Southern Plains Transportation Center
CYCLE 1

FINAL REPORT

2023–2024

USDOT BIL Regional UTC
Region 6

Integration and Deployment of Novel Tools for Rapid Assessment of Pavement Conditions and Remaining Life

Southern Plains
Transportation Center

Disclaimer

Technical Report Documentation Page

1. Report No. CY1-TTI-01	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Integration and Deployment of Novel Tools for Rapid Assessment of Pavement Conditions and Remaining Life		**5. Report Date** 11/1/2025
		6. Performing Organization Code Texas Transportation Institute
7. Author(s) Garrett Dorsett, 0009-0007-9761-298, https://orcid.org/0009-0007-9761-2298 Tom Scullion, 0000-0001-5531-5411, https://orcid.org/0000-0001-5531-5411		**8. Performing Organization Report No.** CY1-TTI-R1.2
9. Performing Organization Name and Address Texas Transportation Institute 1111 Rellis Pkwy Bryan, TX 77807		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. 69A3552348306
12. Sponsoring Agency Name and Address Southern Plains Transportation Center 202 West Boyd St., Room 213B The University of Oklahoma Norman, OK 73019		**13. Type of Report and Period Covered** Final Report, September 2023-September 2024
		14. Sponsoring Agency Code
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation as a part of University Transportation Center (UTC) program.		

16. Abstract

Extreme heat events expose pavements to more intense and prolonged stress. These events, coupled with soil movement from heavy rainfall and drought also threaten pavement functional and structural life. State and local agencies have benefited from innovative technologies and tools developed to rapidly assess pavement condition, but data has not yet been widely implemented into pavement management systems that provide cohesive, wholistic assessments of state roadways. A hybrid approach combining traffic speed deflectometer (TSD) and air-coupled ground penetrating radar (GPR) is examined that will allow for large-scale data collection and analysis for use in state pavement management systems. The ideas presented in this study outline best practices for leveraging deflection data produced by TSD at the network- and project-levels, including merging TSD and GPR field data to enhance pavement engineers' understanding of in-situ pavement structural conditions. These strategies were applied in the field and greatly assisted in identifying failed and at-risk pavements and prioritizing future projects. The remaining life estimation and material modulus backcalculation methods produced in this study will continue to be modified and improved to better match predictions generated by existing state practices.

17. Key Words Deflection, Extreme Weather, Falling Weight Deflectometer, Ground Penetrating Radar, Pavement Condition, Pavement Life, Pavement Management, Pavement Structure, Resilience, Traffic Speed Deflectometer		**18. Distribution Statement** No restrictions. This publication is available at www.sptc.org and from the NTIS.	
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 48	**22. Price** N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

INTEGRATION AND DEPLOYMENT OF NOVEL TOOLS FOR RAPID ASSESSMENT OF PAVEMENT CONDITIONS AND REMAINING LIFE

FINAL REPORT
SPTC Project Number: CY1-TTI-01

Submitted by
Garrett Dorsett (PI)
Tom Scullion (Co-PI)

Texas Transportation Institute
The University of Texas A&M

Prepared for
Southern Plains Transportation Center
The University of Oklahoma
Norman, OK

SOUTHERN PLAINS
TRANSPORTATION CENTER

November 2025

Table of Contents

Executive Summary 1
Chapter 1. Introduction 2
Task 1: Texas TSD Data Collection and Literature Search 3
Task 2: Assist Oklahoma Researchers in Oklahoma Testing Program 3
Task 3: Integration of TSD and GPR Data 5
Task 4: Pavement Structural Analysis and Remaining Life Prediction 5
Chapter 2. Literature Review 6
Chapter 3. Materials and Methodologies 10
Pavement Layer Modulus Backcalculation Methodology 10
Pavement Remaining Life Estimation Methodology 12
Chapter 4. Results and Discussion 14
Results of Texas TSD Data Collection and Analysis 14
Using TSD Outputs to Define Project Sections 14
Oklahoma Testing Program – Results and Discussion 15
Analysis of TSD Outputs 18
Prototype Program to Integrate TSD and GPR Data 26
Remaining Life Prediction Results 27
Pavement Layer Modulus Backcalculation from TSD Deflection Measurements 29
Chapter 5. Conclusions and Recommendations 34
Chapter 6. Implementation of Project Outputs 35
Chapter 7. Technology Transfer and Community Engagement and Participation (CEP) Activities 36
Chapter 8. Invention Disclosures and Patents, Publications, Presentations, Reports, Project Website, and Social Media Listings 37
References 38

List of Tables

Table 1. SSI for Pavement Type 10. 8
Table 2. MODULUS Upper Layer Strength Classification. 8
Table 3. MODULUS Lower Layer Strength Classification. 9
Table 4. MODULUS Subgrade Layer Strength Classification. 9
Table 5. Oklahoma Test Section Pavement Structure and Modulus Values. 16
Table 6. Texas Pavement Condition Case 1 Criteria. 18
Table 7. Texas Pavement Condition Case 2 Criteria. 18
Table 8. Texas Pavement Condition Case 3 Criteria. 19
Table 9. Texas Pavement Condition Case 4 Criteria. 19
Table 10. TSD Collected Data. 26
Table 11. Test Section Survey Information for Remaining Life Estimation. 27
Table 12. TSD Backcalculation Test Parameters and Results. 32

List of Figures

Figure 1. Aerial Photography of Hurricane Harvey Flooding in Texas (Civil Air Patrol, 2022). 2
Figure 2. ARRB Systems' iPAVe TSD (ARRB Systems, n.d.). 3
Figure 3. Map of Oklahoma TSD and Test Sections. 5
Figure 4. TSD Sensor Array (Elsefi, et al., 2018). 6
Figure 5. TSD Deflection Survey Methodology (ARRB Systems, n.d.). 6
Figure 6. MODULUS Software Landing Page. 10
Figure 7. MODULUS Backcalculation Input Window. 11
Figure 8. MODULUS Backcalculation Graphical Results Window. 11
Figure 9. MODULUS Remaining Life Analysis Input Screen. 12
Figure 10. MODULUS Remaining Life Result Charts. 13
Figure 11. Oklahoma TSD Data Collection Route, 2021. 16
Figure 12. Annotated GPR Scan from Section 1. 17
Figure 13. FWD and TSD Maximum Deflection Comparison. 18
Figure 14. Case 1: Good Pavement Surface and Structure in Oklahoma. 20
Figure 15. Case 2: Good Pavement Surface and Poor Pavement Structure in Oklahoma. 21
Figure 16. Case 3: Poor Surface and Good Pavement Structure in Oklahoma. 22
Figure 17. Case 4: Poor Pavement Surface and Structure in Oklahoma. 23
Figure 18. TSD Data for Section 2 and 3 on IH 35 in Oklahoma. 24
Figure 19. TSD Deflection Indices for Section 2 and 3 on IH 35 in Oklahoma. 24
Figure 20. Percent Sand Content from 12 – 36 inches along IH 35 in Oklahoma (USDA, n.d.). 25
Figure 21. Prototype Software Layout. 26
Figure 22. Potential Future Layout of GPR Program. 27
Figure 23. The Rut (a) and Crack (b) Remaining Life Estimations from FWD and TSD for Typical Test Sections. 28
Figure 24. Measured and Simulated Deflection Bowls for a Weak (Left) and Strong (Right) Pavement 29
Figure 25. Recorded and Simulated TSD Maximum Deflection. 30
Figure 26. a) - c) Deflection Bowl Comparison between Test Cases and Field TSD Data. 33

List of Equations

Equation 1. Surface Curvature Index. 7
Equation 2. Base Curvature Index (Li, 2020). 8
Equation 3. TSD Surface Curvature Index. 14
Equation 4. Subgrade Curvature Index. 15

List of Abbreviations and Acronyms

BCI	Base curvature index
CTB	Cement-treated base
D0	Maximum deflection
DOT	Department of Transportation
E	Modulus
ESAL	Equivalent single axle load
FB	Flexible base
FWD	Falling weight deflectometer
GPR	Ground penetrating radar
GPS	Global positioning system
HMA	Hot mix asphalt
iPAVe	Intelligent pavement assessment vehicle
IRI	International roughness index
OWP	Outside wheel path
SCI	Surface curvature index
SCI36-60	Subgrade curvature index
SCI8	TSD Surface curvature index
SSI	Structural strength index
SUBB	Subbase
SUBGR	Subgrade
SURF	Surface
T	Thickness
TSD	Traffic speed deflectometer
TSDD	Traffic speed deflectometer device
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation

Executive Summary

Extreme heat events expose pavements to more intense and prolonged stress. These events, coupled with soil movement from heavy rainfall and drought threaten pavement functional and structural life. Current practices to identify and address premature failure rely on visual inspections and localized testing which disrupts traffic and introduces potential safety concerns. State and local agencies have benefited from innovative technologies and tools developed to rapidly assess pavement conditions, namely, traffic speed deflection devices (TSDDs). TSDDs collect pavement deflection data at traffic speeds so there is no need for traffic control. This allows for pavement structural data to be collected over a vast roadway network in a relatively short period of time. In particular, the traffic speed deflectometer (TSD) utilized by ARRB systems to collect data in the United States, called the intelligent Pavement Assessment Vehicle (iPAVe), has been outfitted with a large array of sensors that allow the system to collect data on pavement functional metrics such as grade, cracking, rutting, and roughness in addition to pavement deflections. In this research, a hybrid approach that combines TSD and air-coupled ground penetrating radar (GPR) is evaluated that allows for large-scale data collection and analysis for use in Oklahoma pavement management systems. Researchers defined four tasks to accomplish this goal.

Initial tasks included a literature search of what departments of transportation (DOTs) have been doing with the TSDD data to meet their pavement management needs, including reporting experiences with TSD in Texas. It will include information gained from the national TSDD webinars organized by the University of Virginia. Additionally, one of the initial tasks was completed with a research team from the University of Oklahoma. Oklahoma had recently collected approximately 250 miles of TSD data on its interstate highways (IH). The Texas Transportation Institute (TTI) research team provided GPR and FWD data collection along selected sections of IH 35 and IH 40. These sections were defined by the Oklahoma team.

Another project task provided direction for the Oklahoma DOT to merge the TSD data with GPR data. Integration of the data can greatly enhance the usefulness of the deflection and condition data collected by the TSD. This would also allow districts to gain a more wholistic knowledge of pavement structural conditions and better understand the impact of structural anomalies/deficiencies on functional pavement metrics to promote more informed decisions within pavement management decision trees.

The final task included developing a process to make determinations of pavement structural condition and to predict the remaining life of the pavement. Such a framework currently exists for FWD deflection measurements, but due to the localized nature of FWD testing, the resulting predictions were not suitable for network-level pavement management decisions.

Six key indices are recommended, as reported by the TSD, that can be used to make determinations on overall pavement condition: maximum deflection (D0), the TSD surface curvature index (SCI8), the subgrade curvature index (SCI36-60), the total cracking (reported as a percentage), the rut depth in the outside lane, and the international roughness index (IRI) reported in inches per mile. This study provides the development of the first iteration of software that integrates TSD measurements with GPR. TSD data was also used in a remaining life routine that had good agreement with FWD predictions of pavement remaining life until failure due to cracking.

Chapter 1. Introduction

Extreme heat events expose pavements to more intense and prolonged stress. These events, coupled with soil movement from heavy rainfall, flooding (example shown in Figure 1), hard freezes, and drought, while also incurring greater traffic loads, threaten pavement functional and structural life. Transportation agencies must address the resulting severe distresses and premature pavement failures within their pavement networks. A goal of this project is to leverage new technologies to rapidly assess pavement structural conditions by integrating them into existing pavement structural analysis practices and network management systems.

Figure 1. Aerial Photography of Hurricane Harvey Flooding in Texas (Civil Air Patrol, 2022).

Traffic speed deflection devices (TSDDs) are testing equipment used to measure, or otherwise report, pavement deflections beneath a moving load. Such devices have been in broad use in Europe, but the use of TSDDs in the United States has been limited to the intelligent Pavement Assessment Vehicle (iPAVe) operated by ARRB Systems shown in Figure 2. This system will be referred to as the Traffic Speed Deflectometer (TSD) in this report. The TSD is capable of collecting continuous pavement deflection data at posted traffic speeds. This ability presents a large improvement over current testing strategies that use falling weight deflectometers (FWDs) on both a logistical and safety front. Due to the stop-and-go nature of FWD testing, deflection data is limited to localized, discrete points along the roadway. The standard reporting interval is every 0.1 mile, but the operator may choose to test at a higher or lower frequency. Additionally, traffic control is required for this testing. These limitations prevent FWD testing from being feasible for network-level structural assessment operations. The TSD, however, collects continuous data, and can report data every 2 inches if desired. Because data collection is completed at traffic speeds, there is no need for disruptive traffic control.

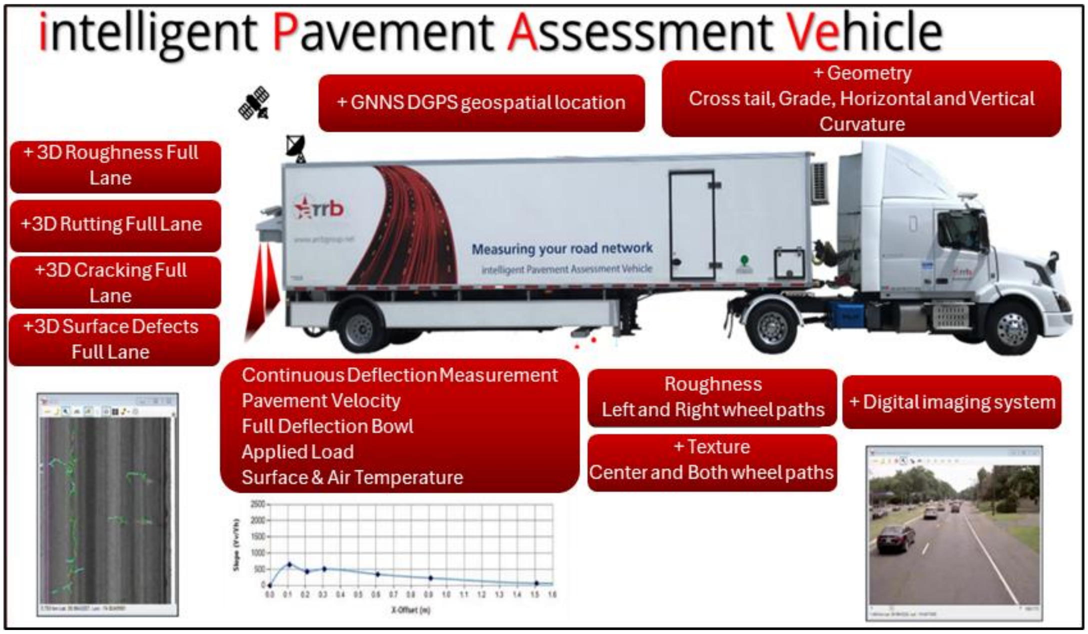


Figure 2. ARRB Systems' iPAVe TSD (ARRB Systems, n.d.).

Because the TSD has the ability to collect vast amounts of structural data in such a short amount of time, this technology is well suited for network-level pavement structural evaluations and analysis, and several DOTs are actively working to implement TSD data into their pavement management systems. The TSD could feasibly be utilized to build a deflection database for a state or organization's roadways that will allow engineers access to up-to-date pavement structural data.

