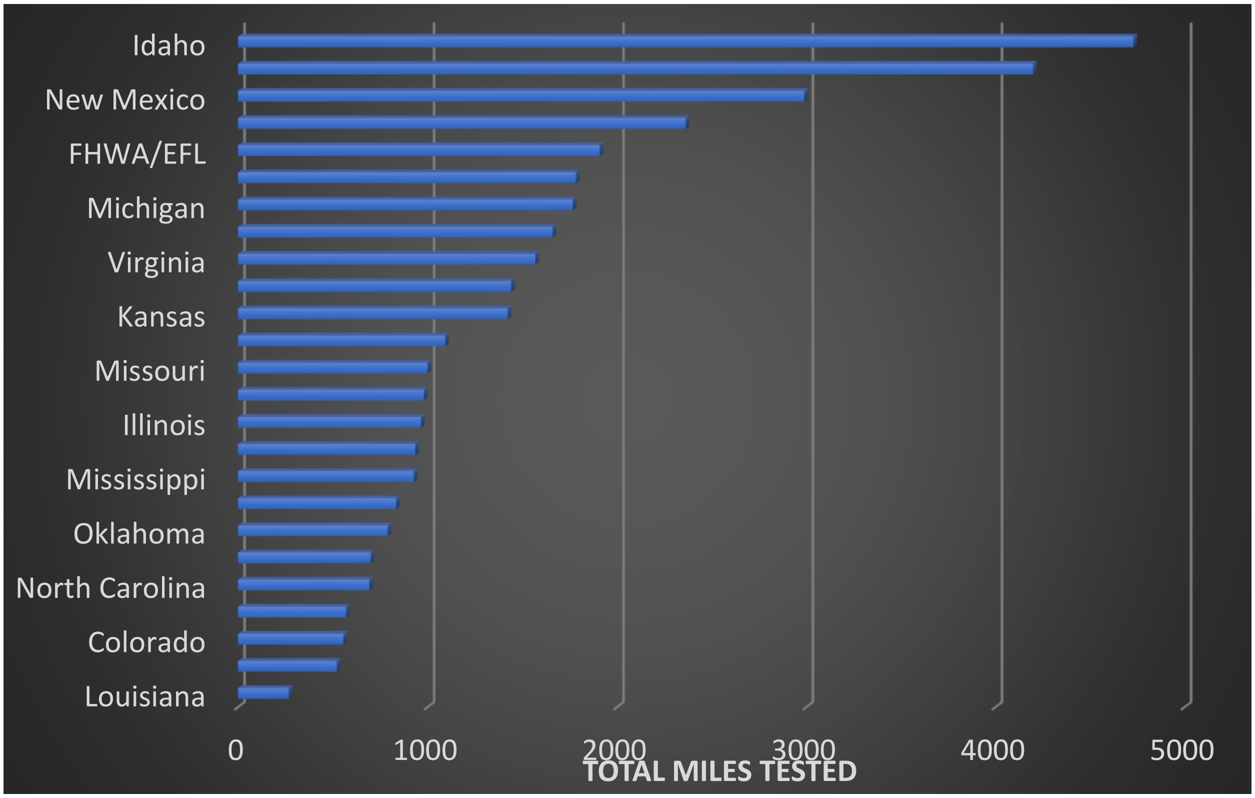

Figure 4. Total lane-miles of collected data by State.

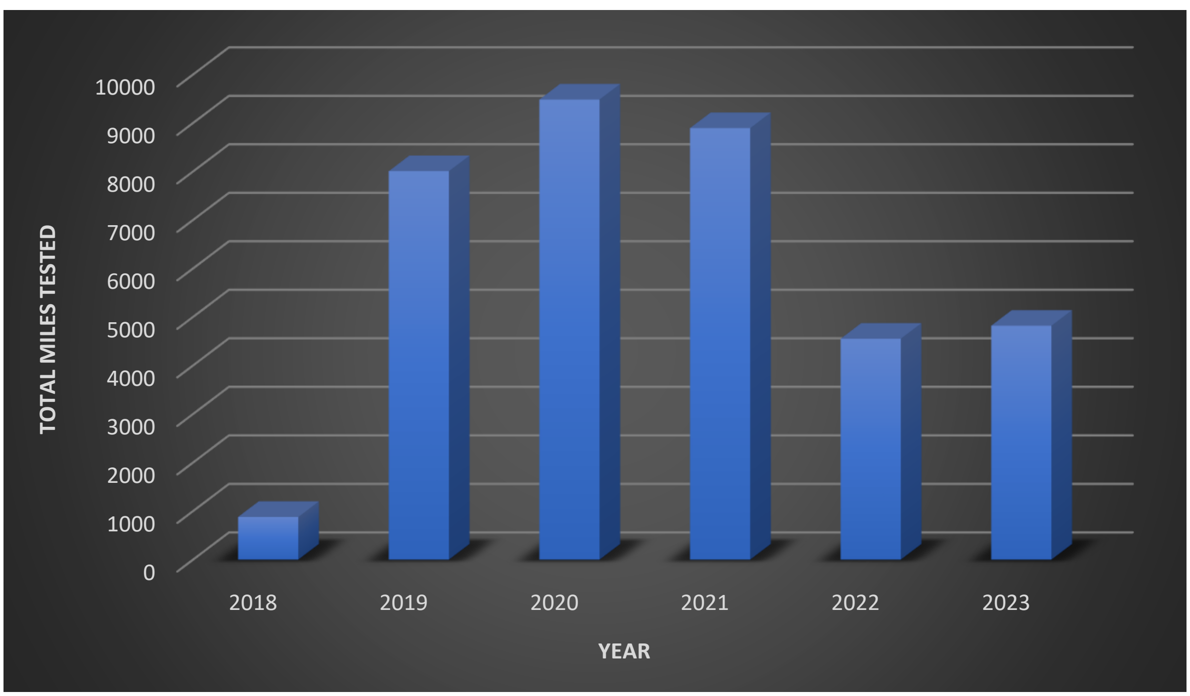

Figure 5. Total lane-miles collected each year.

