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Determine the Feasibility and Methodologies of Using Structural Data from the Traffic Speed Deflectometer in Network- and Project-Level Treatment Decision-Making

Technical Report 0-7107-R1

Cooperative Research Program

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16. Abstract

The traffic speed deflectometer (TSD) offers TxDOT a highway-speed, nondestructive testing tool, which can significantly assist TxDOT districts with development of their four-year plans. In this project, the TSD was initially compared to the deflections measured by the falling weight deflectometer (FWD). Good correlation was observed in the maximum deflections reported by both devices. However, because the loading methods are significantly different, the resultant shapes of the deflection bowls are also different. To assist with developing TxDOT maintenance plans, the data filters evaluated in this report should be used to classify projects based on structural strength (as measured by the TSD) and surface conditions (e.g., rutting, cracking, etc.). Because of TxDOT's extensive maintenance program, many roadways may appear to be in reasonable condition but are in fact structurally weak. This information should be provided to TxDOT district teams responsible for developing the four-year plans.

Several network-level applications were also evaluated to process the TSD data. The first generated a structural strength index with a scale from 0 to 100, indicating poor or good structural condition, respectively. The second evaluated the potential for developing remaining life estimates. Inadequate layer thickness information and accurate traffic load estimates limited these applications. Third, an experimental backcalculation procedure was evaluated that utilized the 3D-Move software to predict pavement responses under TSD loading. The use of TSD data for project-level applications was also explored by linking the TSD data to TxDOT's existing ground penetrating radar (GPR) system, which is used to identify layer thicknesses and possible defects. This study recommends that a certification methodology be implemented to ensure TSD data collection and processing are reasonable.

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DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The researcher in charge of this project was Tom Scullion.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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LIST OF SYMBOLS AND ABBREVIATIONS

2-CST	Two-course surface treatment
ADT	Average daily traffic
BCI	Base curvature index
CRCP	Continually reinforced concrete pavement
CTB	Cement-treated base
D0	Maximum deflection
DFO	Distance from origin
E	Modulus
ESAL	Equivalent single axle load
FB	Flexible base
FDR	Full-depth reclamation
FHWA	Federal Highway Administration
FWD	Falling weight deflectometer
GPR	Ground penetrating radar
GPS	Global positioning system
HMA	Hot mix asphalt
HRhb	Heavy rehabilitation
iPAVe	Intelligent pavement assessment vehicle
IRI	International roughness index
JCP	Jointed concrete pavement
JCRP	Jointed reinforced concrete pavement
LRhb	Light rehabilitation
M_r	Resilient modulus
MRhb	Medium rehabilitation
NB	Northbound
OCST	One course surface treatment
OWP	Outside wheel path
PA	Pavement Analyst
PI	Plasticity index
PM	Preventative maintenance
PMIS	Pavement Management Information System
RS	Ride score
SB	Southbound
SCI	Surface curvature index
SN_{eff}	Effective structural number
SN_{req}	Required structural number
SSI	Structural strength index
T	Thickness
TPF	Transportation pooled fund

TPP	Transportation Planning and Programming
TRM	Texas reference marker
TSD	Traffic speed deflectometer
TSDD	Traffic speed deflectometer device
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
USDA	United States Department of Agriculture
VOR	Value of Research

CHAPTER 1. PROJECT BACKGROUND

INTRODUCTION

The Texas Department of Transportation (TxDOT) spends hundreds of millions of dollars annually to manage the transportation infrastructure and preserve the roadway pavement. Advancements in pavement maintenance practices have demonstrated that incorporating pavement structural condition along with the pavement surface condition into a pavement management decision-making process leads to better decisions and more cost-effective pavement rehabilitation and preservation strategies. While the falling weight deflectometer (FWD) has been routinely used in Texas for over 30 years for pavement management applications and project-level structural evaluations, it is inefficient at the network-level. FWD measurements are made at discrete points along a highway, and the equipment has to remain stationary for typically 1–2 minutes on the road at each testing point. This protocol requires traffic control and lane closures that disrupt traffic flow, which limits productivity and the number of discrete measurement points that can reasonably be included.