Task 1: Texas TSD Data Collection and Literature Search

The goal of task 1 was to conduct literature review and to assist agencies in disseminating the TSD data to the appropriate personnel and to teach district engineers how to leverage the data to identify project sections of interest for closer evaluation. Such sections may have needed maintenance or structural repair, been recently constructed, or were in good condition. In this way, the collected data could be used to assist the districts in pavement management activities and/or assess district priorities. The result of this task would be that district personnel had a greater understanding of TSD testing and data, and greater trust in the technology would be established.

Task 2: Assist Oklahoma Researchers in Oklahoma Testing Program

Task 2 was completed with a research team from the University of Oklahoma. Oklahoma had recently completed around 250 miles of TSD data collection on their interstate highways. The TTI research team provided GPR and FWD data collection along the selected sections of IH 35 and IH 40 shown in

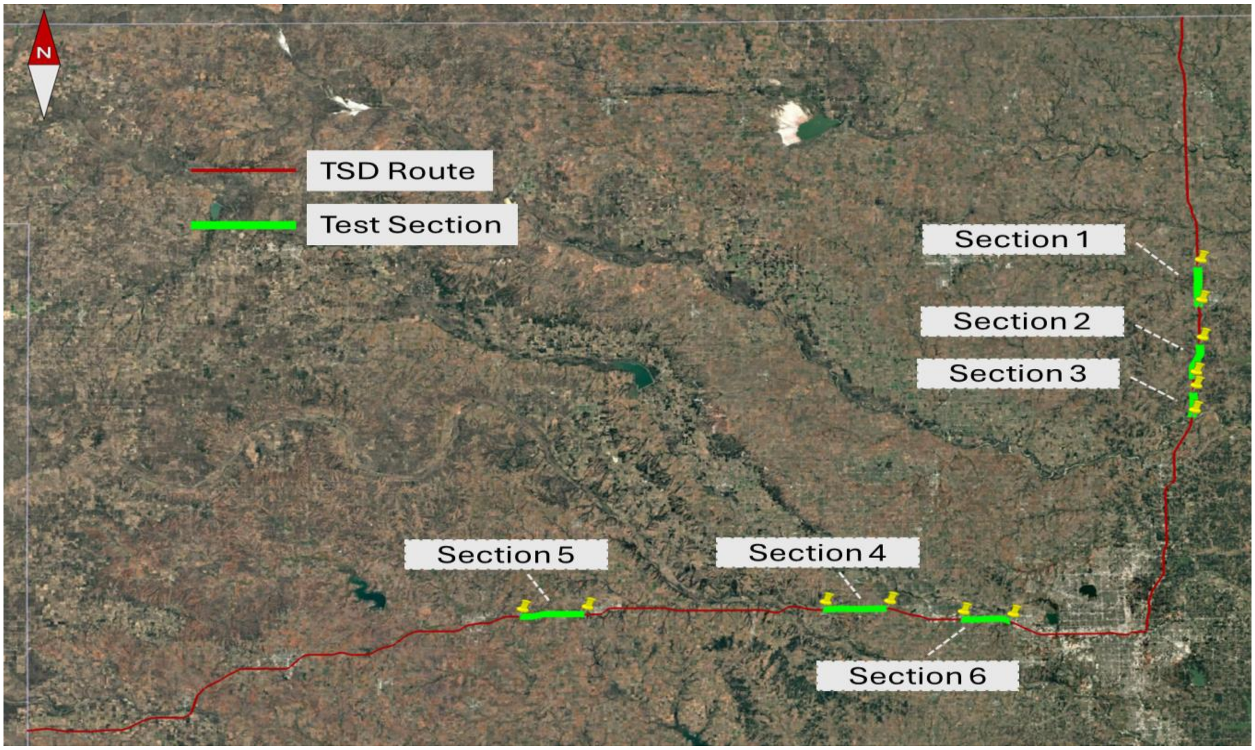


Figure 3. These sections were defined by the Oklahoma team using previous experience and TSD data. The test sections were to be representative of 1 of 4 pavement conditions:

1. Pavement surface and structure are in good condition.
2. Pavement surface is in good condition, but the structure is in poor condition.
3. Pavement surface is in poor condition, but the structure is in good condition.
4. Pavement surface and structure are in poor condition.

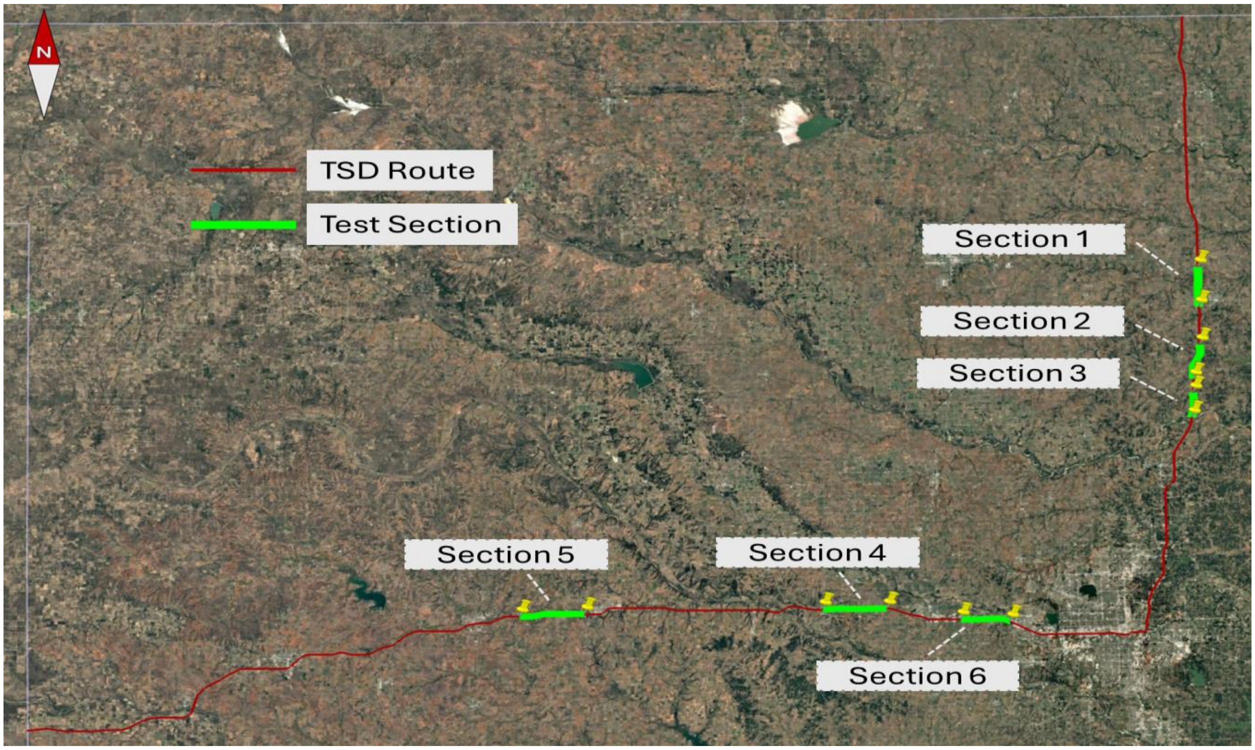


Figure 3. Map of Oklahoma TSD and Test Sections.

Task 3: Integration of TSD and GPR Data

Task 3 included developing a prototype software package that integrated TSD data with GPR data. GPR is currently used at the project-level to determine pavement layer thickness and identify structural anomalies/deficiencies. It is the belief of the researchers that layer thickness data is required to make an appropriate pavement management decision. When combined with FWD, layer thickness data enables engineers to backcalculate the pavement layer modulus values.

A primary motive of this research is to utilize TSD data to provide meaningful network-level data for use within existing pavement management structures. This task addresses it by integrating TSD and GPR data. This would allow districts to gain a more wholistic knowledge of pavement structural conditions and better understand the impact of structural anomalies/deficiencies on functional pavement metrics to promote more informed decisions within pavement management decision trees.

Task 4: Pavement Structural Analysis and Remaining Life Prediction

Task 4 developed a process to categorize pavement structural condition and predict remaining life. Remaining life predictions are used within DOT pavement management systems to develop rehabilitation and maintenance plans. Therefore, the results of the proposed remaining life routine developed for TSD data would need to be easily interpreted within any DOT pavement management system to support development of maintenance plans. Such a framework currently exists for FWD deflection measurements, but due to the localized nature of FWD testing, the resulting predictions are not suitable for network-level pavement management practices.

Chapter 2. Literature Review

The TSD measures pavement responses beneath the moving load by way of Doppler Laser sensors as shown in Figure 4**.** Pavement deflections are reported at 12 locations surrounding the load center: 18, 12, and 8 inches behind the load center, directly beneath the load center, and 8, 12, 18, 24, 36, 48, 60, and 72 inches in front of the load center. These deflection values are derived from the vehicle speed and the vertical deflection velocity of the pavement, which is being measured by the Doppler sensors, via the Area Under the Curve Method (ARRB Systems, n.d.). The TSD measurement methodology is illustrated in Figure 5. It is important to note that the TSD does not directly measure pavement deflection like FWD. This difference in measurement principle indicates that, while the deflection outputs from both devices should be similar in amplitude, the TSD and FWD are not expected to provide exact one-to-one deflection results.

Figure 4. TSD Sensor Array (Elsefi, et al., 2018).

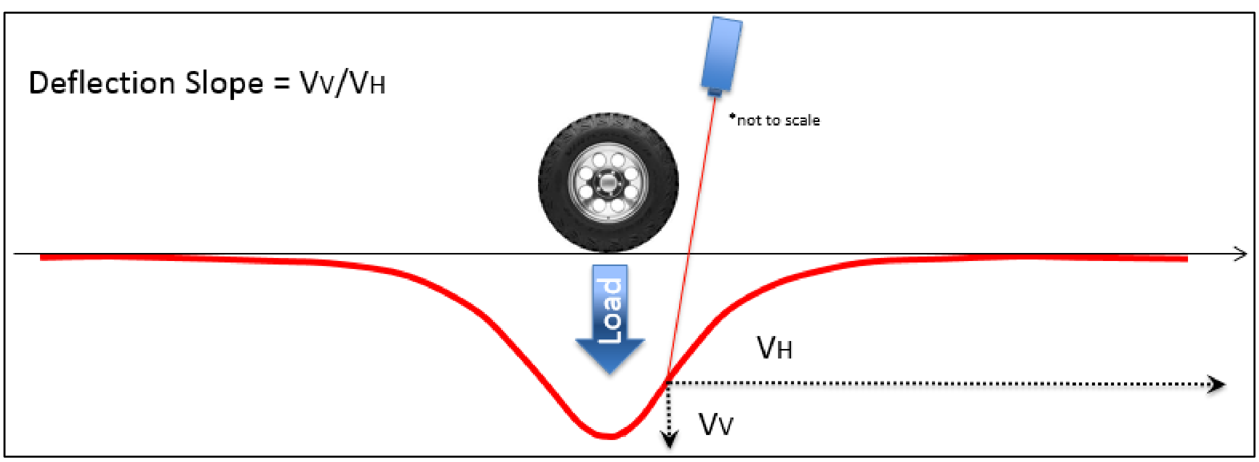


Figure 5. TSD Deflection Survey Methodology (ARRB Systems, n.d.).

The section describes the uses of FWD data within the Texas Department of Transportation (TxDOT) for developing structural strength indicators. A similar system can be developed for Oklahoma. TxDOT currently uses a database within its pavement management system to classify pavement type (Scullion, et al., 2024). The 10 pavement classifications listed below describe the pavement material and thickness:

1. Continuously reinforced concrete pavement.
2. Jointed reinforced concrete pavement.
3. Jointed plain concrete pavement.
4. Thick asphaltic concrete pavement (greater than 5.5 inches).
5. Intermediate thickness asphaltic concrete pavement (2.5 to 5.5 inches).
6. Thin surfaced flexible base pavement (less than 2.5 inches).
7. Asphalt surfacing with heavily stabilized base.
8. Overlaid and/or widened old concrete pavement.
9. Overlaid and/or widened old flexible pavement.
10. Thin surfaced flexible base pavement (surface treatment/seal coat combination).

The pavement type classifications can be used to enhance the structural strength index (SSI) of pavement. SSI is determined by table lookup and depends on the temperature corrected surface curvature index (SCI) given by Where:

W0 = maximum deflection recorded directly beneath the load center (mils)

W12 = deflection recorded at the second FWD sensor located 12 inches away from the load center (mils)

Equation 1 and the subgrade support represented by the deflection measured at the outer sensor (W7) (Scullion, 1988). An example of the FWD SSI schema is given in Error! Reference s ource not found. for pavement type 10.

$$SCI = W0 - W12$$

Where:

W0 = maximum deflection recorded directly beneath the load center (mils)

W12 = deflection recorded at the second FWD sensor located 12 inches away from the load center (mils)

Equation 1. Surface Curvature Index.

Table 1. SSI for Pavement Type 10.

W7 (mils)	SCI (mils)	SSI
< 1.2	< 20	1.00
< 1.2	20 – 25.9	.80
< 1.2	26 – 30.9	.60
< 1.2	31 – 35.9	.40
< 1.2	36 – 40	.30
< 1.2	> 40	.20
1.3 – 1.9	< 20	.90
1.3 – 1.9	20 – 25.9	.70
1.3 – 1.9	26 – 30.9	.50
1.3 – 1.9	31 – 35.9	.35
1.3 – 1.9	36 – 40	.25
1.3 – 1.9	> 40	.15
> 2.0	< 20	.80
> 2.0	20 – 25.9	.55
> 2.0	26 – 30.9	.40
> 2.0	31 – 35.9	.30
> 2.0	36 – 40	.20
> 2.0	> 40	.10

The MODULUS software is used to backcalculate pavement layer moduli and estimate remaining life within TxDOT's pavement design practices. MODULUS utilizes the W7 and SCI FWD indices to make determinations of subgrade and pavement strength classifications, but the software also incorporates the base curvature index (BCI) given by Where:

W24 = deflection recorded at the third FWD sensor located 24 inches away from the load center

Equation 2 to determine the strength of the base material in a pavement structure.

Table 2,

Table 3, and Table 4 display the MODULUS software schema for all three deflection indices to estimate the pavement layer strength for different asphalt thicknesses, based on a FWD 9,000 pound load (Texas A&M Transportation Institute, 2019).

$$BCI = W12 - W24$$

Where:

W24 = deflection recorded at the third FWD sensor located 24 inches away from the load center

Equation 2. Base Curvature Index (Li, 2020).

Table 2. MODULUS Upper Layer Strength Classification.

Asphalt Thickness (inches)	> 5	2.5 – 5	1 – 2.5	< 1	Condition
SCI (mils)	< 4	< 6	< 12	< 16	**Very Good**
SCI (mils)	4 – 6	6 – 10	12 – 18	16 – 24	**Good**
SCI (mils)	6 – 8	10 – 15	18 – 24	14 – 32	**Medium**
SCI (mils)	8 – 10	15 – 20	24 – 30	32 – 40	**Poor**
SCI (mils)	> 10	> 20	> 30	> 40	**Very Poor**

Table 3. MODULUS Lower Layer Strength Classification.

Asphalt Thickness (inches)	> 5	2.5 – 5	1 – 2.5	< 1	Condition
BCI (mils)	< 2	< 3	< 4	< 8	Very Good
BCI (mils)	2 – 3	3 – 5	4 – 8	8 – 12	Good
BCI (mils)	3 – 4	5 – 9	8 – 12	12 – 16	Medium
BCI (mils)	4 – 5	8 – 10	12 – 16	16 – 20	Poor
BCI (mils)	> 5	> 10	> 16	> 20	Very Poor

Table 4. MODULUS Subgrade Layer Strength Classification.