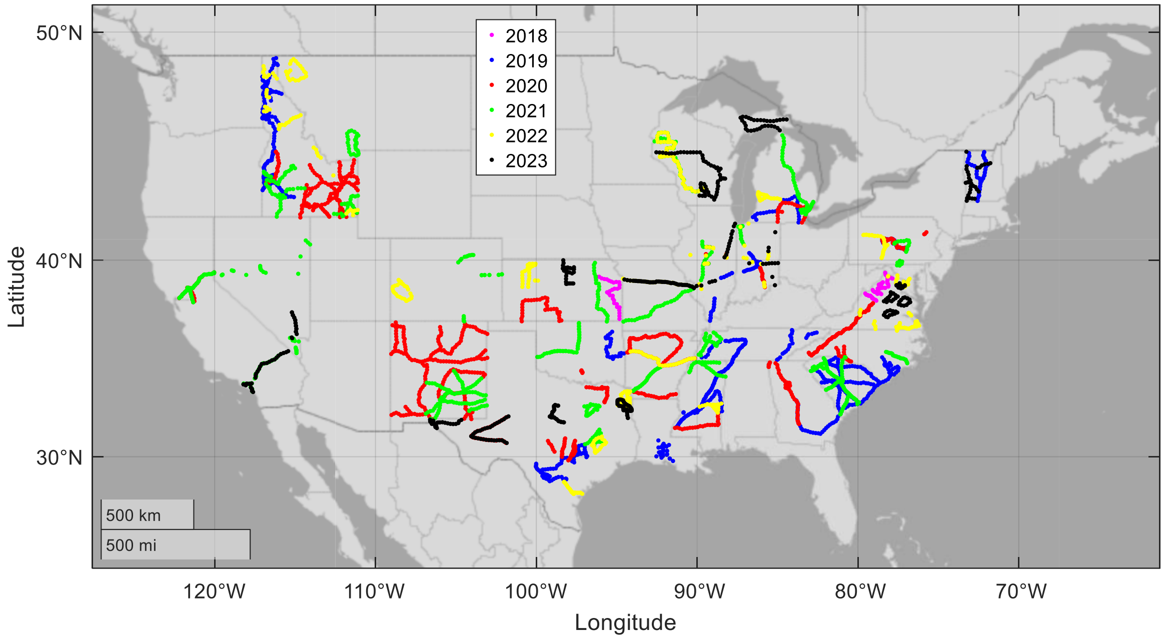

Figure 6. Network of collected TSD data for each year.

CHAPTER 3: POOLED FUND PRODUCTS AND PUBLICATIONS

This chapter lists the Pooled Fund products and publications.

Reports

Overview of TSDD Technologies and their Network- and Project-Level Applications (Task 1)

This product consists of a report documenting the (1) available TSDDs in the United States, (2) the data analysis methods used to interpret TSDD measurements, (3) results of studies that have evaluated the repeatability and reproducibility of TSDDs, and (4) network-level and project-level applications of TSDDs. At the start of the Pooled Fund study, three devices, namely the Greenwood TSD, the Dynatest Raptor, and the ARA rolling wheel deflectometer (RWD) were potentially available in the United States. However, the RWD was retired in 2020 and the Raptor was in the United States for only a brief time. The measurement principle of the RWD and Raptor is based on distance-measuring lasers and the "spatially coincident methodology" to determine the pavement deflection based on the deflected and undeflected profiles. This approach is very sensitive to pavement macrotexture, and the Raptor uses a wide footprint laser to minimize this effect. The TSD uses Doppler lasers to measure the pavement deflection velocity, which divided by the vehicle speed gives the pavement deflection slope. This approach is not affected by the pavement macrotexture, but its drawback is that the deflection needs to be calculated from the deflection slope using (numerical) integration.

Analysis of TSDD measurements ranges from data averaging and denoising to the calculation of structural parameters such as the pavement effective structural number (SN_{eff}) or layer moduli. TSDDs collect data at relatively high frequencies (more than 1 kHz) and averaging of the measurements is done to reduce the amount of data to a practical level needed for pavement analysis and also to reduce the amount of noise. The typical averaging length currently used is 10 to 16 m, with 16 m being chosen because it is equivalent to 0.01 miles, which is one tenth of the popular pavement condition reporting data of 0.1 miles. For the TSD, the deflection is calculated from the deflection slope using numerical integration. Deflection bowl indices are popular parameters that are based on a linear combination of the measured deflections (see Rada et al. 2016). The most popular of those are based on the difference between two measured deflections, which are used to characterize the structural condition of different pavement layers and also to estimate the strain at different locations of the pavement. The SN_{eff} and subgrade M_r are also very popular due to their connection to the American Association of State Highway and Transportation Officials (AASHTO) pavement design methodology. Finally, researchers have also used data collected by TSDDs to estimate the pavement layer moduli with generally successful results.

Accuracy and precision of the TSD and RWD have been well documented by Rada et al. (2016), and their results are compatible with the estimates reported by Flintsch et al. (2013). Short- and long-term repeatability has been documented in Katicha et al. (2017) as part of Pooled Fund TPF-5(282). Comparisons with FWD measurements have generally shown that TSDDs and

FWDs produce similar results, although fundamental differences between the two technologies are important.

Most applications of TSDDs have been developed for flexible pavements at the network level. Some efforts for project-level applications and rigid and composite pavement applications have been investigated but not to a practical level of routine implementation.

Guidelines for the Collection of Network-Level Structural Condition Data with Traffic Speed Deflectometer (Task 2)

This document provides guidelines for the collection of TSD pavement deflection velocity data. It describes how to perform data collection and how to implement a data quality management plan. A chapter on how to perform the data collection describes pavement loading, laser Doppler vibrometers (LDVs), measurement of the deflection velocity, calculation of the pavement deflection slope, and calculation of the pavement deflection. Important parameters to consider during data collection are surface reflectivity and laser focus.

A chapter on specifications and quality management describes equipment specifications with the needed instrumentation for adequate data collection, survey testing procedure including periodic device checks, temperature control in the trailer, the minimum data reporting requirements that need to be collected and recorded, and device validation, verification, and calibration. Suggested data reporting forms are provided in an appendix.