Over the past decade, traffic speed deflectometers (TSDs), which can near-continuously measure pavement structural condition at highway traffic speeds, have been developed and are undergoing trial implementation in Texas and throughout the United States. As a participant in the Federal Highway Administration's (FHWA) transportation pooled fund study, TPF-5(385) Pavement Structural Evaluation with Traffic Speed Deflection Devices (TSDDs) [1], TxDOT has collected more than 3,000 miles of TSD data since 2019 and is expected to continue collecting TSD data in the upcoming years. Figure 1 shows the TSD vehicle used in Texas, which is an upgraded version of the Australian TSD vehicle—the intelligent Pavement Assessment Vehicle (iPAVe). The TSD collects many other condition items in addition to continuous deflection (see Figure 1).

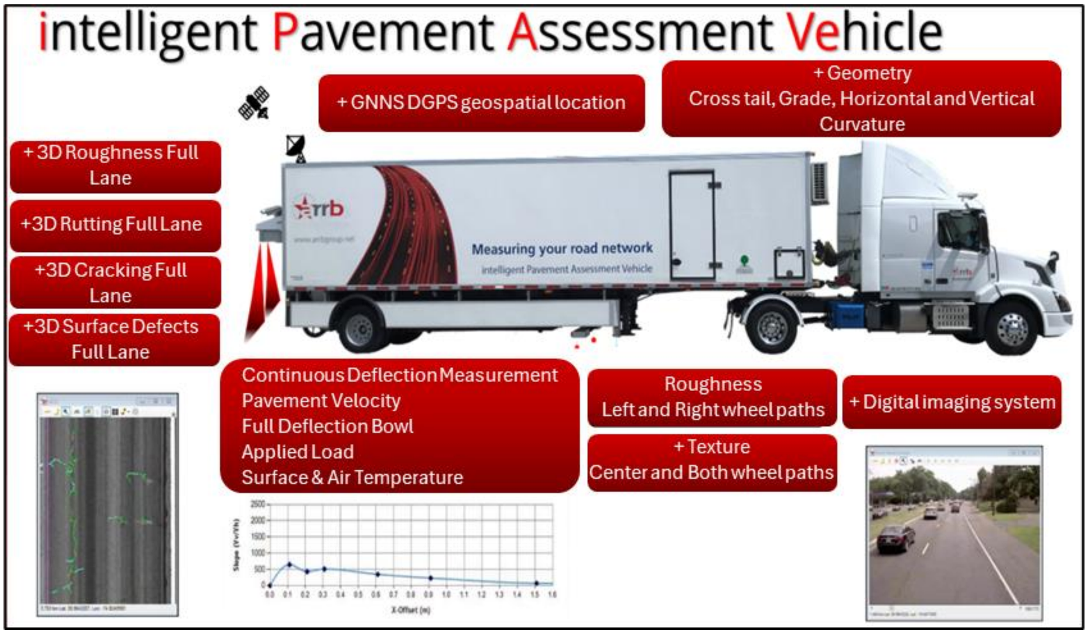


Figure 1. TSD Vehicle used in Texas [2].

The data are stored and made available online through ARRB System's Hawkeye software package. Figure 2 provides an example display of a roadway section in Texas.