W7 (mils)	Condition
< 1	Very Good
1 – 1.4	Good
1.4 – 1.8	Medium
1.8 – 2.2	Poor
> 2.2	Very Poor

Chapter 3. Materials and Methodologies

All backcalculation procedures conducted in this study are in accordance with TxDOT's standard practices. The methodology used to backcalculate layer modulus and estimate pavement remaining life are outlined as follows.

Pavement Layer Modulus Backcalculation Methodology

The MODULUS program is a flexible pavement backcalculation software that was developed by TTI for TxDOT. It is designed to function with deflection data gathered using FWD and is widely used by TxDOT for project-level applications, including layer modulus backcalculation. The MODULUS software utilizes a linear-elastic program to calculate a database of deflection bowls. The software searches the database to match the measured FWD deflection bowl, such that the error between the calculated and measured deflection bowl is minimized (Uzan, et al., 1988).

The MODULUS landing page is shown in Figure 6. To begin the backcalculation procedure, the user must first read the .fwd file produced by the FWD into MODULUS by clicking the "Read FWD" dropdown menu and selecting the desired data. Once the user has loaded the .fwd file, the "Drop Select" page is automatically opened so the FWD data can be viewed.

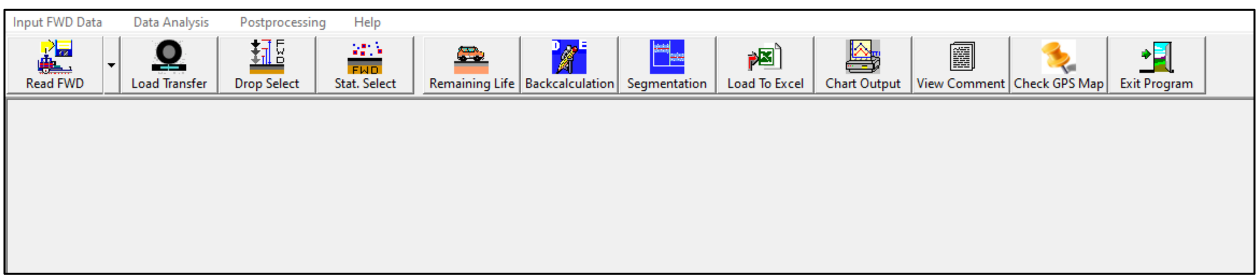


Figure 6. MODULUS Software Landing Page.

After the FWD data has been loaded into the program, clicking the "Backcalculation" button will open the input window shown in Figure 7. In this window, the user must input the layer thickness data gathered from construction typical sections or field testing, as well as the layer material types. Adjusting the asphalt temperature and material types will automatically adjust the expected moduli range. Alternatively, the user has the ability to manually input the expected moduli range. Lastly, the user may choose to assume a semi-infinite subgrade layer by checking the "semi-infinite" box to the left of the window. Clicking run will execute the backcalculation procedure and open the window in Figure 8. The graph at the top of the screen displays the measured deflection values from each of the seven sensors over the test section distance, while the graph at the bottom of the screen displays the backcalculated moduli values for each pavement layer over the test section distance. From this window, the user can continue to view the output from the backcalculation procedure in graphical format or open the results in text format by clicking the "View Result File" icon in the menu ribbon.

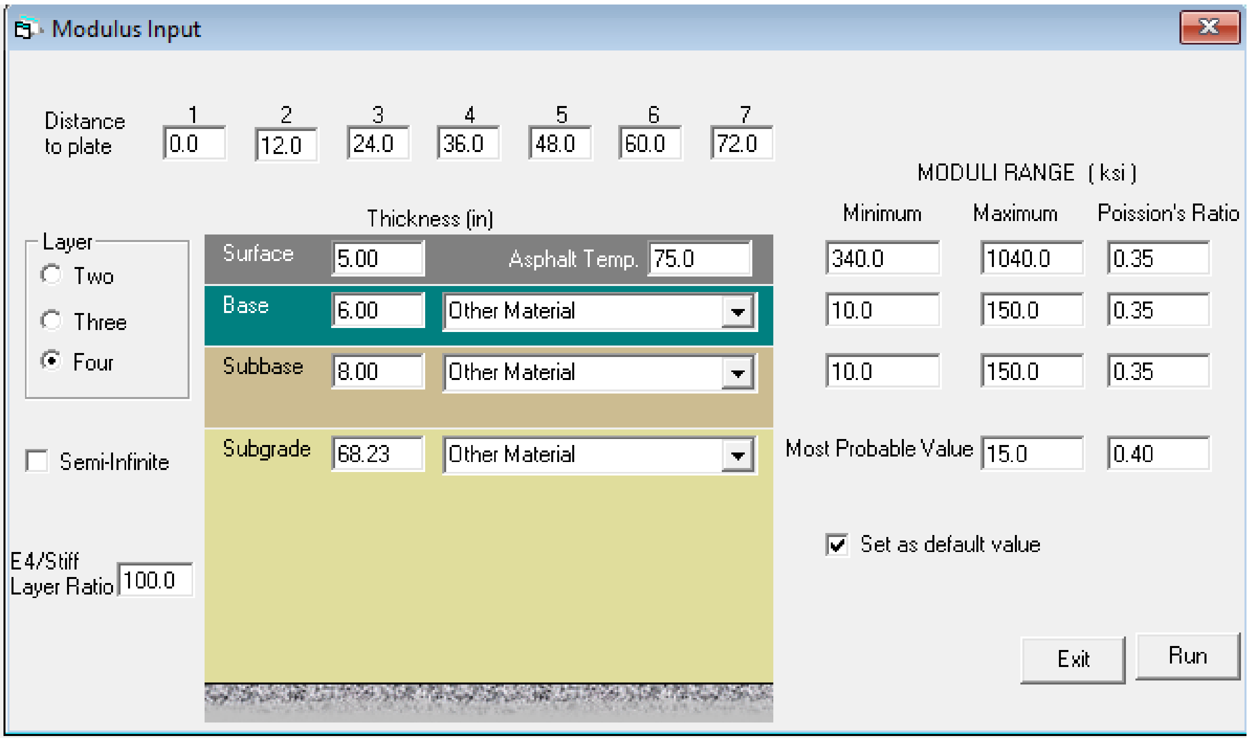


Figure 7. MODULUS Backcalculation Input Window.

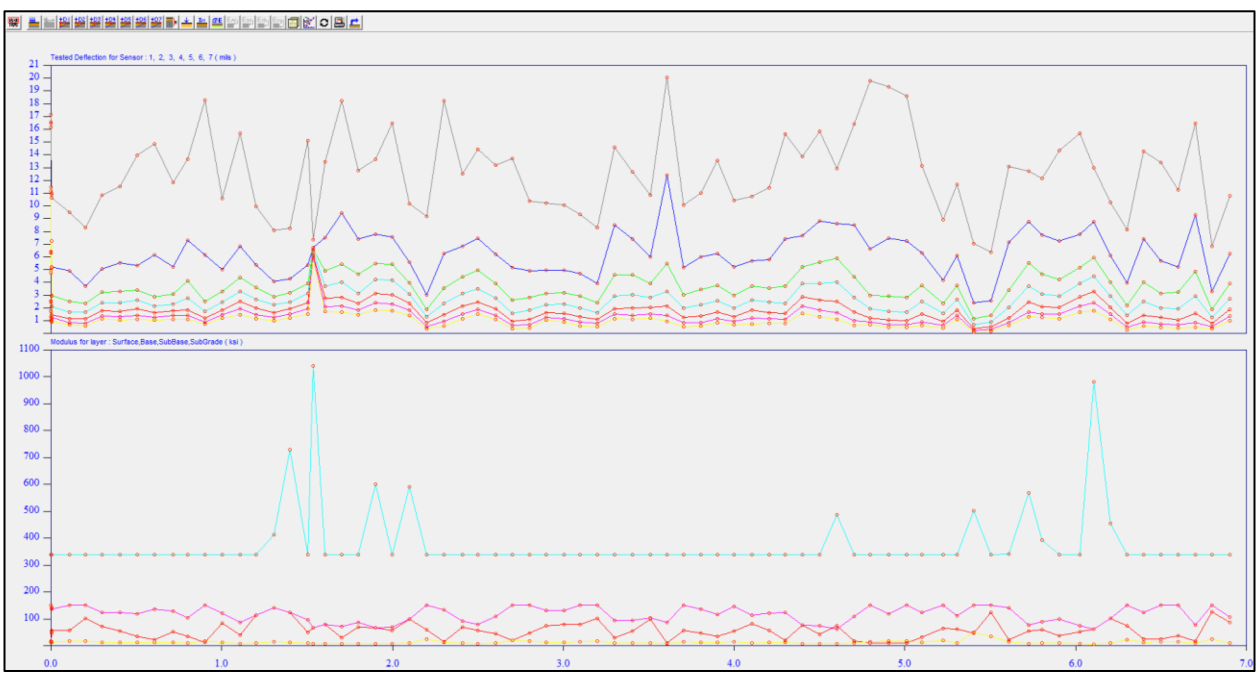


Figure 8. MODULUS Backcalculation Graphical Results Window.

Pavement Remaining Life Estimation Methodology

MODULUS estimates two remaining life values. The first estimate is the remaining life until the pavement fails due to rutting, which is related to the strength of the subsurface unbound layers. The second is the remaining life until the pavement fails due to cracking, which is related to the SCI and existing surface distresses.

The process to load .fwd data into the MODULUS software to perform a remaining life analysis is the same as the process to conduct backcalculation. After loading and reviewing the FWD data, the user selects the "Remaining Life" button on the MODULUS landing page and the input window shown in Figure 9 opens. The user is prompted to input information collected from pavement surveys, including the number of lanes, the surface layer thickness, the average rut depth in inches, the percentage of alligator cracking in the lane, and the traffic load. This information is typically collected and stored within TxDOT's pavement management system. When the required information has been entered, the user clicks the "Run" button, and the window shown in Figure 10 is opened. The chart at the top of the screen displays the crack and rut remaining life in years along the test section, while the chart in the middle of the screen shows the layer strength category for each FWD drop along the test section. The bottom chart displays the deflection indices for each FWD drop along the test section. The user has the ability to manipulate the displayed data by selecting the boxes in the menu ribbon. The user may also choose to view the result in tabular form.

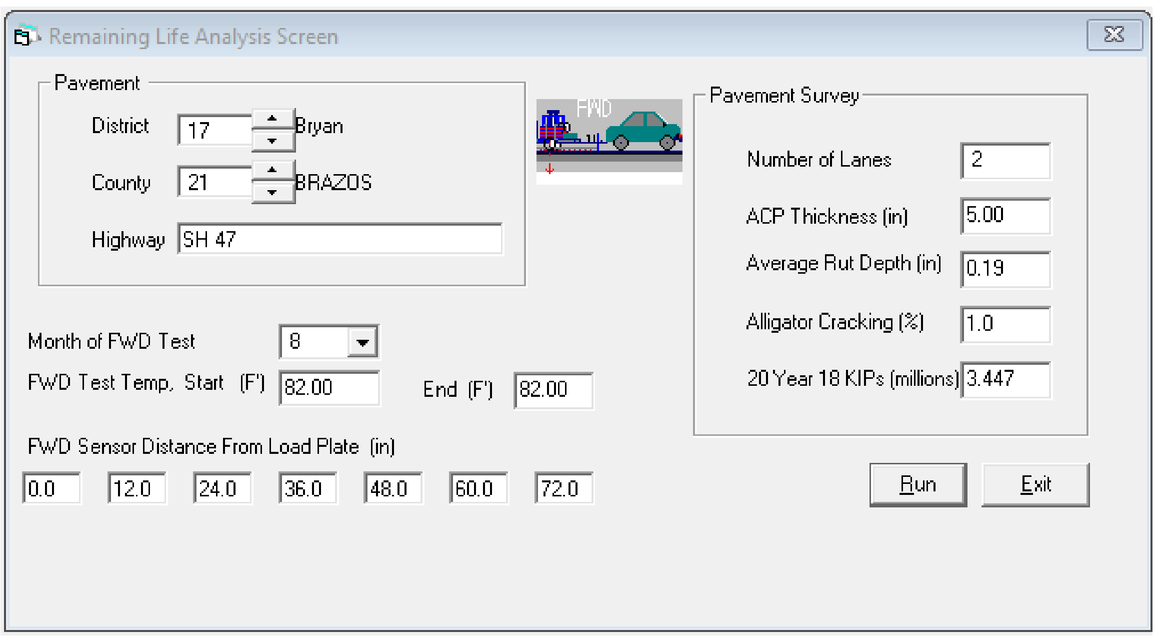


Figure 9. MODULUS Remaining Life Analysis Input Screen.

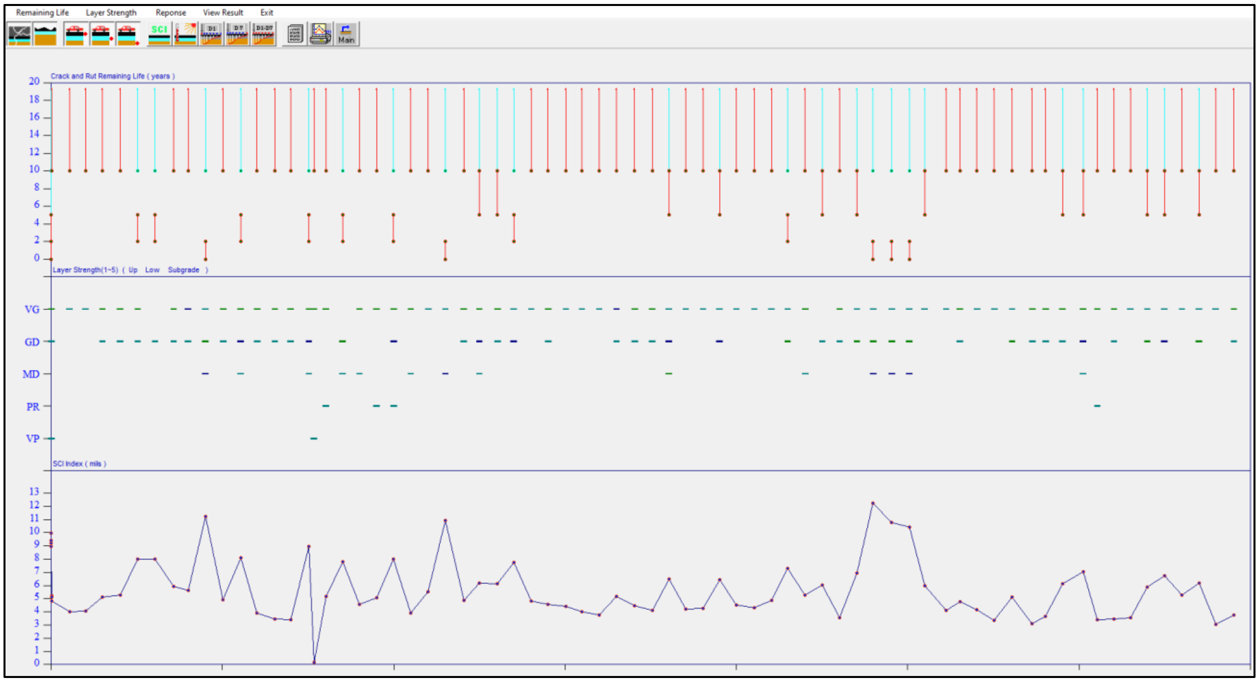


Figure 10. MODULUS Remaining Life Result Charts.