Guide for Network-Level Flexible Pavement Structural Evaluation and Management (Task 3)

The guide presents approaches that State highway agencies can use to incorporate pavement structural condition information into the pavement management decision-making process at the network level. The guide first explains the difference between strategic-level, network-level, and project-level pavement management and highlights the importance of the pavement structural condition on the rate of pavement deterioration. To incorporate the structural condition in the pavement management system, an agency needs to decide on the structural index(es) to use. The choice of appropriate index(es) should be guided by (1) current approach used by the agency for pavement structural assessment, (2) ease of computation for network-level applications, (3) intended use of the index(es) in the pavement management system, and (4) index(es) recommended by others.

The pavement SN_{eff} and the deflection bowl indexes (e.g., surface curvature index) are some of the most popular and easily implemented indexes. Once indexes are selected, thresholds to classify the pavement condition into different structural performance categories (e.g. good, fair, and poor) need to be developed. These thresholds can be based on expert knowledge, statistical analysis of the data, or mechanistic principles. It is important to keep in mind that the pavement structural condition needs to account for the truck traffic level.

Implementation of the selected index(es) in the pavement management system depends on how they will be used. Some uses include (1) delineating weak and strong sections, 2) identifying sections that are good candidates for preservation, (3) determining required overlay thickness, (4) modifying treatments selected based on surface condition, (5) developing pavement deterioration models, (6) performing a pavement needs analysis, (7) determining budget needs, and (8) optimizing resource allocations.

Use of the Traffic Speed Deflectometer for the Structural Assessment of Jointed Concrete Pavements (Task 4)

This report investigates how data collected from the TSD can be used to assess jointed concrete pavements. Limited research has shown that high-resolution (1 m or higher resolution) TSD data can be used to detect localized weak spots such as weak joints in a jointed concrete pavement. This report went further in analyzing TSD data at a 5-cm (2-inch) resolution.

First it was discovered that if the pavement deflection basin varies rapidly along the spatial dimension, then the deflection slope is not equal to the deflection velocity divided by the longitudinal travel speed. In this case, there is an additional term in the measured velocity that is related to the change in the pavement deflection bowl. Moreover, this term becomes the dominant term of the measured velocity near the joints.

A slab on a Pasternak foundation (a foundation modeled as springs plus a membrane that can resist shearing) was used to model the joint load transfer efficiency and a back-calculation procedure was developed to estimate the slab material properties and the joint load transfer efficiency using the measured TSD deflection velocity and the model.

Idaho Pavement Structural Evaluation Using the Traffic Speed Deflectometer (Task 5)

This project combined data collected from the TSD and GPR to calculate the structural number and remaining life and overlay thickness for more than 1,315 lane-miles, and the report was published to the Idaho Transportation Department's public online platform.

The report includes an example project-level analysis showing how the data can be used to diagnose the sources of pavement deficiencies and can lead to rehabilitation recommendations that appropriately address these sources. Repeatability analysis was performed comparing data collected in 2016 and data collected in 2020 showing that the data is consistent. Furthermore, areas where structural improvement was performed between 2016 and 2020 were also identified in the data. A cost analysis shows that obtaining this equivalent information through traditional FWD testing and coring would incur 9 times the cost of the testing performed with the TSD and GPR.

Structural Evaluation of Natchez Trace and Blue Ridge Parkway Using the Traffic Speed Deflectometer (Task 5)

This is a report on the structural evaluation of the Natchez Trace and the Blue Ridge Parkway using the TSD and GPR data. The SN_{eff} and SN_{req} for a design period of 20 years were used to calculate the required overlay thickness, and SN_{eff} and SN_{design} (sum of layer thicknesses multiplied by layer coefficients) were used to calculate the remaining structural service life.

Because trucks are generally not allowed on the Natchez Trace and Blue Ridge Parkway, the SN_{req} is relatively low, suggesting that the current pavement is structurally adequate to carry the traffic loading for the next 20 years. On the other hand, the SN_{eff} was much lower than the

SN_{design}, suggesting the pavement structure has considerably deteriorated (compared to a new pavement with similar layer thicknesses).

A sensitivity analysis on the calculation of SN_{eff} was performed. This involved evaluating the effect of sensor used to calculate the subgrade resilient modulus on AASHTO 1993 approach to calculate SN_{eff} and comparing the AASHTO 1993 approach to the Rohde equation to calculate SN_{eff}. The results showed that the Rohde equation gives much higher SN_{eff} results and, even within the AASHTO equation approach, the calculated SN_{eff} is affected by the sensor used to determine the subgrade resilient modulus.

Webinar Series 1 – Circular (Task 7)

Nine webinars were conducted, with the first six webinars (Series 1) summarized in a circular. The aim of the webinars was to share knowledge between the Pooled Fund member agencies, present research being performed, and provide consultants' perspectives on the analysis of TSDD data. The topics addressed by each of the six webinars were:

- Webinar 1 topic: Processing of TSD data (one presentation)
- Webinar 2 topic: Segmentation of TSD data (one presentation)
- Webinar 3 topic: Integration of TSD data into the pavement management system (two presentations)
- Webinar 4 topic: Case study implementation of TSD in Idaho (one presentation)
- Webinar 5 topic: Consultants' perspectives on analysis of TSD data (two presentations)
- Webinar 6 topic: Consultants' perspectives on analysis of TSD data (one presentation)

The date, title, and presenters of the webinars are provided in Table 1.

Table 1. Transport Pooled Fund Program TPF-5(385) summary webinars

Webinar No.	Date	Title	Presenter(s)	Presenter(s) Organisation(s)
1	08/17/2020	Demonstration of TSD Data Extraction and Processing Tool	Senthil Thyagarajan Ph.D., P.E.	Transportation Engineer. Maintenance Division. TxDOT
2	10/29/2020	Pavement Data Segmentation	Samer Katicha Ph.D., P.E.	Virginia Tech Transportation Institute
3.1	03/17/2021	Network Level TSD Implementation Case Studies. Review of current status from TxDOT	Jenny Li Ph.D., P.E.	Texas DOT
3.2	03/17/2021	Traffic Speed Deflectometer Device (TSDD) Data In Pavement Management System	Charles Pilson; Eric Perrone; Aaron Gerber	The Kercher Group
4	05/19/2021	Implementation of Traffic Speed Deflectometer in Idaho	Ken Maser, Infrasense Nick Weitzel, NCE Samer Katicha, VTTI Jim Poorbaugh, ITD	Infrasense / NCE / VTTI / ITD
5.1	08/25/2021	Comparison of TSDD and FWD Interstate 64 Westbound. James City and York Counties, VA	Amy Simpson, Ph.D., P.E.	Wood
5.2	08/25/2021	New Mexico TSD. Data Analysis Results	Linda Pierce, PhD, PE Nick Weitzel, PE	NCE
6	12/08/2021	Implementation of Traffic Speed Deflectometer Data into the Pavement Management System	Amir Arshadi, PhD, PE Mirkat Oshone, PhD, PE Gerhard du Toit, PE	AECOM