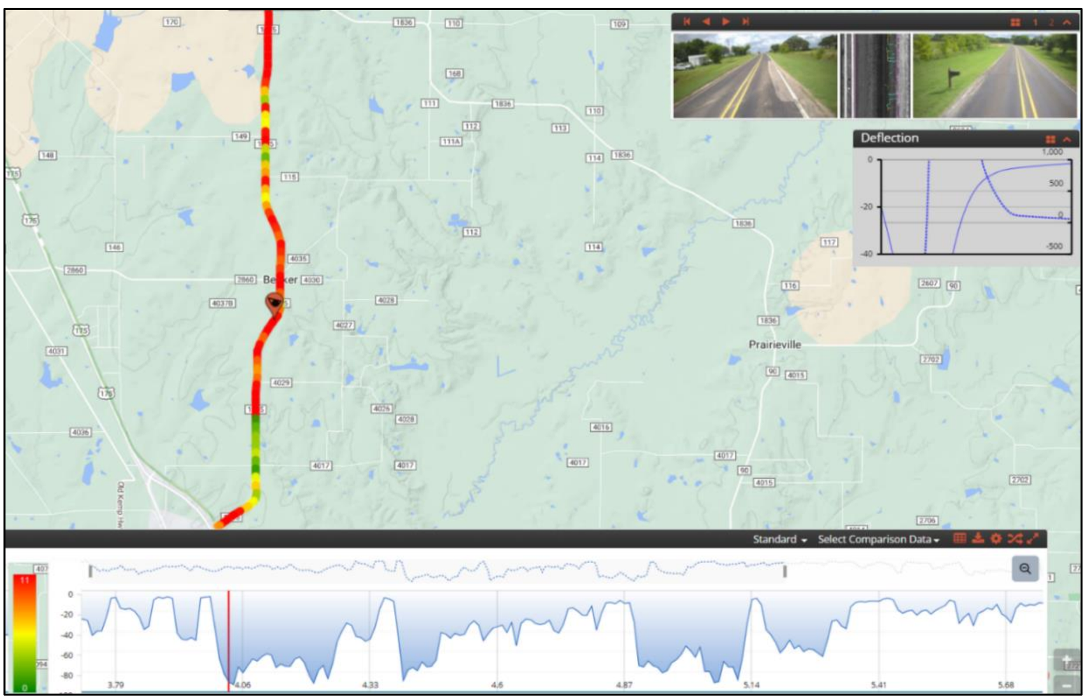


Figure 2. Example Display of a Texas Roadway Section Showing a Color-Coded Map of Pavement Deflections and a Deflection Plot (Vertical Scale 0–100 mils).

The condition item of principle interest to TxDOT is the continuous deflection. Figure 3 (a) and (b) distinguish the FWD and the TSD data collection methods, respectively. The FWD uses an impact load to measure deflections on the pavement surface with geophones, while the TSD uses Doppler laser measurements between the load wheels to measure the pavement response. Note that the deflection measurement principle is completely different between the TSD and FWD. Table 1 summarizes the operation mode differences between the two devices.

(a) **(b)**

Figure 3. Device Operation Modes: (a) FWD Geophone and (b) TSD Laser Sensor Array [3].

Table 1. Comparison of the TSD and FWD Devices [4].

TSD	FWD
Obtains continuous data	Obtains data at discrete points
Obtains deflection velocity data on specific points according to Doppler lasers	Obtains deflection data at the load center and at specific points from the load center
Operates on a moving vehicle at highway traffic speeds without the need for traffic control or traffic flow disruption	Operates on a stationary vehicle with the need for traffic control and traffic flow disruptions
Utilizes a comparison of undeflected and deflected pavement conditions (spatially coincident method)	Utilizes falling weight loading
Applies an elliptical-shape loading	Applies a circular loading
Based on vertical deflection velocity	Provides actual surface deflection

TXDOT'S CURRENT APPROACH FOR PROCESSING TSD DATA

Implementation of a system to process TSD data at the network level is well advanced within TxDOT. The current system is described in detail in a PowerPoint presentation entitled, "Implementation of Structural Strength Data for Network-Level Pavement Management" [5]. Details of the current approach are summarized below.

The primary computed strength index—the structural condition index—can be calculated as follows:

$$\text{Structural condition index} = \text{SNeff}/\text{SNreq} \qquad \text{(Eq. 1-1)}$$

where the effective structural number (SN_{eff}) is calculated from a recalibrated Rhode's equation [6] as follows:

$$SN_{eff} = K_1 SIP^{K_2} H_p^{K_3} \qquad \text{(Eq. 1-2)}$$

where:

SIP = structural index of pavement (μm) calculated as $D_0 - D_{1.5Hp}$.
D_0 = peak deflection under normalized load (temperature corrected).
$D_{1.5Hp}$ = surface deflection measured at a distance of 1.5 times H_p (temperature corrected).
H_p = total pavement thickness (mm).
K_1, K_2, K_3 = 0.4369, −0.4768, 0.8182, respectively, for TSD measurements.