Chapter 4. Results and Discussion

Researchers developed and completed the following 4 tasks to address the problem statement:

- Task 1: Texas TSD data collection and analysis.
- Task 2: Assist Oklahoma researchers in Oklahoma testing program.
- Task 3: Integration of TSD and GPR data.
- Task 4: Pavement structural analysis and remaining life prediction.

The format of this chapter will address the findings of each task.

Results of Texas TSD Data Collection and Analysis

TSD data was collected in the state of Texas in 2023 through TxDOT's participation in transportation pooled fund study-5(385) (Federal Highway Administration, 2024). Collection included roadways of specific interest to individual regions. Researchers coordinated with each region to assist with data analysis and facilitate understanding of TSD technology.

Using TSD Outputs to Define Project Sections

At the project level, 3 deflection indices from FWD are used for structural evaluation:

1. Maximum deflection (D0)
2. Surface curvature Index (SCI)
3. Outer sensor deflection (W7)

To evaluate the use of TSD at the project level, researchers used 3 corresponding deflection indices calculated from the TSD:

1. Maximum deflection (D0)
2. TSD surface curvature index (SCI8)
3. Subgrade curvature index (SCI36-60)

The SCI8 and SCI36-60 TSD indices are calculated from Equation 3 and Equation 4. Subgrade Curvature Index.

, respectively.

$$SCI8 = D0 - D8$$

Where:

D0 = maximum deflection calculated directly beneath the load center (mils)

D8 = deflection calculated at the second TSD sensor located 9 inches away from the load center (mils)

Equation 3. TSD Surface Curvature Index.

$$SCI36-60 = D36 - D60$$

Where:

D36 = deflection calculated at the sixth TSD sensor located 36 inches away from the load center (mils)

D60 = deflection calculated at the eighth TSD sensor located 60 inches away from the load center (mils)

Equation 4. Subgrade Curvature Index.

The proposed TSD deflection indices were analyzed with pavement functional indices to evaluate pavement surface condition along TSD collection routes to identify project sections. The functional indices are listed below:

1. Rut depth in the outside wheel path (OWP) in inches.
2. Surface roughness reported as the international roughness index (IRI).
3. Total cracking reported as a percentage.

Together, the TSD deflection indices and functional metrics allowed researchers to wholistically evaluate current pavement conditions in a manner that emphasized the relationship between pavement surface condition and structural strength.

The TSD D0 and rut data was used to identify a change in pavement structure along the same roadway. Although the pavement type within the pavement management system was homogeneous between the two pavements, the D0 and rut measurements increased drastically from one section to the other. Further inspection of the SCI8 and SCI36-60 indices revealed that the subgrade in the high deflection and rut depth section was significantly weaker than the low deflection and rut section. With this information, the rehabilitation plans for the roadway could be adjusted to address the distresses appropriately.

In central Texas, a hard freeze in early 2024 caused premature failure along roadways. By evaluating the structural and functional conditions from TSD data collected in 2022, TxDOT personnel hoped to detect additional sections that may have experienced failure due to the adverse weather conditions. In this way, the forecasting capabilities of TSD data were assessed. Evaluation of TSD D0, rutting, and cracking data discovered two at-risk pavement sections. The first section had higher deflections and rut depth than surrounding pavement that indicated a structural issue. Imagery data of the site confirmed faulting in the OWP. Following the freeze event, the section experienced failure and was patched, but no structural repair was completed. Visual inspection in the Spring of 2024 confirmed that the structural issue persisted. The second site had increased rut depth and cracking, but the deflections reported at the site were not abnormal. Imagery data confirmed previous maintenance at the site that had begun to degrade. This section also failed and was patched following the freeze.

Oklahoma Testing Program – Results and Discussion

TSD data was collected along IH 35 and IH 40 as shown in Figure 11 in 2021 in Oklahoma as part of a separate research project. The color-coded map indicates D0. The Oklahoma research team collaborated with TTI to collect GPR and FWD data along 6 test sections within the collection route to compare to TSD deflection data. The test sections were selected such that a variety of pavement functional and structural conditions would be represented in the research.

The test section pavement structures were estimated using GPR data, and the pavement layer moduli were backcalculated from FWD deflection data. Estimations of the pavement structures and moduli are summarized in Table 5.

It should be noted that the layer thickness and moduli estimates contained in this report are not verified using construction plans or field samples. It is recommended that the results presented in the table be verified before any design, maintenance, or rehabilitation work is initiated.

Table 5. Oklahoma Test Section Pavement Structure and Modulus Values.

Test Section	SURF T (in)	SURF E (ksi)	BASE T (in)	BASE E (ksi)	SUBB T (in)	SUBB E (ksi)	SUBGR E (ksi)
IH35 S1	2.5	340	6*	102	8	39	14
IH35 S2	13**	2,216	—	—	—	—	13
IH35 S3	8	240	10	14	—	—	16
IH40 S4	1.5	663	8	118	8	25	11
IH40 S5	4.5	169	10	146	10	72	18
IH40 S6	20**	2004	—	—	—	—	7

*Cement treated base (CTB)
**Concrete

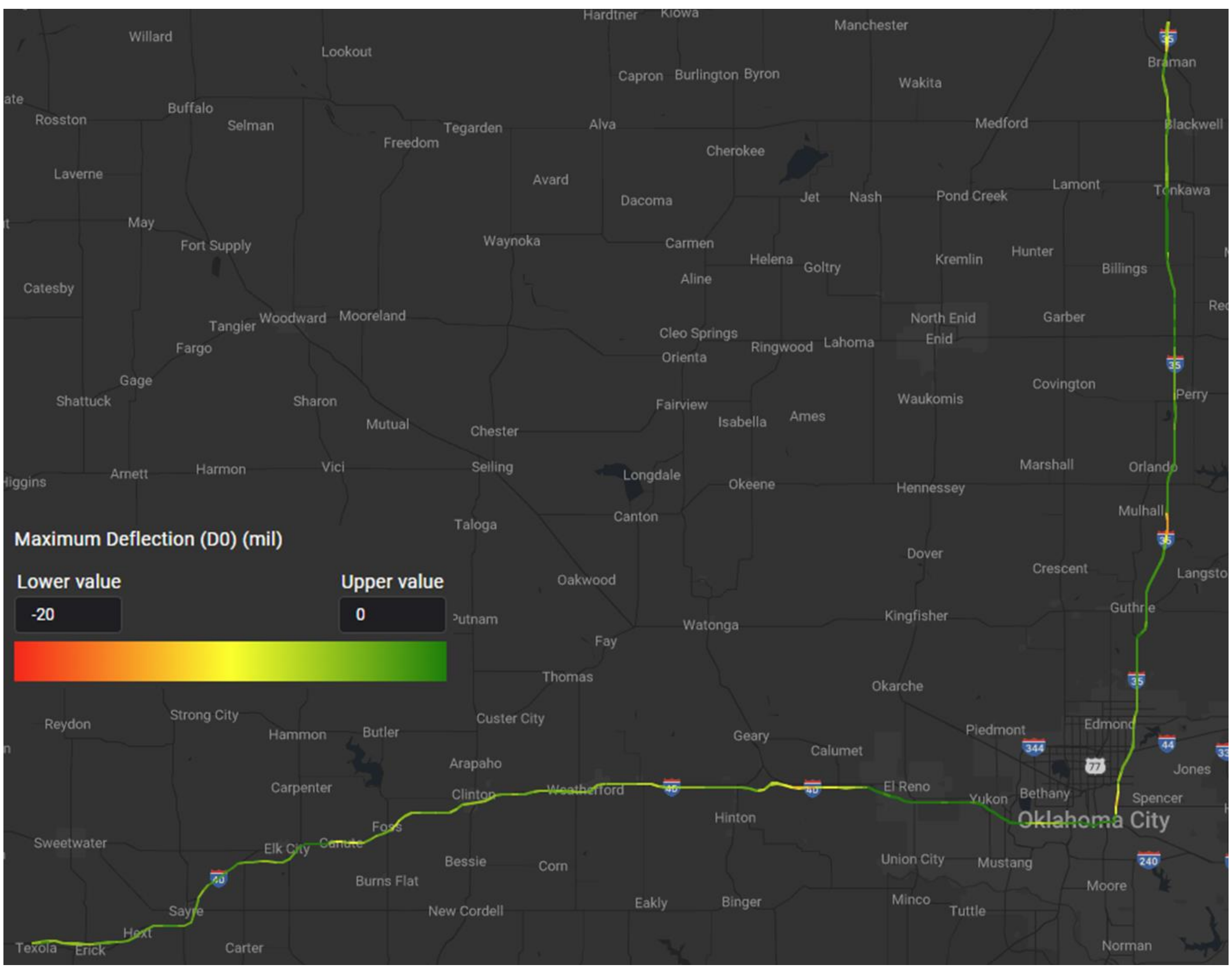


Figure 11. Oklahoma TSD Data Collection Route, 2021.

In total, 4 test sections had flexible pavement structures, and 2 were concrete/rigid pavements. The initial prediction of the Section 1 structure made from the GPR data shown in Figure 12 was a 2.5 inch HMA surface over 12 inches of concrete pavement, and the high dielectric reading circled in the figure was thought to be the concrete reinforcement. However, the FWD maximum deflections in Section 1 were 10 – 14 mils, which were deflection values consistent with flexible pavement. The expected deflections recorded on rigid pavements is less than 5 mils. Further analysis of the SCI and outer sensor deflection data indicated a weak subbase layer. For this reason, the prediction of the pavement structure was amended to a thin HMA surface over a 6 inch CTB material with an 8 inch subbase layer. The resulting backcalculation of the layer modulus produced an average error of 8 percent between the calculated and measured deflection bowls.

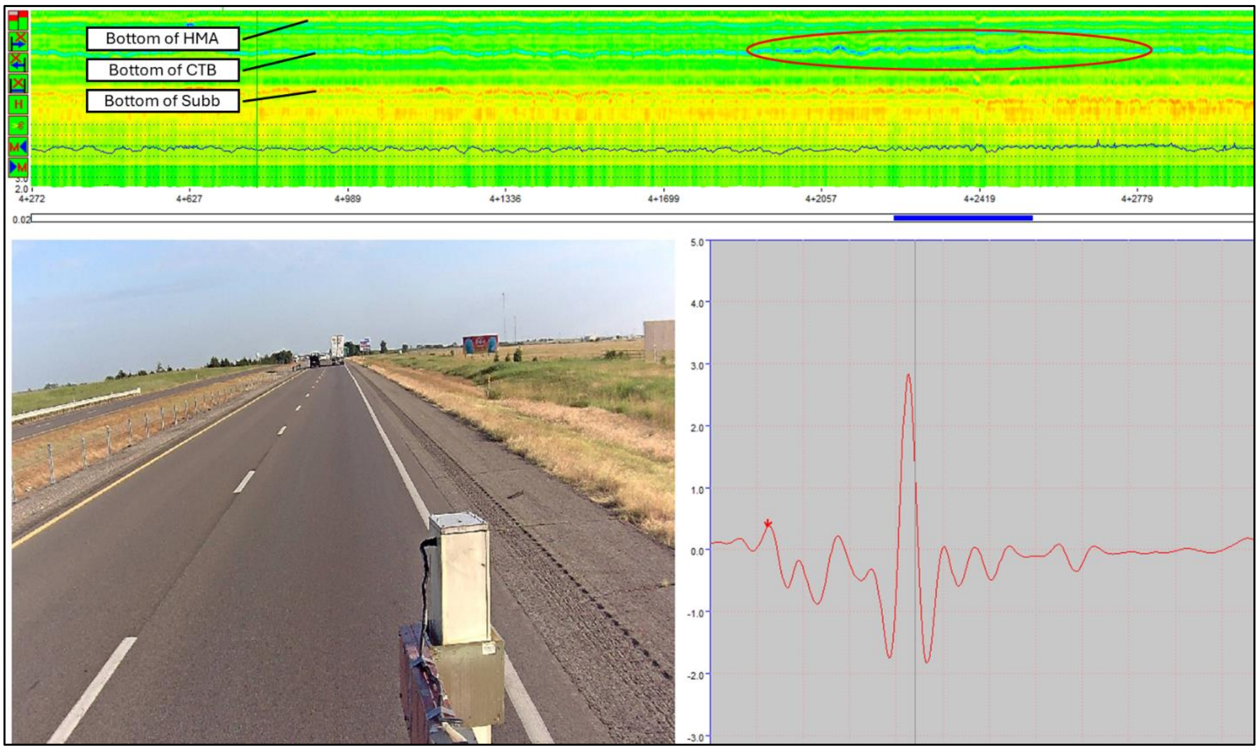


Figure 12. Annotated GPR Scan from Section 1.

The maximum deflection data measured and recorded by FWD and TSD for each test section is displayed in Figure 13. Temperature data is not available within ARRB Systems' Hawkeye TSD data viewer, and the pavement temperature during FWD testing was 85-90 degrees. It is likely that the pavement temperature at the time of testing influenced the magnitude of the FWD and TSD deflections. The data in the figure is averaged over every 0.5 mile. In general, the deflection measured by FWD is greater than the deflection reported by TSD. However, the deflection trends between the two devices are very similar. The FWD and TSD identified the same relative strong and weak sections. The magnitude of the deflections matched closest in Section 3, but the TSD values recorded for the remaining test sections are roughly half the measured FWD deflections, regardless of flexible or rigid pavement type.

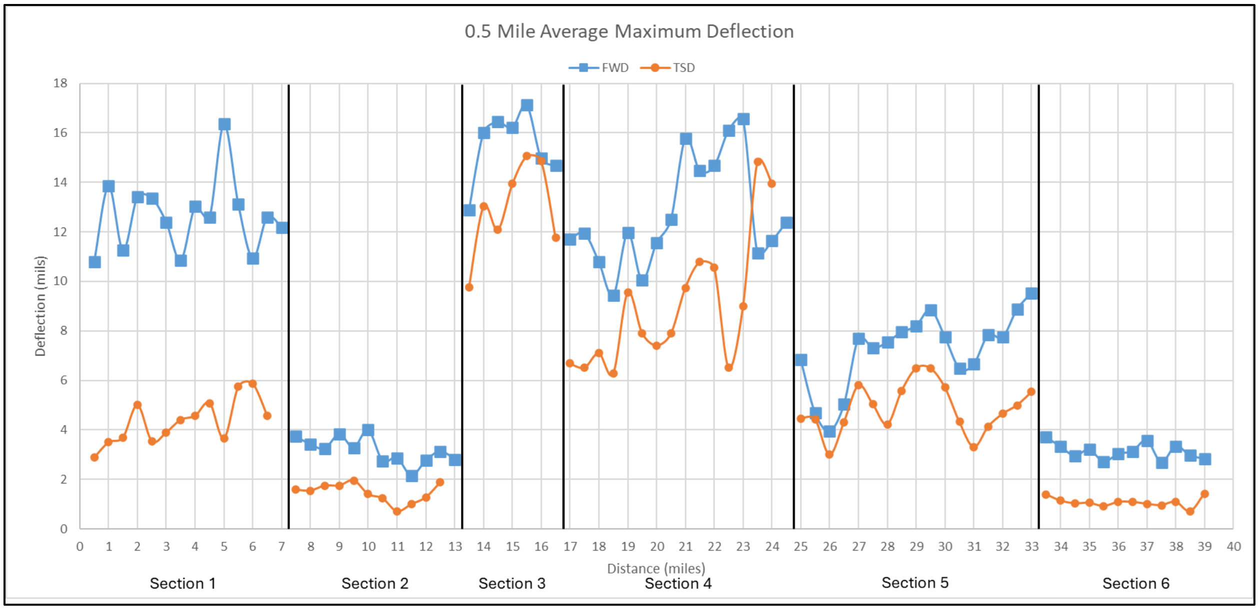


Figure 13. FWD and TSD Maximum Deflection Comparison.