First and Second Symposium on Pavement Structural Evaluation with TSDDs (Task 7)

The Pooled Fund organized two symposiums: the first on September 27, 2022, held at the Virginia Tech Executive Briefing Centre in Arlington, Virginia, and the second on the August 15 and 16, 2023, also in Arlington, Virginia. In the first symposium, the presentations focused on different Department of Transportation (DOT) experiences and efforts at implementing TSDD data. The presentation title, presenter name, and the State represented by the presenter are provided in Table 2. The presentations made during the second symposium are listed in Table 3.

Table 2. Presentations made at the first symposium

Presentation No.	Title	Presenter(s)	Presenter(s) Organisation(s)
1	MDOT's TSD Story: What we've done and plan to do	Mr. Tucker Stafford and Mr. Jim Poorbaugh	Mississippi DOT
2	Application of Falling Weight Deflectometer-Based Structural Indicators to the Traffic Speed Deflectometer Data	Mr. Seonghwan Cho	Indiana DOT
3	Kansas Research "Efforts" with Traffic Speed Deflection Devices	Mr. Rick Miller and Chris Jones	Kansas DOT
4	Comparison and Analysis of FWD and TSD Data for Effective Pavement Preservation Program	Mr Emad Kassem	Idaho DOT
5	Evaluation of Traffic speed Deflectometer for Collecting Network-level Pavement Structural Data in Tennessee	Miaomiao Shang	Tennessee DOT
6	Wisconsin's Share for Pavement Structural Evaluation Using TSD Data	Mr. Ali Morovatdar	Wisconsin DOT
7	Illinois' Experience	Mr. John Senger	Illinois DOT
8	Nevada DOT – TSD experience to-date	Mr. Peter Schmalzer	Nevada DOT
9	Incorporating TSD Results into NPS PMS Models – Results and Lesson's Learned To Date	Mr. James Bryce	Eastern Federal Lands DOT
10	Analysis of joints in concrete pavements with a Traffic Speed Deflectometer	Mr. Martin Scavone	Virginia Tech - VTTI
11	Determine the Feasibility and Methodologies of Using Structural Data from the Traffic Speed Deflectometer in Network level Treatment Decision Making (TxDOT	Mr. Tom Scullion	Texas DOT
12	Oklahoma DOT's Efforts with Traffic Speed Deflection Device Data : A Brief Summary	Mr. Angel Gonzalez	Oklahoma DOT

Table 3. Presentations made at the second symposium

Presentation No.	Title	Presenter(s)	Organization(s)
1	Verification of TSDD Measurements	Gonzalo Rada	WSP
2	Update on Traffic Speed Deflectometers Devices	Dirk Jansen	BASt
3	Comparing E-Moduli from TSD and FWD	Helene Pehrsson	Greenwood Engineering
4	Integration of 3DGPR with the Traffic Speed Deflectometer	Ken Maser	Infrasense
5	Basics of 3D GPR	Jacopo Sala	Kontur
6	DSteel – A New Program for Simulating Flexible Pavement Response under Moving Loads: Preliminary Lessons Learned	Hyung Lee	ARA
7	Identify and Appropriate Structural Indicator to Interpret Traffic Speed Deflectometer Data Assessing Full-Depth Asphalt Pavements	Seonghwan Cho, Bongsuk Park	Indiana DOT, Purdue Univeristy
8	Beyond the Network: Leveraging iPAVE Data at the Network, Corridor and Project Level	Jim Poorbaugh	Mississippi DOT
9	Incorporating TSD Results into NPS PMS Models – Results and Recommendations	James Bryce	West Virginia University
10	A Proposed Approach for Verification of TSD Measurements	Mahdi Nasimifar	FHWA
11	TSD for Concrete Pavement Surveying. What Have we Learned so Far?	Martin Scavone	Virginia Tech
12	iPAVe FAQs and Future Development	Nathan Bech	ARRB Systems
13	Determine the Feasibility and Methodologies of Using Structural Data from the Traffic Speed Deflectometer in Network Level Treatment Decision Making	Tom Sculion, Garrett Dorsett	TTI
14	Metrics for Structural Evaluation Using Traffic Speed Deflectometer Data	Samer Katicha	Virginia Tech
15	VDOT Implementation Efforts of TSD Structural Data into the Pavement Management System	Samer Katicha	Virginia Tech

Verification of TSD Measurements at the Virginia Smart Roads

A series of four experiments were conducted at the Virginia Smart Roads testing facility to develop an accurate and robust procedure to verify TSD measurements. Lessons learned in each experiment were used to improve subsequent experiments. The final experiment consisted of verification testing on the urban Surface Street section and the Rural Roadway section of the Virginia Smart Roads, with data collected from the TSD compared to data collected for LDVs, geophones, and FWD. The tested sections, experimental setup, and results are summarized in the following three subsections.

Tested Sections

The tested sections consisted of the Surface Street section and the Rural Roadway section of the Virginia Smart Roads (Figure 7). The Highway section of the Virginia Smart Roads was tested in previous experiments and deemed to be not as effective (the section is very strong, not straight, and has a 4% horizontal grade). The selection of the testing locations on each section was based on extensive FWD testing and road geometric considerations to best accommodate the TSD driving on each section.