The required structural number (SN_{req}) is currently available as a table lookup (see Table 2).

Table 2. Required Structural Numbers for Different Traffic Load and Subgrade Support Conditions [5].

SN_{req}		20–Year Accumulated Traffic in ESALs					
		Category	Very Low	Low	Medium	High	Very High
M_r (psi)	**Category**	**Range**	50,000–945,000	945,000–1,687,000	1,687,000–2,430,000	2,430,000–3,172,000	3,172,000–50,000,000
	Low	1,000–5,400	4.3	5.1	5.3	5.6	7.1
	Medium	5,400–7,500	3.5	3.9	4.2	4.3	6.0
	High	7,500–40,000	2.3	2.6	2.8	2.8	3.9

In Table 2, the resilient modulus (M_r) value can be obtained from the following single-layer solution:

$$M_r = 0.33 * \left(\frac{0.24P}{dr*r}\right) \qquad \text{(Eq. 1-3)}$$

where:

P = load (pounds).
d_r = deflection at r inches from load center (r = 72 inches for FWD and r = 48 inches for TSD).

The ability to process TSD data at the network level is now fully operational within TxDOT's Pavement Analyst (PA) system. Efforts are underway to use the system to assist district designers with their project-level evaluations and four-year plan development. Figure 4 shows the computed structural condition index (in red) and the SN_{eff} (in green) for a section of IH 20 in the Odessa District.

A clear break in the data occurred at Texas reference marker (TRM) 109.1. The first mile of the project (from TRM 108 to 109) had a structural condition index of less than 1, meaning this section is too weak for the current predicted traffic loads. The large spike in the data is TSD data collected on a bridge deck. These data will be useful in considering future project-level decisions—for example, determining (a) why the structural strength break at TRM 109 occurred, and (b) whether a different rehab strategy should be applied from TRM 108 to 109.

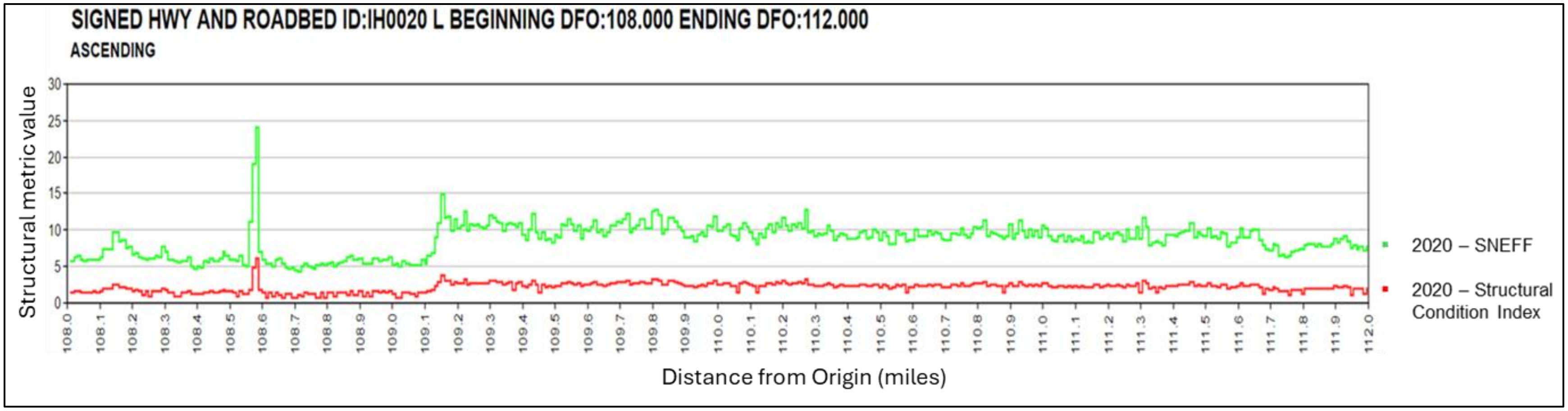


Figure 4. Processed TSD Data from a Section of IH 20 Considered for Rehabilitation (x-Axis is DFO).