Analysis of TSD Outputs

TSD data has been successfully used by DOTs to categorize pavement conditions into 1 of 4 cases:

1. Pavement surface and structure are in good condition.
2. Pavement surface is in good condition, but the structure is in poor condition.
3. Pavement surface is in poor condition, but the structure is in good condition.
4. Pavement surface and structure are in poor condition.

The Hawkeye data viewer has the capability to overlay data filters on the TSD data map. The filter queries used in this section were developed for use in Texas. It is recommended that Oklahoma develops similar criteria to classify pavement conditions at the network-level using TSD data. Table 6, Table 7,

Table 8, and Table 9 list the criteria developed for TxDOT for each condition case.

Table 6. Texas Pavement Condition Case 1 Criteria.

Distress	Threshold
IRI (in/mi)	≤ 95
Total Cracking (%)	≤ 5
Rut Depth OWP (in)	≤ 0.2
D0 (mils)	≤ 20

Table 7. Texas Pavement Condition Case 2 Criteria.

Distress	Threshold
IRI (in/mi)	≤ 95
Total Cracking (%)	≤ 5
D0 (mils)	≥ 30

Table 8. Texas Pavement Condition Case 3 Criteria.

Distress	Threshold
IRI (in/mi)	≥ 171
Total Cracking (%)	≥ 20
D0 (mils)	≤ 20
or	**or**
IRI (in/mi)	≥ 171
Rut Depth OWP (in)	≥ 0.4
D0 (mils)	≤ 20
or	**or**
Total Cracking (%)	≥ 20
Rut Depth OWP (in)	≥ 0.4
D0 (mils)	≤ 20

Table 9. Texas Pavement Condition Case 4 Criteria.

Distress	Threshold
IRI (in/mi)	≥ 171
Total Cracking (%)	≥ 20
D0 (mils)	≥ 20
or	**or**
IRI (in/mi)	≥ 171
Rut Depth OWP (in)	≥ 0.4
D0 (mils)	≥ 20
or	**or**
Total Cracking (%)	≥ 20
Rut Depth OWP (in)	≥ 0.4
D0 (mils)	≥ 20

The pavement condition filters were applied to the TSD data collected in Oklahoma, and are displayed in Figure 14, Figure 15, Figure 16, and Figure 17, for cases 1, 2, 3, and 4, respectively. Test sections 5 and 6 along IH 40 fall within case 1 criteria for pavements with good surface and strong structure. The deflections in both of these sections are less than 10 mils, and section 5 is a flexible pavement while section 6 is concrete.

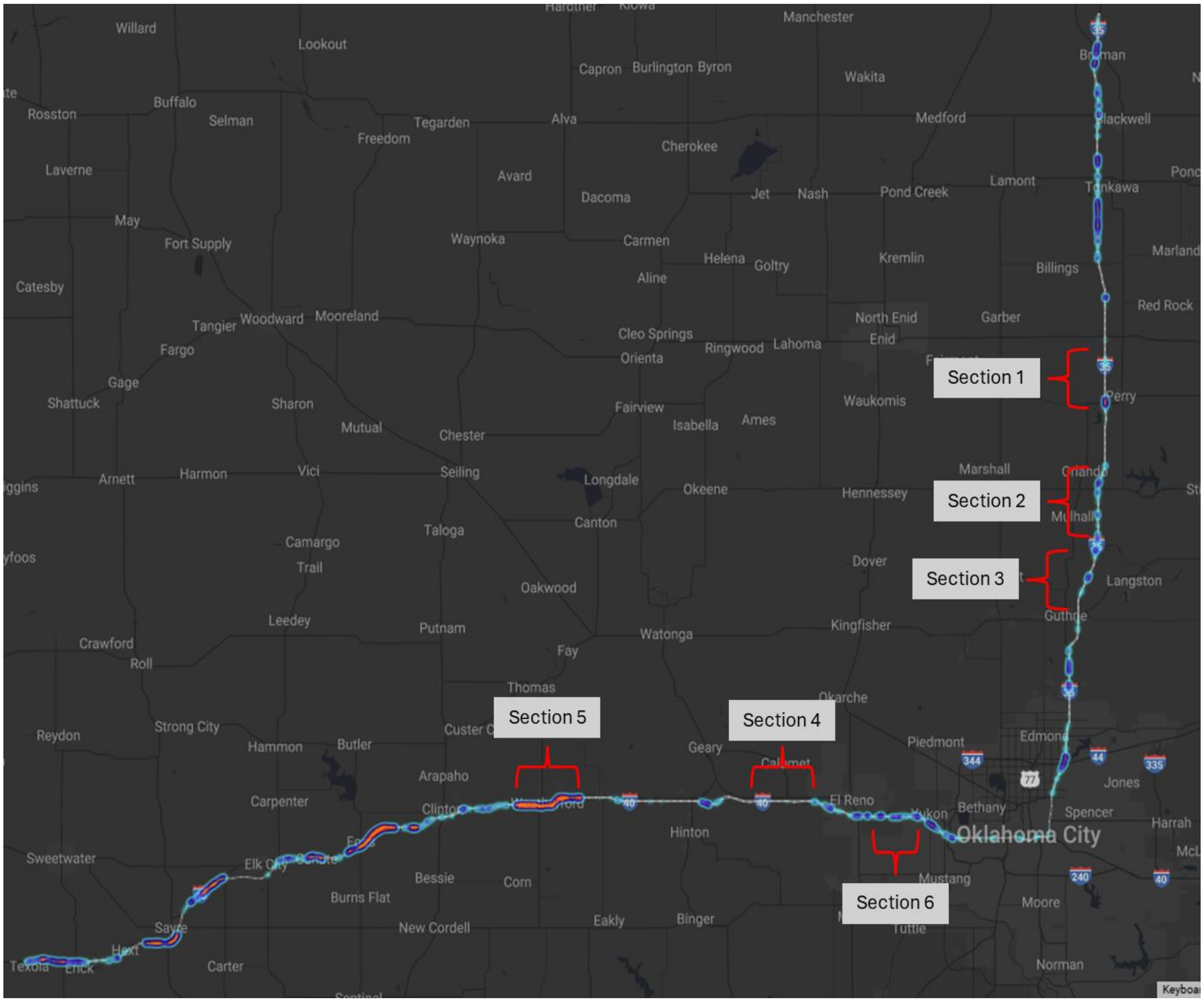


Figure 14. Case 1: Good Pavement Surface and Structure in Oklahoma.

The filter for case 2 for pavements with good surface and poor structure did not indicate any sections met the criteria. However, adjusting the filter to include SCI8 data instead of D0 revealed that portions of section 3 and section 4 had weak structures.

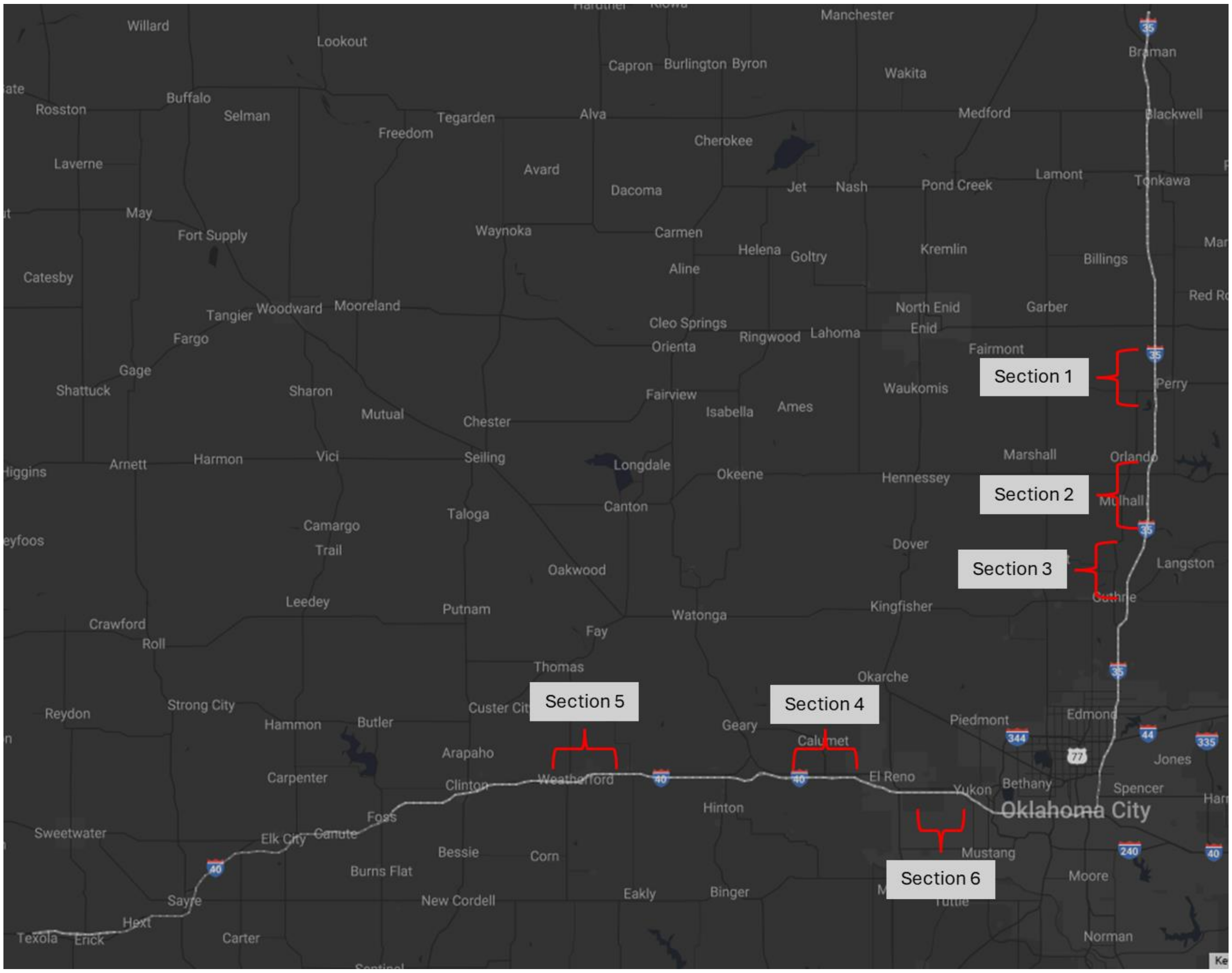


Figure 15. Case 2: Good Pavement Surface and Poor Pavement Structure in Oklahoma.

Sections 3 and 4 met the criteria for case 3 for pavements with poor surface and good pavement structure. GPR data suggested that both of these sections were flexible pavement. Section 3 had an 8 in HMA layer over a base layer, while section 4 had 1.5 in of HMA over a base and subbase. Both test sections had high levels of cracking. Section 3 had transverse cracking across the lane while section 4 had longitudinal cracking in both wheel paths.

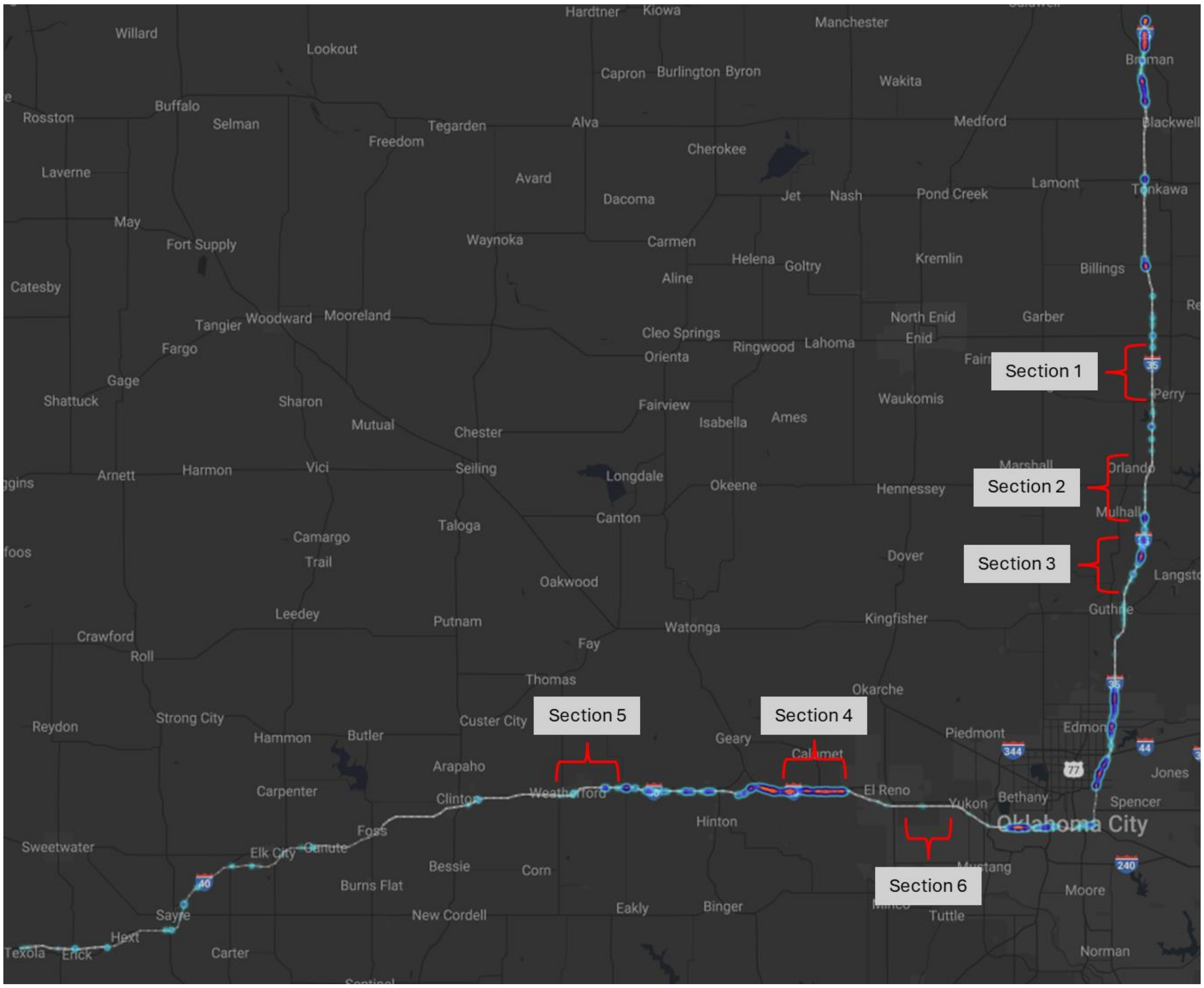


Figure 16. Case 3: Poor Surface and Good Pavement Structure in Oklahoma.

Both sections 3 and 4 met the criteria for case 4 for poor pavement surface and structure. Because these sections also met the criteria for the adjusted case 2 for pavements with good surface and poor structure, these sections may be more at risk for failure than the other test sections. The common trait between both cases is poor structure, indicated by high deflections, which suggests the root cause of pavement surface distress is poor structural support.