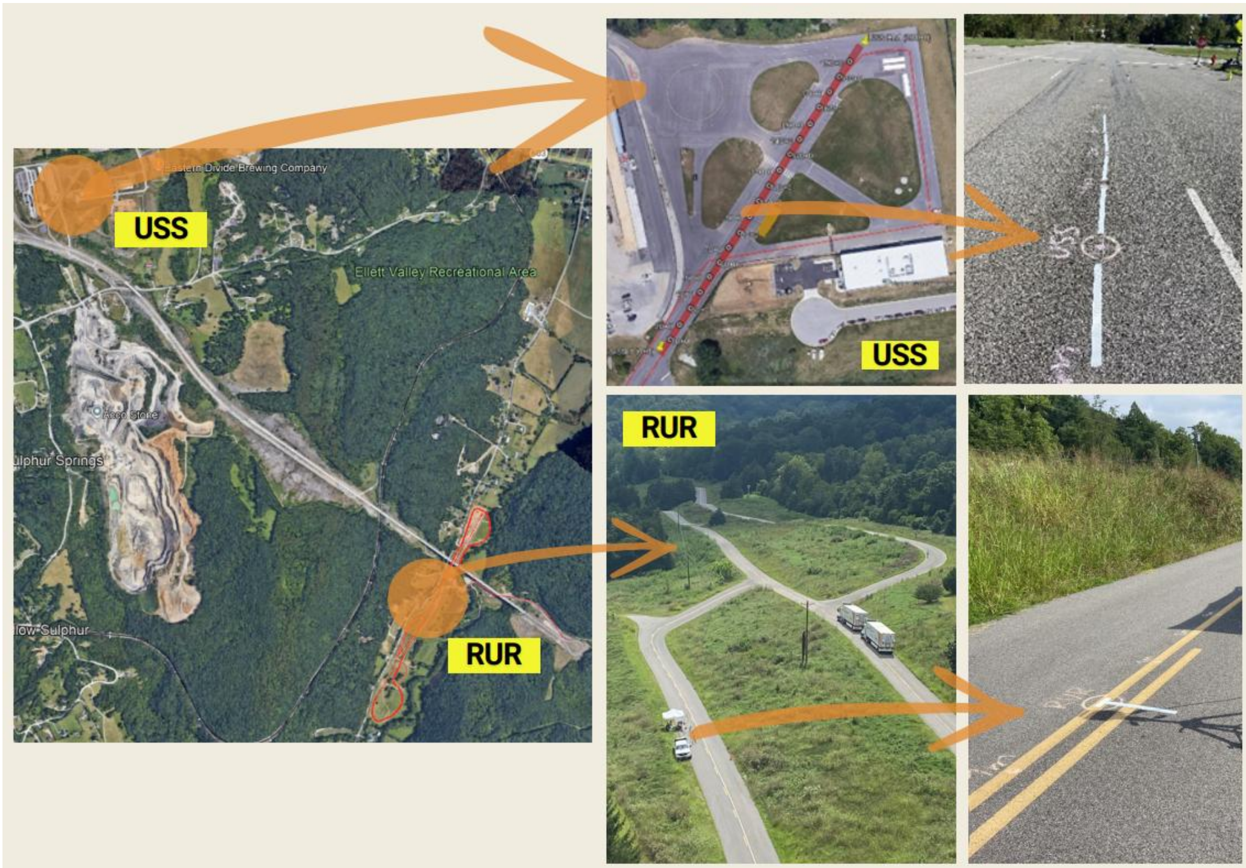

Figure 7. Selected locations for testing on the Surface Street section and Rural Roadway section of the Virginia Smart Roads.

Test Setup

The test setup consisted of LDVs, geophones, and FWD testing on the Surface Street section and LDVs and FWD testing on the Rural Roadway section. Figure 8 shows the LDVs set up with the TSD passing over the laser target points. Figure 9 shows the LDV's target points.

Figure 8. LDV setup on the Surface Street section (left) and Rural Roadway section (right).

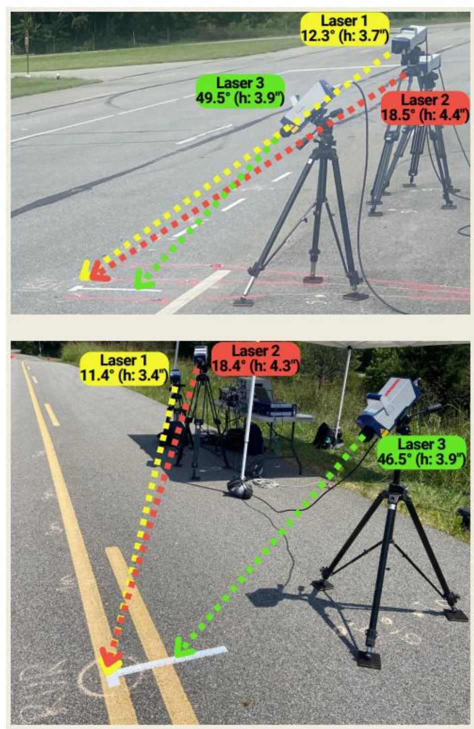

Figure 9. LDV target points on the Surface Street section (top) and Rural Roadway section (bottom).

Figure 10 shows the location of the three geophones installed on the Surface Street section with the LDV target points located between the first and second geophones along the driving direction.

Figure 10. Geophones set up on the Surface Street section; red tape shows location of geophones; white tape shows location of LDV target points.

Results

Tests were performed at target speeds of 25 mph and 35 mph at the Surface Street section and the Rural Roadway section with TSD data collected at 2-inch (5-cm) intervals. Figure 11 and Figure 12 show the results of the verification testing at a target speed of 25 mph on the Rural Roadway section and the Surface Street section, respectively. The Surface Street section is stronger than the Rural Roadway section, which is reflected in the lower recorded pavement deflection velocity. In general, the TSD measurements agreed with the LDV measurements on the Rural Roadway section and with the LDV and geophone measurements on the Surface Street section.