As with all analysis systems, information is needed on the current in-situ pavement layer thicknesses (surface and total). This information is currently not available within TxDOT's PA system, which is a major limiting factor in any network-level application development in Texas. To address this deficiency, the following equations have been proposed to define default pavement layer thickness estimates:

$$\text{Surface layer } (t_{surf}) \quad \text{(Eq. 1-4)}$$

If equivalent single axle loads (ESALs) < 1 million, $t_{surf} = 1$ inch

Else $t_{surf} = 2.65 \times \log e\,(\text{ESALs}) - 35$ inches

$$\text{Total pavement thickness } (t_{Hp}) \quad \text{(Eq. 1-5)}$$

If ESALs < 0.25 million, $t_{Hp} = 6$ inches

Else $t_{Hp} = 2.9 \times \log e(\text{ESALs}) - 30$ inches

$$\text{Base layer thickness} = t_{Hp} - t_{surf} \quad \text{(Eq. 1-6)}$$

These proposed equations can be overwritten by district staff who are familiar with the section. In the future, thicknesses will be provided by ground penetrating radar (GPR) surveys, which are widely used by TxDOT districts.

The system for processing TSD data at the network level is well advanced and has been implemented within districts where TSD data are available. Limitations and areas of concerns with the current systems are as follows:

- The in-situ layer thickness information is based on network-level traffic estimates available within the PA system, which are known to be poor. Comparisons with project-level data from weigh-in-motion systems have shown that these values are frequently low, often by a factor of four.
- The structural number concept is not used in Texas, and it is not well understood by TxDOT designers.

REPORT CONTENTS AND ORGANIZATION

This report consists of 10 chapters, including this introductory chapter that provides the background, status of current implementation efforts, and scope of work for this project. The remaining chapters are organized as follows:

- Chapter 2 presents the results of a survey administered to TxDOT district staff to determine their needs for improving the selection and prioritization of projects for inclusion in their four-year plans.
- Chapter 3 provides a comparison of the TSD and FWD deflection data collected on repeated runs on nine test sections established on SH 47 in the Bryan District.
- Chapter 4 outlines the lessons learned during TSD data collection in the Bryan District in 2021 and 2022.
- Chapter 5 describes the use of the ARRB System's Hawkeye software package in selecting appropriate funding levels for highways in Texas. This package includes filters for allocating projects to different funding categories (e.g., maintenance, light rehab, medium rehab, heavy rehab/full reconstruction).
- Chapter 6 provides recommendations for additional applications of the TSD for network-level analysis within TxDOT's PA system, including a structural strength index and remaining life estimate.
- Chapter 7 describes the merging of TSD with GPR data, which is critical for making project-level decisions. GPR provides information on layer thicknesses, pavement breaks, and subsurface defects.
- Chapter 8 discusses applications of the 3D-Move software package to assist in processing TSD data and provides a look at an experimental backcalculation procedure using TSD deflection data. This package represents the state of the art for predicting pavement responses under moving loads, and it will be crucial to incorporate 3D-Move in future TSD processing procedures.
- Chapter 9 provides case studies of projects identified by TxDOT district staff that are under consideration of incorporation into their four-year plan or that are exhibiting unusual pavement distresses.
- Chapter 10 presents the conclusions of this study and recommendations for future research.

CHAPTER 2. NEEDS IDENTIFIED BY TXDOT DISTRICT STAFF

One undertaking of this project was to contact TxDOT districts where TSD data has been collected and determine how the data has been used in conjunction with their four-year plan development efforts. To accomplish this, a questionnaire was developed and distributed to the following five districts: Austin, Odessa, Paris, Dallas, and San Antonio). The survey was intended to focus on the following three areas:

1. Data currently used by the districts to select projects for inclusion in their four-year plans.
2. Staff familiarity with existing TSD processing outputs provided by both TxDOT's PA and ARRB System's Hawkeye systems.
3. Desired future outputs from the TSD data processing system.

Appendix A contains the detailed survey results. A summary of the survey findings follows.