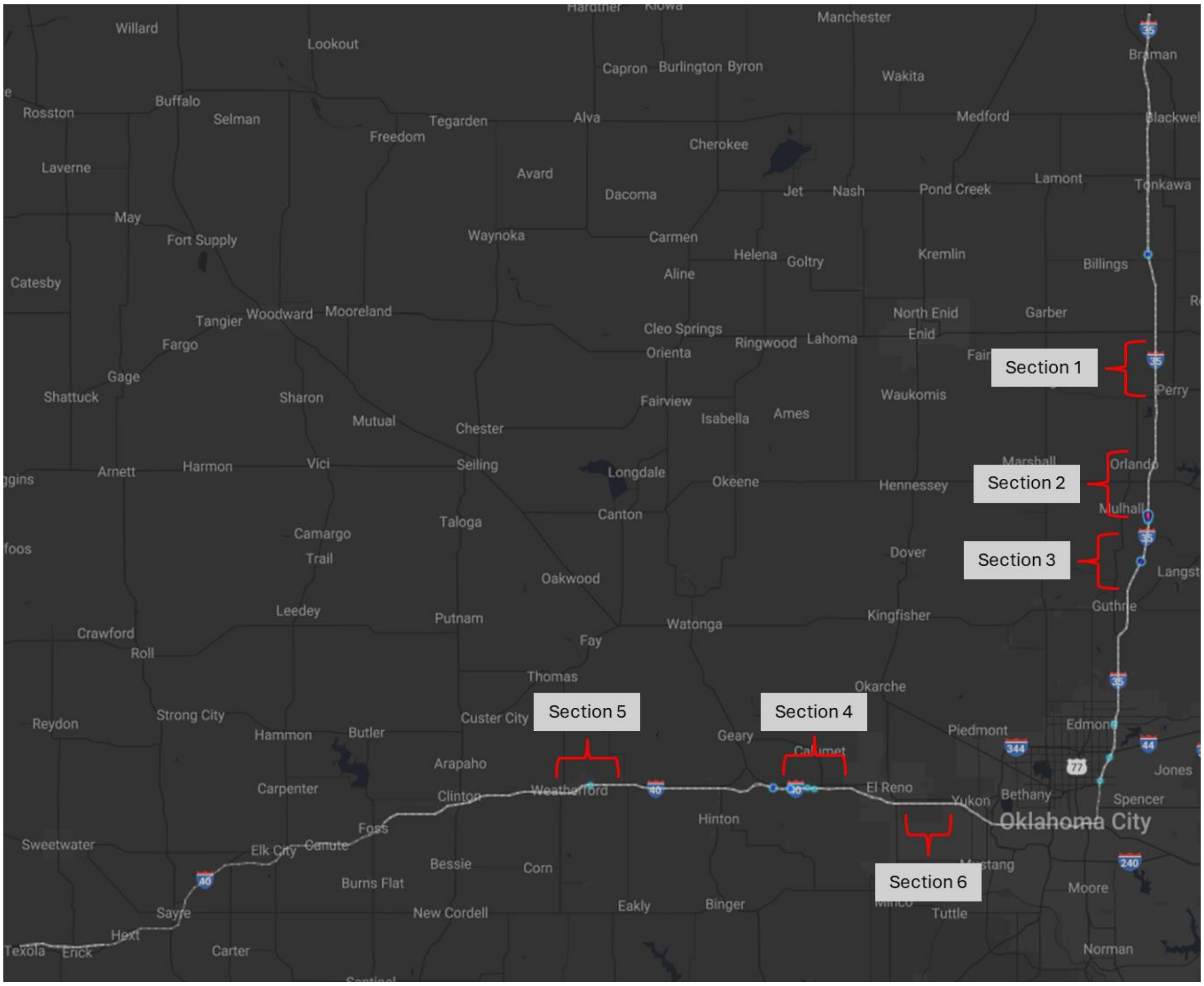


Figure 17. Case 4: Poor Pavement Surface and Structure in Oklahoma.

Case Study: Test Section 3

Both section 2 and section 3 include southbound IH 35 near Orlando and Mulhall shown in Figure 18. Section 2 ends just after SH 51 and section 3 limits are IH 35 from Mulhall to the Cimarron River. The graph at the bottom of the figure includes the D0 (light blue)and the relative rut (yellow), cracking (red, blue, and green dots), and roughness data (black line) at the transition from section 2 to section 3. The data indicates an increase in D0 and cracking from section 2 to section 3, but the rutting and roughness data decreases. The D0 (blue), SCI8 (yellow), and SCI36-60 (black) deflection indices shown in Figure 19 for the same section of IH 35 increase from section 2 to 3 as well. The average SCI8 increased from less than 2 mils in section 2 to 4 mils in section 3, while the average SCI36-60 increased from less than 2 mils to 2 mils. These indices have been used by other DOTs to identify weakening of the base and subgrade materials. Soils analysis completed by the USDA support that a main cause of the increase in deflections between the two sections is a change in subgrade materials. The percent sand content within the subgrade displayed in Figure 20 increases from less than 20 to over 50 percent as IH 35 approaches the river.

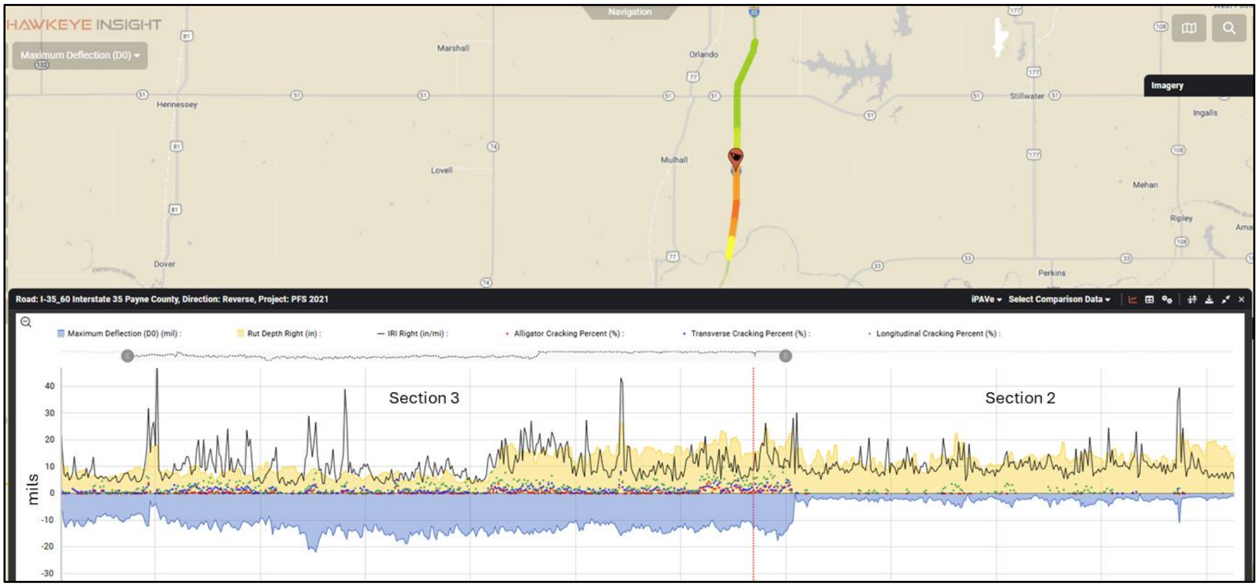


Figure 18. TSD Data for Section 2 and 3 on IH 35 in Oklahoma.

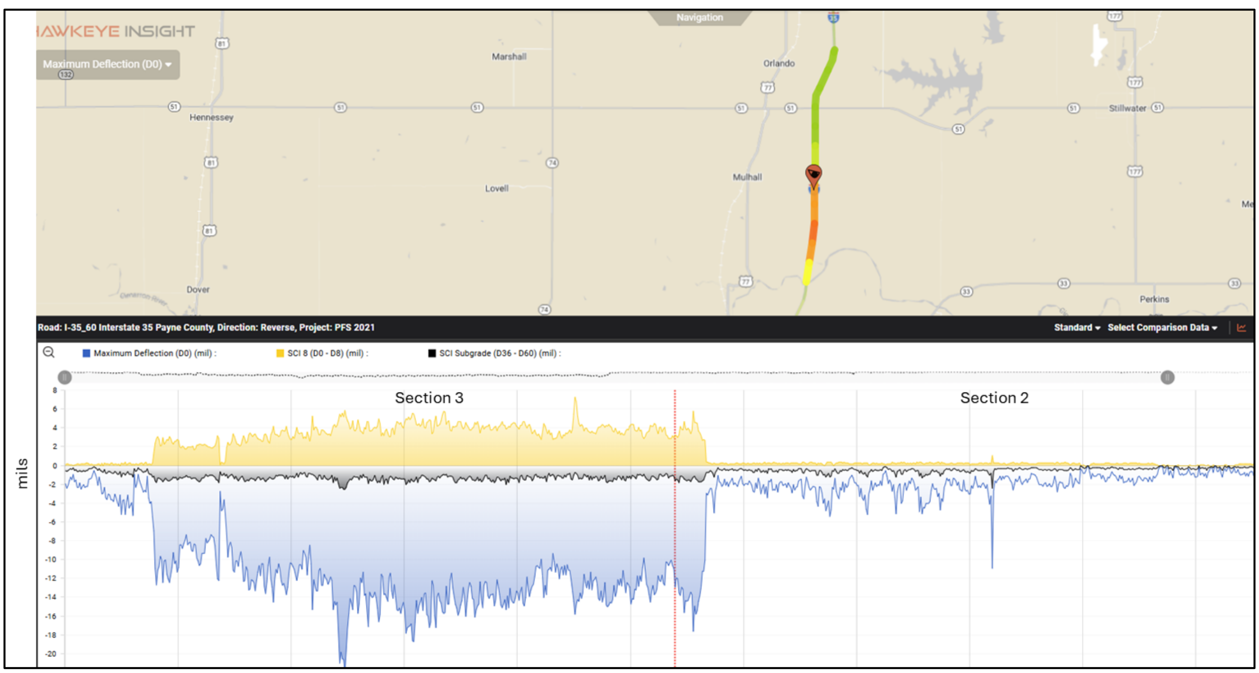


Figure 19. TSD Deflection Indices for Section 2 and 3 on IH 35 in Oklahoma.

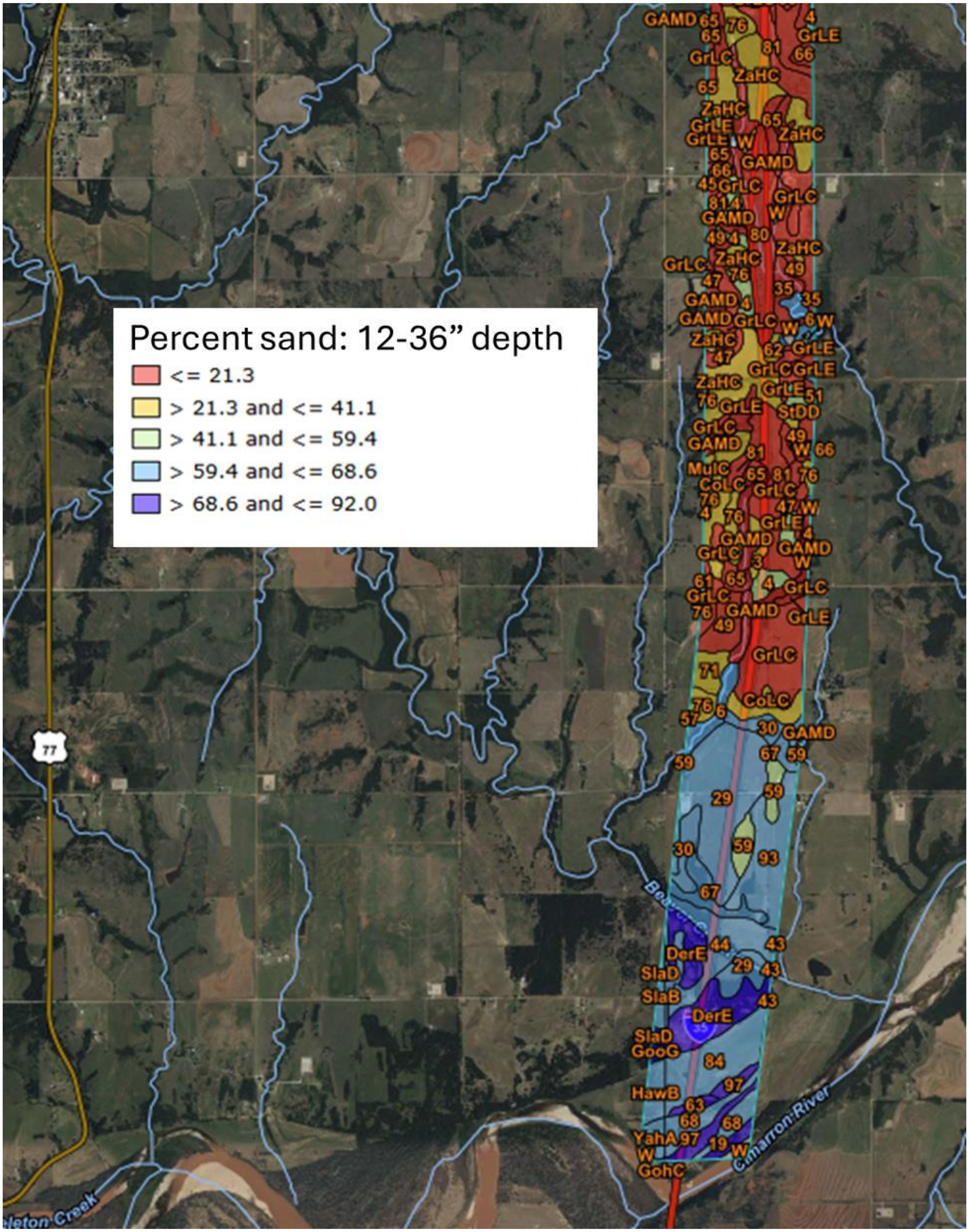


Figure 20. Percent Sand Content from 12 – 36 inches along IH 35 in Oklahoma (USDA, n.d.).

Prototype Program to Integrate TSD and GPR Data

Use of GPR within pavement management systems is standard practice. Software to read and analyze the data was developed by TTI researchers. As part of this project, researchers developed an updated prototype of this software that would integrate GPR data with data from TSD. The general layout of the prototype is given in Figure 21. The chart at the top of the screen is the TSD D0 data, while the colored chart at the bottom is the output from the GPR.

The TSD currently collects the pavement deflection and functional metrics listed in Table 10. The user has the ability to toggle between all data, or select multiple datasets collected by the TSD to display in tandem with the GPR data. The data from the two devices is location matched using global positioning system (GPS) coordinates.

Table 10. TSD Collected Data.