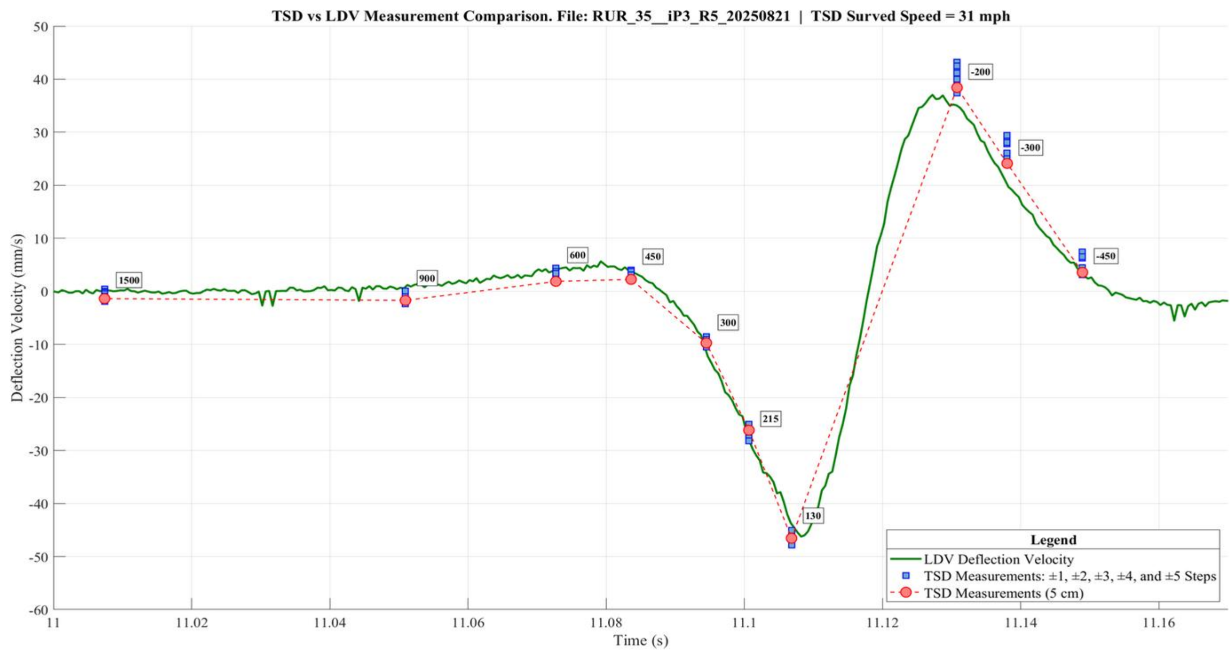

Figure 11. Verification testing of the TSD with LDVs on the Rural Roadway section at a target speed of 25 mph (actual test speed was 31 mph).

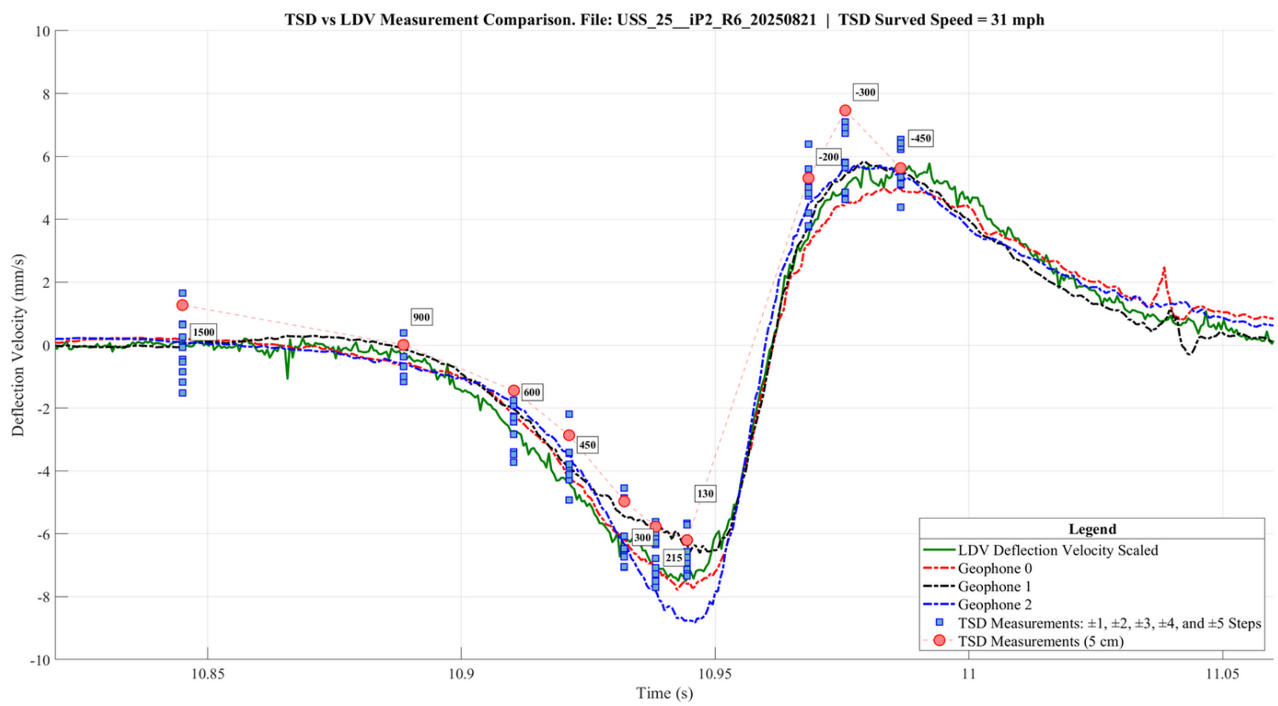

Figure 12. Verification testing of the TSD with LDVs and geophones on the Surface Street section at a target speed of 25 mph (actual test speed was 31 mph).

Repeated Testing in Virginia

Repeated testing was conducted on select road sections for the purpose of investigating the rate of structural deterioration and ascertaining an appropriate frequency of network-level data collection. The testing was performed in September 2025, and the data will be analyzed in the future. The analysis will consist of determining the rate of change of the structural condition of pavement sections over a period of up to 8 years, from 2017 to 2025. A total of 1,573 miles of data was collected on the roads shown in Figure 13.