CURRENT METHOD OF SELECTING PROJECTS FOR FOUR-YEAR PLAN

This survey section was intended to gauge the importance of TxDOT's PA system and determine the most useful data for identifying projects for the district's four-year plan. For each of the following questions included in this survey section, key responses and recommendations from district staff included the following:

1. What level of importance does the PA system play in identifying new projects?

    - Staff in each of the districts responded that the PA system was *very important* in their ongoing job of identifying projects.

2. What data in the PA system are used to identify projects for inclusion in the four-year plan?

    - Staff in each of the districts responded that each of the key pavement scores computed within the PA system—pavement score, distress score, and ride score—were equally important when identifying projects.
    - The level of load associated distress—alligator cracking, rutting, and patching—was also used by staff in each of the districts.

3. What data in the PA system are used to select treatment options?

    - Staff in each of the districts reported using the ride score when selecting treatment options.
    - Staff in four of the five and three of the five districts reported using the distress score and level of load associated distress, respectively, when selecting treatment options.
    - Only one district reported using overall pavement score.

4. How can the PA system be improved to better fit your needs?

    - Provide a report that merges the *section needs* report/data with the planned projects in TxDOT-Connect and TxDOT's Maintenance Management System, allowing district staff to compare the recommended and planned treatments. Merging these data would make it easier for staff to determine which needs are already being met and allow them to focus on the unmet needs.
    - Consider allowing the PA system to pull projects with other funding sources that have pavement work planned. This capability could affect the predicted Pavement Management Information System (PMIS) score analysis that is performed each year.
    - To make the data more useful, develop a more interactive graphical user interface (i.e., a map that allows users to select roadways, define limits, and select overlays that can be turned on or off depending on the type of data of interest.

FAMILIARITY AND CURRENT USE OF TSD DATA

The second part of the survey was intended to gauge the levels of exposure to the TSD data by district staff. Additionally, these questions helped determine the usefulness of the TSD data in determining projects for inclusion in the four-year plan. For each of the following questions included in this survey section, key responses and recommendations from district staff included the following:

1. Have you received training on how to process TSD data in the PA system?

    - Staff in only two of the five districts said that they had received training on how to process the TSD data in the PA system. This low affirmative response rate could be tied to recent new hires and retirements.

2. Are you familiar with AARB System's Hawkeye Insight data system?

    - Staff in three of the five districts said they were familiar with how to use the Hawkeye Insight data system, perhaps based on training provided by ARRB Systems.
    - This system was highlighted in a response from staff in one district who asked the Texas A&M Transportation Institute (TTI) research team to develop color-coded maps showing the strength of their interstate pavements. The request to display data on maps was a recurring theme among the responses.

3. Have you reviewed the TSD data collected in your district?

    - Staff in four of the five districts reported having at least looked at the TSD data.

4. Were the current TSD data used to select projects for inclusion in the four-year plan?

    - While staff in only two of the five districts reported using the TSD data to select projects, this number was encouraging given the early stage of implementation.

5. If so, how were the data used?

    - TSD data were viewed and used as part of the overall decision-making process in the four-year plan development.
    - Because the technology was new, the TSD data were included as contributing information, but more weight was placed on familiar information sources such as static FWD, TxDOT’s collected ride data, etc.
    - The information was used as a comparative baseline for roadways with data collected conventionally. Two upcoming projects can be compared: SH 19 in Hopkins County and FM 275 in Rains County.
    - One respondent speculated that the TSD data could be utilized with greater assurance in timely decision-making. If most high traffic district roadways were collected just before the four-year plan development period, the data would be relatively current compared to conventional collection methods. In addition, the overall data collected would be more than is typically collected via the PMIS due to the rolling deflection information it offers.
    - When selecting routes for the district's four-year plan rehab projects, the TSD graphs and video helped identify locations with distress and high deflections.

6. Given a map of projects on which TSD data were collected, which projects have been included in your current four-year plan, and what level of treatment is proposed?