Structural Data	Functional Data
Continuous Deflection Measurement (mils)	Pavement Geometry
Pavement Deflection Velocity	Roughness and Texture (IRI)
Applied Load	Pavement Cracking (Percent)
3D GPR Measurements	Wheel Path Rut Depth (in)

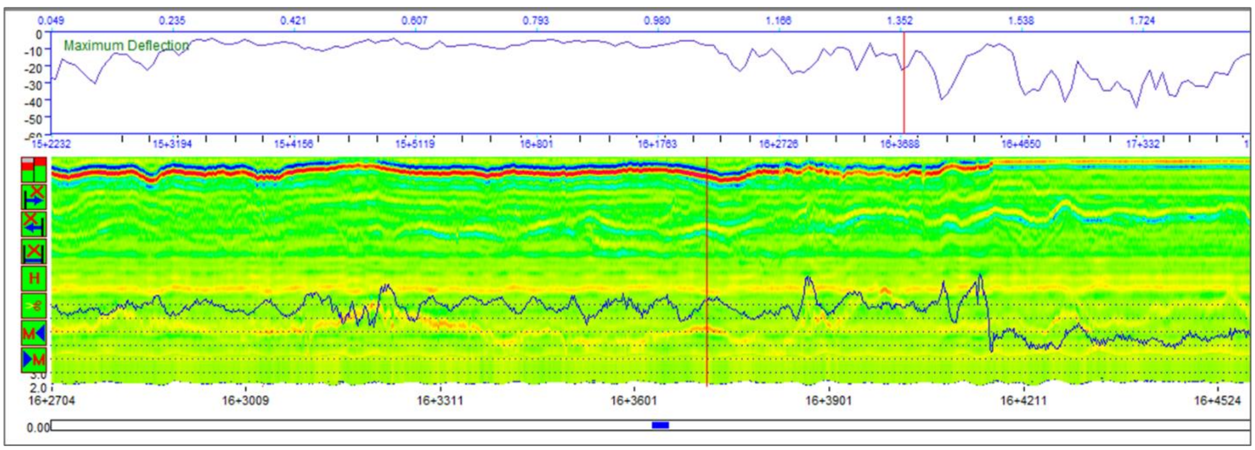


Figure 21. Prototype Software Layout.

Future iterations of the software may include access to an online database that stores the TSD data in a map format. ARRB Systems currently distributes and displays collected TSD data within such a database, called Hawkeye. Within this system, the TSD data is primarily displayed on a map that is color-coded to the dataset that is being viewed. It is feasible that the GPR data viewer would access an online system that is matched to the GPR data using GPS coordinates. A potential user interface is shown in Figure 22.

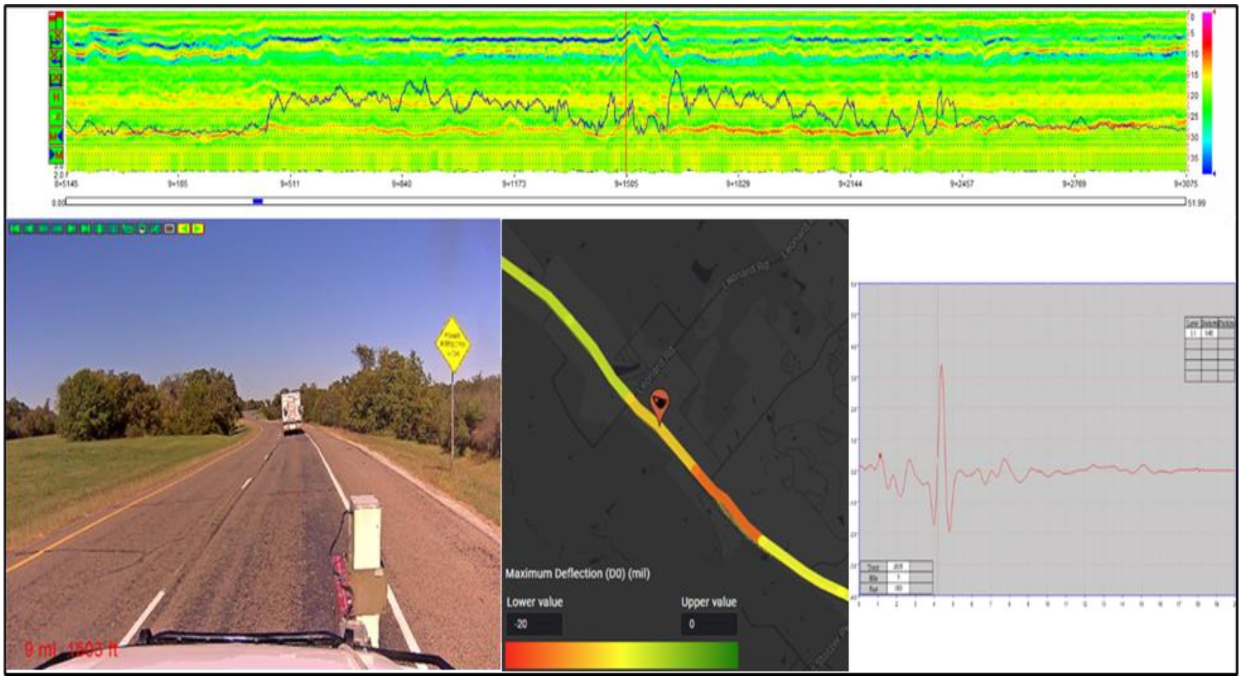


Figure 22. Potential Future Layout of GPR Program.

Remaining Life Prediction Results

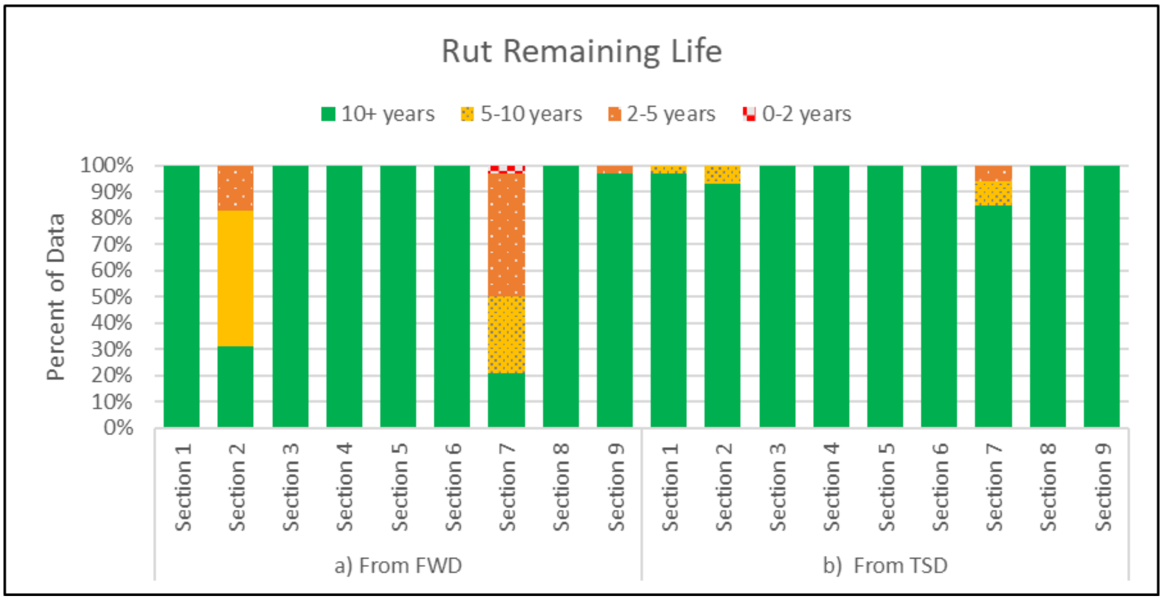
Using TSD roadway data from 2021, nine typical test sections were identified to estimate pavement remaining life from TSD deflection data and results were compared with FWD. FWD data was collected along these test sections at the same interval as TSD. Characteristic functional indices and traffic data, reported in equivalent single axel loads (ESALs), were used as inputs for the MODULUS remaining life analysis. The pavement survey information used to run the remaining life analysis in the MODULUS program is shown in Table 11 for each test section.

Table 11. Test Section Survey Information for Remaining Life Estimation.

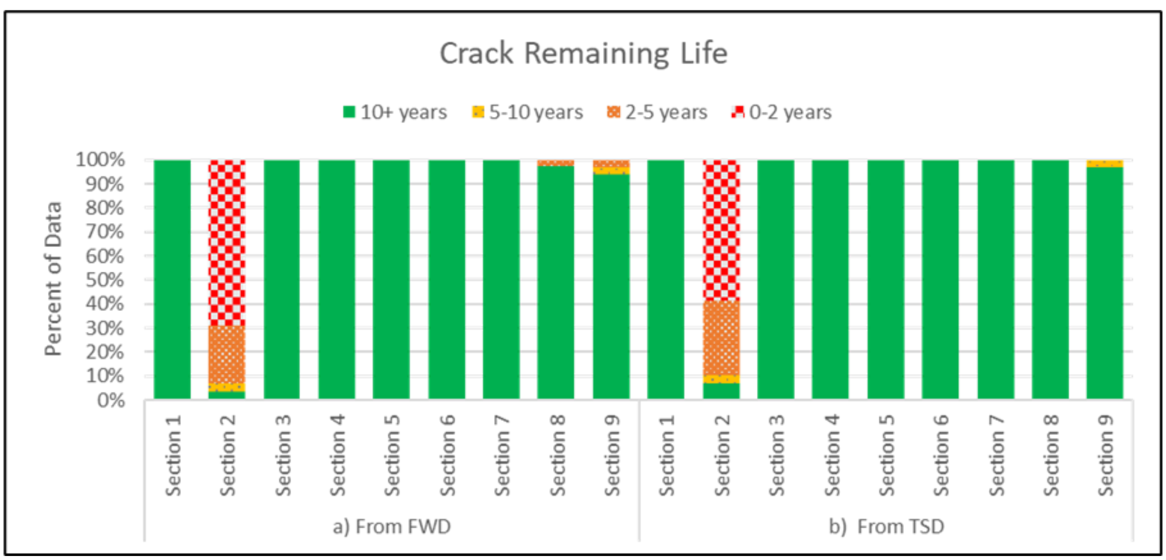
Section Number	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9
Surface Thickness (in)	2.2	5.4	7.6	5.7	7.5	2.8	2.5	5.5	5.0
Average Rut Depth (in)	0.13	0.15	0.15	0.15	0.11	0.17	0.17	0.19	0.19
Cracking (%)	3.3	2.37	0.25	0.25	0.75	1.5	1.5	1.0	1.0
20-Year 18-kip ESALs (million)	3.447	9.912	9.912	9.912	9.912	9.912	9.912	3.447	3.447

The MODULUS remaining life estimation produces 2 remaining life estimates: remaining life until failure due to rutting, and remaining life until failure due to cracking. The rut remaining life is dependent upon the strength of the pavement subsurface layers, while the crack remaining life is dependent upon the SCI deflection index. The rut and crack remaining life estimates calculated from FWD and TSD for all 9 test sections are displayed in Figure 23.

The FWD estimated the section 2 and section 7 would fail due to rutting within 2-5 years. However, the rut remaining life estimated from TSD did not find that any of the sections were at risk of premature rutting failure. The discrepancy in rut remaining life estimates is likely due to the different loading mechanisms and deflection indices between FWD and TSD. The FWD delivers a static impulse load to the pavement that may be characterized as linear elastic, while the TSD delivers a rolling dynamic load that produces a viscoelastic pavement response. As such, the BCI and W7 deflection indices are used within the MODULUS system to evaluate the strength of subsurface pavement layers. These indices are not suitable for the TSD loading mechanism, thus the difference in loading is unaccounted for within the TSD remaining life estimates. Unlike the rut remaining life comparison, the remaining life until cracking failure estimated by both devices was in good agreement. The cracking remaining life is dependent upon the existing surface condition and the SCI deflection index. Both the FWD and the TSD estimated section 2 would fail due to cracking within the next 2 years.



a)



b)

Figure 23. The Rut (a) and Crack (b) Remaining Life Estimations from FWD and TSD for Typical Test Sections.

Pavement Layer Modulus Backcalculation from TSD Deflection Measurements

To further facilitate the implementation of TSD deflection data into project- and network-level pavement management practices, researchers attempted to develop a pavement layer modulus backcalculation procedure using TSD reported deflections. The procedure was similar to the backcalculation process implemented within the MODULUS program, in which deflection bowls reported from field testing are compared to a database of deflection bowls calculated from known pavement structures and layer moduli values. The moduli values that minimize the error between the calculated and the measured deflection bowl are selected as the material modulus.

The deflection bowl library was generated through the use of the 3D-Move program, developed by the University of Nevada Reno. The 3D-Move program is capable of simulating pavement viscoelastic responses beneath static and dynamic truck loadings, making it optimal for this application. Figure 24 displays the TSD reported and simulated deflection bowls for test sections 9 and 1 used in the remaining life analysis. Test section 9 is considered a weak pavement and section 1 is a strong pavement. The maximum deflections simulated for each of the 9 test sections are compared to the average values collected from the field in Figure 25. The 3D-Move simulation was shown to reasonably simulate the pavement responses beneath the TSD. The difference in the section 2 D0 values shown in Figure 25 is due to an HMA deficiency in that section, which was not accounted for within 3D-Move.

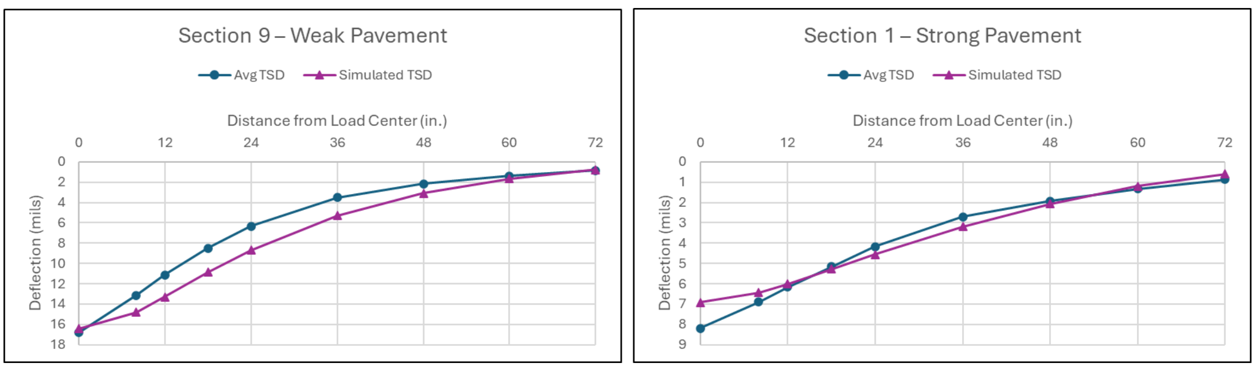


Figure 24. Measured and Simulated Deflection Bowls for a Weak (Left) and Strong (Right) Pavement.