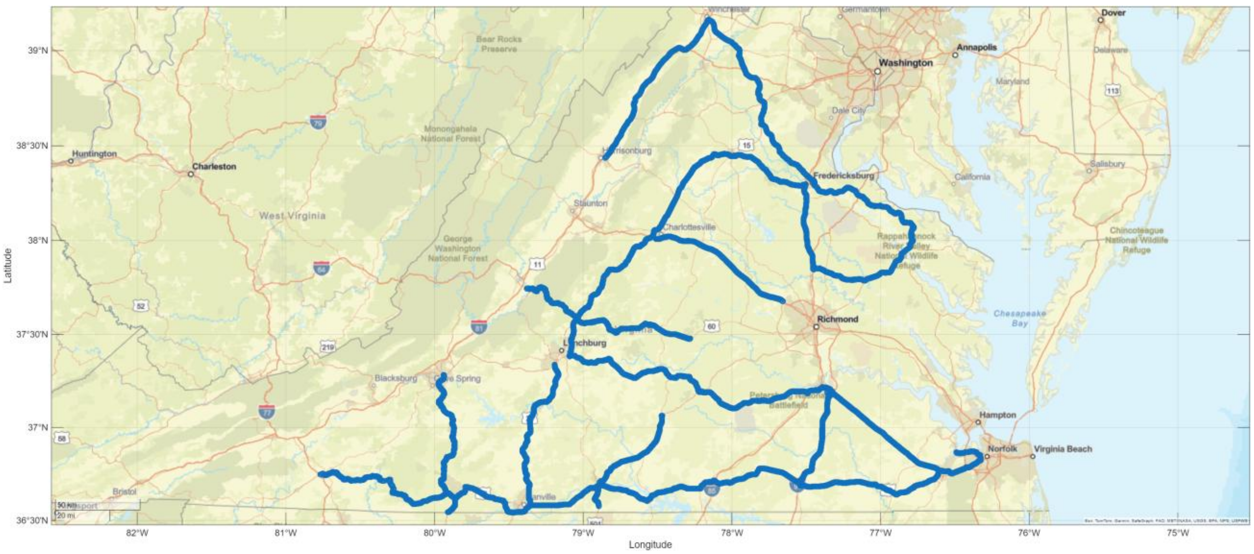

Figure 13. Map showing location of data collection.

Scholarly Work and Publications

The pooled fund resulted in scholarly work including two dissertations, nine journal articles, and eight conference papers/presentations.

Dissertations

Scavone, M. (2022). *Use of the traffic speed deflectometer for concrete and composite pavement structural health assessment: A big-data-based approach towards concrete and composite pavement management and rehabilitation*.

Shrestha, S. (2022). *Network level decision-making using pavement structural condition information from traffic speed deflectometer*.

Published Journal Articles and Conference Presentations

1. Katicha, S. W., Scavone, M., Flintsch, G. W., & Amarh, E. (2024). Learning the appropriate local averaging length for TSD deflection velocity measurements: Application to the analysis of rigid pavement joints response. *Transportation Research Record*, *2678*(12), 1316-1328.

2. Murkey, A., Katicha, S. W., Urbaez, E., Flintsch, G. W., & Diefenderfer, B. (2024). A pilot study to incorporate network-level structural condition into agency pavement management practices. *Transportation Research Record*, *2678*(12), 1416-1427.

3. Scavone, M., Katicha, S.W., Flintsch, G.W., and Diefenderfer, B. (2023) “Reweighted L_1 minimization for network-level weak spot detection from Traffic Speed Deflectometer measurements,” *Journal of Computing in Civil Engineering*, 34(7), 04023016.

4. Scavone, M., Katicha, S. W., Flintsch, G. W., & Amarh, E. (2023). Estimating load transfer efficiency for jointed pavements from TSD deflection velocity measurements, *Transportation Research Record*, 03611981231171923.

5. Katicha, S. W., Flintsch, G. W., & Diefenderfer, B. (2022) “Ten years of TSD research in the United States: A review,” *Transportation Research Record*, 2676(12), 152-165.

6. Scavone, M., Katicha, S.W., Flintsch, G.W., & Amarh, E. (2022). On the TSD deflection velocity measurements: A revision to the current state of the art and discussion over its applicability for concrete pavements. *International Journal of Pavement Engineering*, 1-13. https://doi.org/10.1080/10298436.2022.2138881

7. Shrestha, S., Katicha, S. W., Flintsch, G. W., & Diefenderfer, B. K. (2022). Implementing traffic speed deflection measurements for network level pavement management in Virginia. *Journal of Transportation Engineering, Part B: Pavements*, *148*(2), 04022021.

8. Shrestha, S., Katicha, S. W., Flintsch, G. W., & Diefenderfer, K.K. (2021). Pavement deterioration modelling and network-level pavement management using continuous deflection measurements. *ASCE Journal of Infrastructure Systems*, *27*(3).

9. Scavone, M., Katicha, S. W., & Flintsch, G. W. (2021). Identifying weak joints in jointed concrete and composite pavements from Traffic Speed Deflectometer measurements by Basis Pursuit. *Journal of Computing in Civil Engineering*, *35*(2), 04020062. DOI: 10.1061/(ASCE)CP.1943-5487.0000951

10. Scavone, M., Katicha, S. W., Flintsch, G. W., & Amarh, E. (2024). Estimating load transfer efficiency for jointed pavements from TSD deflection velocity measurements. *Transportation Research Record*, *2678*(1), 583-594.

11. Urbaez, E., Flintsch, G. W., Katicha, S. W., Diefenderfer, B., & Jafari, R. (2024). *Investigation of Doppler laser technology for measuring deflection velocity during accelerated pavement testing: Initial approach for data modelling*. Transportation Research Board Meeting.

12. Urbaez, E., Flintsch, G., Katicha, S. W., & Diefenderfer, B. (2023). *Virginia US-460 traffic speed deflectometer (TSD) historical structural data comparison (2017 & 2022)*. ASCE International Airfield and Highway Pavements Conference, June 14-17, 2023, Austin, Texas.

13. Scavone, M., Katicha, S. W., & Flintsch, G. W. (2022). Identifying weak joints in jointed concrete pavements from TSD measurements by basis pursuit. *Eleventh International Conference on the Bearing Capacity of Roads, Railways and Airfields, Volume 1*, pp. 430–439.

14. Katicha, S. W., Shrestha, S., Flintsch, G., & Diefenderfer, B.K. (2020). *Development of an approach to incorporate pavement structural condition into the treatment selection process at the network-level*. Transportation Research Board Meeting.