    - The Paris District’s current four-year plan includes one preventative maintenance (PM) project (US 82 from TRM 622 to 628) and three heavy rehabilitation projects (FM 100, SH 19 from TRM 242 to 254, and FM 275).
    - The Austin District’s current four-year plan includes multiple rehab and reconstruction projects on IH 35 (Williamson, Travis, and Hays Counties); two preventative maintenance projects on US 281 (Blanco County), one PM project on US 281 (Burnet County), one preventative maintenance project on US 87 (Mason County) and various rehab projects on US 87 (Gillespie and Mason Counties).
    - The Odessa District’s current four-year plan includes deep mill and inlay projects on IH 20 from Country Club Road to the Pecos River in Pecos, IH 20 from IH 10 to TRM 9.1, and IH 10 from Jeff Davis county line to FM 3078. The proposed level of treatment for projects on IH 20 from FM 1936 to Moss Avenue in Ector County and IH 10 from TRM 241 to TRM 244 were as of yet undecided.

TSD REPORTING IMPROVEMENTS TO BETTER MEET NEEDS

The final section of the survey was intended to determine how TSD data could be presented in the future to provide the most important and meaningful data for districts when selecting projects to include in their four-year plans. For each of the following questions included in this survey section, key responses and recommendations from district staff included the following:

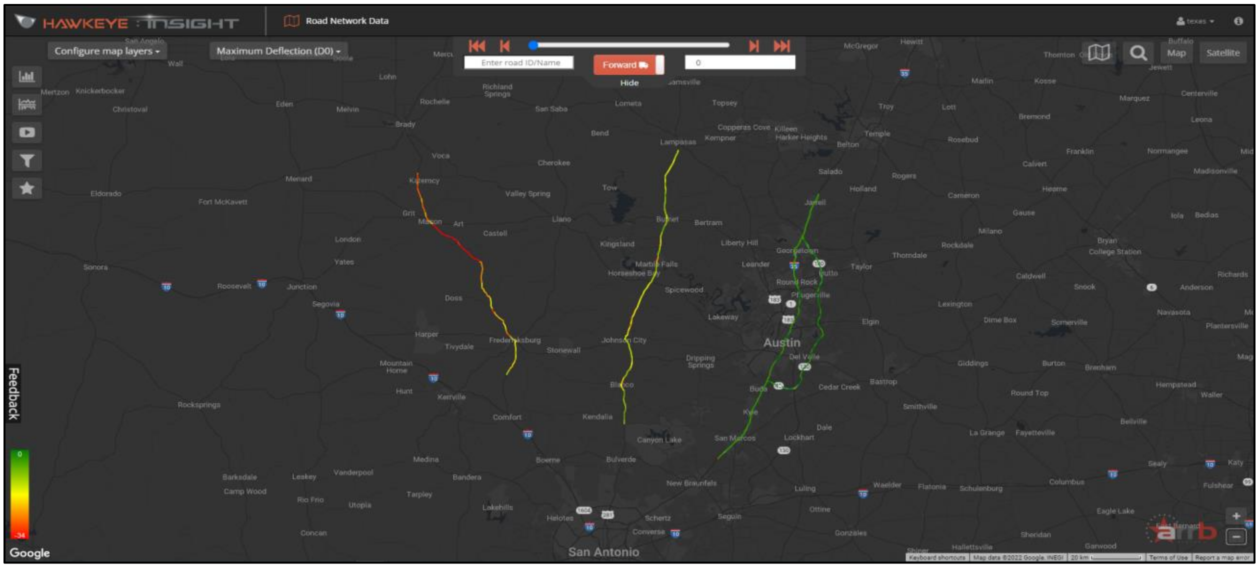
1. On a scale of 0 to 5, how much would you use the following: structural strength index (similar to the MODULUS software outputs), and remaining life estimate (similar to the MODULUS software outputs)?
    - Staff in four of the five districts requested a remaining life estimate (similar to the MODULUS software outputs).
2. What is the best reporting interval for TSD data summaries?
    - Most district staff requested that the system automatically generate limits for problematic sections.
    - As an alternative, some district staff requested a one-tenth mile fixed interval, with the following qualifying statement, “Data for every tenth mile is sufficient but it would be better if we could increase the frequency of the data in areas where there is high deflection to provide quantity in the plans for where base repair is needed.”
    - None of district staff thought that the current 50-ft reporting limit was needed, emphasizing the need to develop a system that condenses the huge amount of data generated into more practical section lengths.
3. How can the TSD processing system be improved to better suit your needs?
    - Provide automated color-coded maps based on deflections.
4. What TSD data format would be most useful for your district.
    - Color-coded maps.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