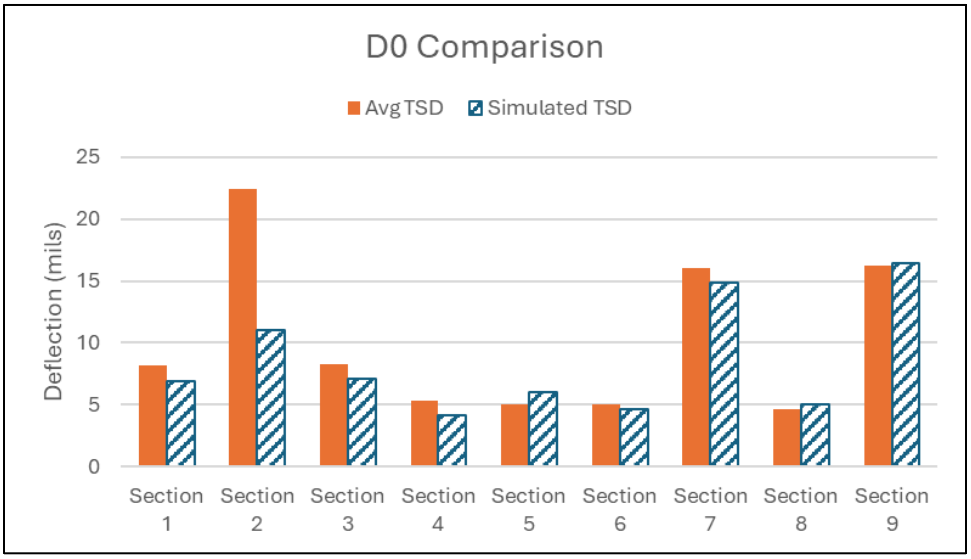


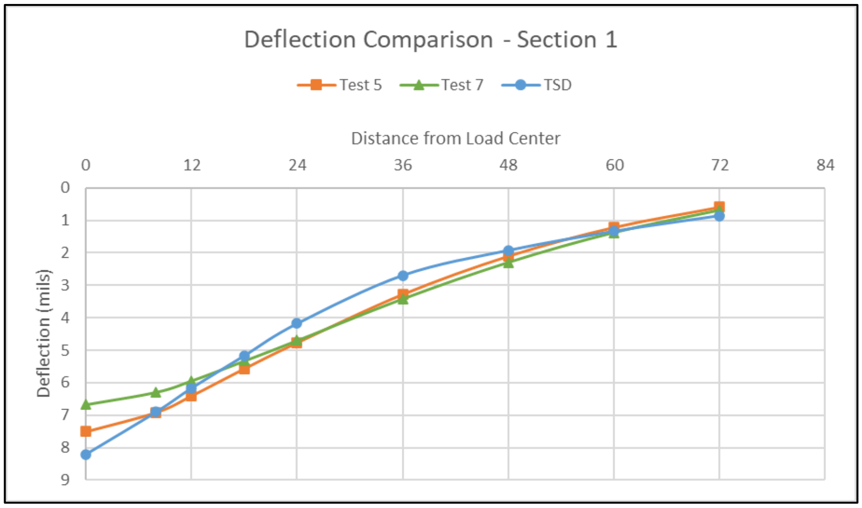
Figure 25. Recorded and Simulated TSD Maximum Deflection.

To evaluate the accuracy of the proposed TSD backcalculation procedure, 7 test cases were developed based on the structures of sections 1, 7, and 9. For each test case, the modulus value for each layer was known except for one "target" layer that was to be backcalculated from the TSD deflections. Table 12 describes each of the test cases and presents the results of the TSD backcalculation for the target layer. In each test the TSD backcalculated modulus was greater than the FWD backcalculated value. The lowest percent difference between the FWD and TSD backcalculated values occurred for test cases 1 and 2, in which the pavement structure consisted of only 3 layers. The deflection bowls simulated using the backcalculated target layer modulus are compared to the deflection bowls recorded from the TSD in

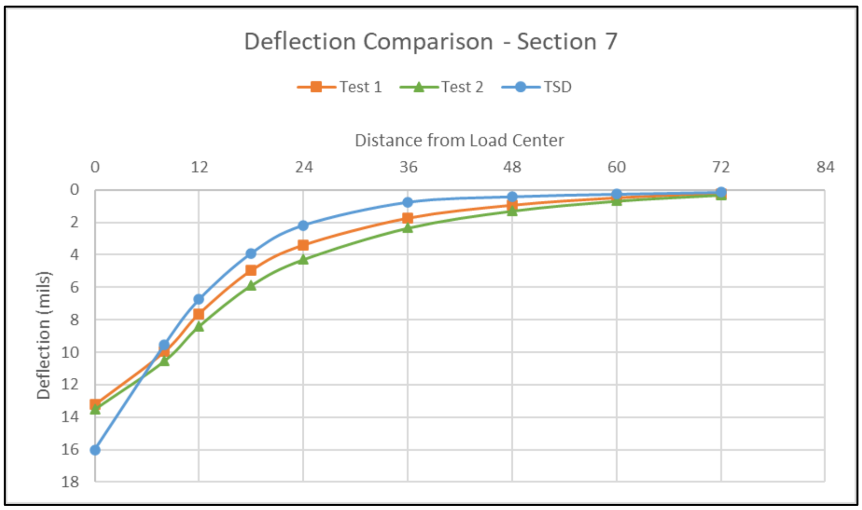
Figure 26. In each case, the simulated deflections at 8, 12, and 72 inches from the load center are more accurate to the field TSD deflections than the simulated maximum deflection and the deflections 24, 36, and 48 inches from the load center. The result of this trend is a “flatter” simulated deflection bowl than what is reported by the TSD.

Table 12. TSD Backcalculation Test Parameters and Results.

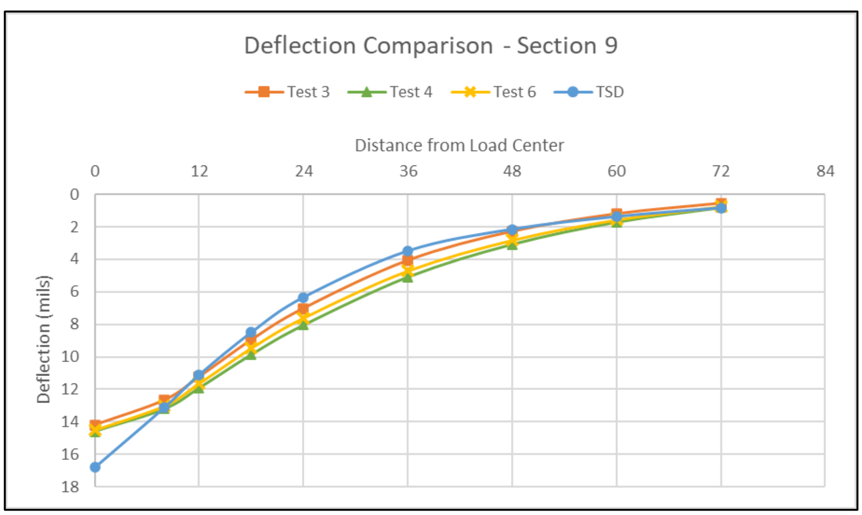
Test Case	Target Layer	Pavement Structure (in)	FWD Backcalculated Target E (ksi)	TSD Backcalculated Target E (ksi)
Case 1	Variable Subgr	SURF – 2.5 BASE – 12.5 SUBGR – N/A	15.7	20
Case 2	Variable Base	SURF – 2.5 BASE – 12.5 SUBGR – N/A	28	35
Case 3	Variable Subgr	SURF – 5 BASE – 6 SUBB – 8 SUBGR – N/A	7.5	10
Case 4	Variable Base	SURF – 5 BASE – 6 SUBB – 8 SUBGR – N/A	18	40
Case 5	Variable Base	SURF – 2.2 BASE – 8 SUBB – 8 SUBGR – N/A	800 (CTB)	550
Case 6	Variable Subb	SURF – 5 BASE – 6 SUBB – 8 SUBGR – N/A	27	65
Case 7	Variable Subb	SURF – 2.2 BASE – 8 SUBB – 8 SUBGR – N/A	44	5



a)



b)



c)

Figure 26. a) - c) Deflection Bowl Comparison between Test Cases and Field TSD Data.

Chapter 5. Conclusions and Recommendations

A primary goal of this research was to validate the utility of TSDDs within existing pavement management systems and to propose strategies that utilize TSDDs to rapidly assess pavement structural conditions to combat distresses and premature failure associated with weather and condition-related events. At the project level, it was determined that the SCI8 and SCI36-60 TSD deflection indices were good indicators of base and subgrade material strength, respectively. To assist in identifying project sections of interest, it is recommended that 6 key functional and structural indices are evaluated along the roadway: the maximum deflection, the rut depth, surface and subgrade curvature index, the roughness, and the total cracking. Because the TSD is capable of collecting all of these data simultaneously, personnel are equipped to plot the data along the same geospatial reference system. These indices were used with good success in Texas to evaluate pavement structural condition following extreme freezing and rainfall events. At the network level, it is recommended that data filters are developed for Oklahoma that categorize pavements into appropriate pavement condition cases that reflect the pavement surface and structural condition. Such a method has been implemented by DOTs with good success. Additionally, GPR data and remaining life estimates are both used in network-level pavement management practices. For TSD data to be practical at the network level, integration with these processes is key. A prototype program was developed that integrated TSD data in graphical form with GPR data within existing GPR software. Both data were displayed synchronously to allow the user to verify the pavement structure relative to TSD deflection data. Future versions of the program may connect to an online database that allows TSD data to be displayed in map format that increases the user's geospatial awareness during data analysis.

TSD data was also used to generate remaining life estimates using the MODULUS program. The remaining life procedure utilizes pavement functional condition surveys, traffic data, and deflection data to classify the strength of the upper, lower, and subgrade pavement materials. These classifications are then used to estimate the remaining pavement life until rut and crack failure. The FWD and TSD estimated the same pavement section was at risk of crack failure. Conversely, the TSD overestimated the rut remaining life on each of the 3 test sections that the FWD estimated would fail within the next 5-10 years. The rut remaining life is estimated by evaluating the strength of pavement base and subgrade layers. The MODULUS program achieves this for FWD through the BCI and W7 deflection indices. However, the rolling dynamic load from TSD is not compatible with these indices. It is recommended that the SCI8 deflection index be used to classify the lower layer material strength and the SCI36-60 index be used to classify the subgrade material strength for use in TSD remaining life estimations.

A critical component of project-level analysis is the ability to backcalculate layer modulus. Therefore, an experimental backcalculation procedure was developed that was similar in structure to the existing MODULUS backcalculation procedure with FWD. In each of the 7 test cases, the modulus backcalculated from TSD deflection data was greater than the modulus backcalculated from FWD. While the pavement responses simulated in 3D-Move matched the maximum and outer sensor deflections calculated in the field with TSD, the intermediate simulated deflections were greater than the field deflections, resulting in a "flat" deflection bowl compared to the field. This may be due to assumptions made by the TSD deflection algorithm regarding the viscoelastic responses of the pavement. Further development of both the TSD model and the backcalculation procedure are required before the system is recommended for use in the field. One major lack in the proposed procedure is the inability to simultaneously backcalculate the modulus values of multiple materials.

Chapter 6. Implementation of Project Outputs

Implementation of the outputs from this research will enhance the understanding of pavement structural conditions at all levels of pavement management. The continuous deflection data reported by TSD integrated with layer thickness information from GPR allows for early detection of structural failure and/or defects from adverse weather events. Additionally, the nature of TSD data collection allows for rapid response to assess pavement condition compared to FWD.

The prototype program to integrate TSD and GPR data similar to the one developed for TxDOT can be developed for Oklahoma. The results of the TSD remaining life estimates and backcalculation procedure are promising. The next step towards widespread implementation of these outputs is to update the current programs for FWD analysis to incorporate the unique loading mechanism and deflection indices from TSD.

An immediate outcome of this research was increased understanding and implementation of TSD data by district personnel for identifying project limits for pavement maintenance and rehabilitation. This outcome was and will continue to be addressed through informational sessions provided by the research team and delivered to the districts. Compared to current pavement management practices involving FWD, the TSD offers a larger quantity of data and a more precise overview of pavement structural and functional condition than can be analyzed and updated in a relatively short period of time for proactive rehabilitation strategies and the formulation of district maintenance plans.

Chapter 7. Technology Transfer and Community Engagement and Participation (CEP) Activities

Technology transfer and community engagement activities relating to this research were limited to the informational sessions delivered to TxDOT district personnel and the prototype software developed for TxDOT. The informational sessions sought to enable district personnel to include TSD data within their decision-making processes by facilitating understanding of the TSD system, collection process, and data analysis. Increased trust in the TSD system and greater familiarity with TSD outputs will result in improved pavement management strategies and prioritization at the project- and network-level.

Chapter 8. Invention Disclosures and Patents, Publications, Presentations, Reports, Project Website, and Social Media Listings

No invention disclosures, patents, publications, presentations, reports, websites, or social media listings were generated as components of this research. The prototype software developed to integrate TSD and GPR data was created for the exclusive use of TxDOT and TTI. Permission to utilize both said software and the MODULUS program discussed within this report must be obtained from TxDOT.

References

ARRB Systems. n.d. *Hawkeye Insight*. Accessed November, 2024. https://us.hawkeyeinsight.com/app#/dataviewer.

ARRB Systems. *intelligent Pavement Assessment Vehicle iPAVe Comprehensive Structural and Functional Pavement Survey Methodology*: 17-18. Informational Borchure. ARRB Systems. Accessed July, 2024.

Civil Air Patrol. 2022. *CAP Aircrew Links 300 Stranded by Harvey Flooding to Needed Help.* Accessed November, 2024. https://www.cap.news/cap-aircrew-links-300-stranded-by-harvey-flooding-to-needed-help/.

Elsefi, Mostafa A. and Zihan, Zia Uddin Ahmed. 2018. *Assessment of the Traffic Speed Deflectometer in Louisiana for Pavement Structural Evaluation.* Louisiana Department of Transportation. Accessed November, 2024. https://www.ltrc.lsu.edu/pdf/2018/FR_590.pdf.

National Cooperative Highway Research Program. 2024. *Pavement Structural Evaluation with Traffic Speed Deflection Devices (TSDDs)*. Accessed November, 2024. https://pooledfund.org/details/study/637.

Scullion, Tom. 1988. *Incoporating a Structural Strength Index into the Texas Pavement Evaluation System.* Texas State Department of Highways and Public Transportation. Accessed July, 2024. https://static.tti.tamu.edu/tti.tamu.edu/documents/409-3F.pdf.

Scullion, Tom, Dorsett, Garrett and Liu, Wenting. 2024. *Determine the Feasibility and Methodologies of Using Structural Data from the Traffic Speed Deflectometer in Network- and Project-Level Treatment Decision-Making.* Texas Department of Transportation. Accessed March, 2024. https://library.ctr.utexas.edu/Presto/content/Detail.aspx?ctID=OWE3NjYzNTktYzJmNC00ZTAwLThmMjItYzhmNzNiYTFmNzdh&rID=Mzc1NzI=&qrs=RmFsc2U=&ph=VHJ1ZQ==&rrtc=VHJ1ZQ==.

Texas A&M Transportation Institute. 2019. "Flexible Pavement Design in TxDOT," *Texas Flexible Pavement Design Course*. Accessed November, 2024. https://events.tti.tamu.edu/conference/pavement-design-in-texas-workshop/.

Li, Jenny. 2020. "Implementation of Structural Strength Data for Network-Level Pavement Management," *Xchange Roadshow On-Demand* Videos. Accessed July, 2024. https://library.ctr.utexas.edu/Presto/content/Detail.aspx?ctID=UHVibGljYXRpb25fMTE2MTA%3D&rID=MzI5NzY%3D&ssid=c2NyZWVuSURfMjEzMjI%3D&bmdc=MQ%3D%3D.

USDA. N.d. *Web Soil Survey*. Acessed January, 2025. https://websoilsurvey.nrcs.usda.gov/app/

Uzan, J., Scullion, T., Michalak, C.H., Paredes, M., Lytton, R.L. 1988. *A Microcomputer Based Procedure for Backcalculating Layer Moduli from FWD Data.* Texas State Department of Highway and Public Transportation. Accessed July, 2024. http://tti.tamu.edu/documents/1123-1.pdf.

SOUTHERN PLAINS
TRANSPORTATION CENTER

The University of Oklahoma | OU Gallogly College of Engineering
202 W Boyd St, Room 213A, Norman, OK 73019 | (405) 325-4682 | Email: sptc@ou.edu