15. Katicha, S. W. (2023). *Metrics for structural evaluation using traffic speed deflectometer data*. 2nd Symposium on Traffic Speed Deflection Devices, Arlington, Virginia.

16. Scavone, M., Katicha, S. W., Flintsch, G. W., & Diefenderfer. (2022). *Case studies on corridor-level structural evaluation of flexible pavements using a traffic speed deflectometer*. Transportation Research Board Meeting.

17. Katicha, S. W., & Flintsch, G. W. (2019). *Joint Pursuit: detecting weak joints using TSD measurements by Basis Pursuit*. Pavement Evaluation 2019, Roanoke, Virginia.

Other Contributions

A number of participating State agencies have conducted or are currently conducting research with universities or consultants using the data they collected as a participating agency in the Pooled Fund study. Tennessee and South Carolina published the following reports:

18. Huang, B., Zhang, M., Gong, H., & Polaczyk, P. (2022). *Evaluation of traffic speed deflectometer for collecting network level pavement structural data in Tennessee* (Report No. RES2020-08). Tennessee Department of Transportation.

19. Huynh, N., Gassman, S., Mullen, R., Pierce, C., Chen, Y, & Ahmed, N. (2021). *Utilization of traffic speed deflectometer for pavement management* (FHWA-SC-21-04). South Carolina Department of Transportation.

Furthermore, the following research papers were published based on TSD data collected in Tennessee.

20. Zhang, M., Fu, G., Jia, X., Ma, Y., Polaczyk, P. A., & Huang, B. (2023). Relationship between fatigue condition of asphalt pavements and deflection lag from traffic speed deflectometer. *Journal of Materials in Civil Engineering*, *35*(7), 04023186.

21. Zhang, M., Jia, X., Fu, G., Polaczyk, P. A., Ma, Y., Xiao, R., & Huang, B. (2023). Traffic speed deflectometer for network-level pavement management in Tennessee. *Transportation Research Record*, 03611981231197665.

22. Zhang, M., Gong, H., Jia, X., Jiang, X., Feng, N., & Huang, B. (2022). Determining pavement structural number with traffic speed deflectometer measurements. *Transportation Geotechnics*, *35*, 100774.

CHAPTER 4: SIGINIFICANT CONTRIBUTIONS AND REMAINING CHALLENGES

The significant contributions of this Pooled Fund study are:

- Collection of more than 36,000 lane-miles of TSD data by 25 highway agencies.
- Development of guides: a guide for data collection and a guide for implementation of TSDD data into the pavement management system can help transportation agencies.
- Tools and analysis methods:
    a. Analysis of concrete pavements: this analysis provided a greater understanding of the TSD measuring principle and the relationship between deflection velocity and deflection slope.
    b. Enhanced AASHTO segmentation procedure: a robust segmentation procedure based on the AASHTO segmentation approach. It is available as a stand-alone app and implemented by ARRB systems for TSD data viewing.
- Network-level implementation case studies: case studies have demonstrated the applicability of structural condition data obtained from TSDDs for network-level pavement management.
- Technology transfer and dissemination: nine organized webinars and two sponsored symposiums.

The Pooled Fund study also identified important areas that still need to be addressed. These are:

- Development of verification and calibration procedures: data collected in Tennessee shows the importance and urgent need to develop reliable verification and calibration procedures. These are essential to provide reliable data interpretation for network-level and project-level applications.
- Assessment of concrete pavements: most of the research with TSDDs focuses on asphalt pavements. Efforts to assess concrete and composite pavements are still very new and more investigation is needed.
- Combination of GPR data and TSDD data: TSD data collected during the study showed the importance of pavement layer composition and thickness information for structural evaluation of the pavement.
- Effect of pavement structural condition on the pavement rate of deterioration: to improve network-level analysis and decision-making, a better understanding of the effect of pavement structural condition on the rate of pavement deterioration is needed. This will allow better pavement condition prediction and better resource allocation.

REFERENCES

Bryce, J., Flintsch, G. W., Katicha, S. W., & Diefenderfer, B. K. (2013a). *Developing a network-level structural capacity index for structural evaluation of pavements*. Virginia Center for Transportation Innovation and Research.

Elseifi, M. A., Abdel-Khalek, A.M., & Dasari, K. (2011). *Implementation of rolling wheel deflectometer (RWD) in PMS and pavement preservation* (No. FHWA/LA. 11/492). Louisiana Transportation Research Center.

Elseifi, M. A., Zihan, Z. U., & Icenogle, P. (2019). *A mechanistic approach to utilize traffic speed deflectometer (TSD) measurements into backcalculation analysis* (No. FHWA/LA. 17/612). Louisiana State University. Department of Civil and Environmental Engineering.

Katicha, S. W., Shrestha, S., Flintsch, G. W., & Diefenderfer, B. K. (2020). *Network level pavement structural testing with the traffic speed deflectometer* (No. VTRC 21-R4). Virginia Transportation Research Council (VTRC).

Maser, K., Schmalzer, P., Shaw, W., & Carmichael, A. (2017). Integration of traffic speed deflectometer and ground-penetrating radar for network-level roadway structure evaluation. *Transportation Research Record*, *2639*(1), 55-63.

Shrestha, S., Katicha, S. W., Flintsch, G. W., & Thyagarajan, S. (2018). Application of traffic speed deflectometer for network-level pavement management. *Transportation Research Record*, *2672*(40), 348-359.

Steele, D. A., Beckemeyer, C. A., & Van, T. P. (2015, June). Optimizing highway funds by integrating RWD data into pavement management decision making. In *9th International Conference on Managing Pavement Assets*.

Thyagarajan, S., Sivaneswaran, N., Petros, K., Rada, G., & Elkins, G. (2019). Optimized treatment selection using structural data for pavement management applications. In *Pavement and asset management* (pp. 635-642). CRC Press.

Zaghloul, S., He, Z., Vitillo, N., & Brian Kerr, J. (1998). Project scoping using falling weight deflectometer testing: New Jersey experience. *Transportation Research Record*, *1643*(1), 34-43.

Zhang, Z., Gaspard, K., & Elseifi, M. A. (2016). Evaluating pavement management treatment selection utilising continuous deflection measurements in flexible pavements. *International Journal of Pavement Engineering*, *17*(5), 414-422.