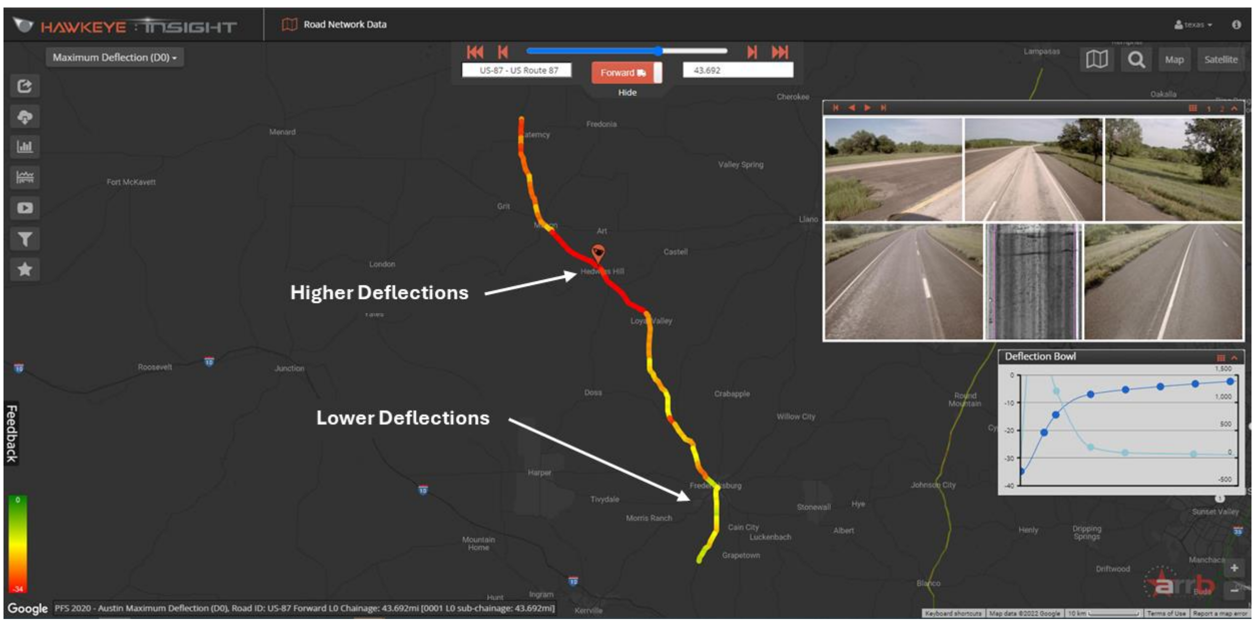
Based on the results of the survey, staff in each of the districts have reviewed their respective data, and most are more familiar with ARRB System’s Hawkeye Insight data system than TxDOT’s TSD data processing system in the PA system. Hawkeye Insight is a web-based data system that allows the user to select the projects they want to view and overlay road characteristics such as deflection, rutting, and cracking. The project is color coded to display the desired data. Additionally, the user can view photos and video of the project to gain a better understanding of the surface conditions.

Comments from the surveyed district staff indicated that a graphical interface like the one provided in the Hawkeye Insight system, which allows the user to toggle through different data and view surface photos/video, would be a useful addition to TxDOT's PA system. Recommended modifications to the TSD reporting process included varying the frequency of data collection surrounding areas of interest (i.e., allow the user to select reporting frequencies if more detailed information is desired) and providing remaining life estimates for tested roads.

The Austin District staff requested that TTI send them color-coded maps reflecting the structural strength of the IH 35 corridor. Several maps were developed and shared. Figure 5 shows two example screenshots of Austin District roadway maps from the Hawkeye Insight system.



(a)



(b)

Figure 5. Hawkeye Insight Data System Screenshots for the Austin District: (a) TSD Projects and (b) FM 969 Detailed View.

When selecting projects for inclusion in the four-year plans, the survey results revealed that TxDOT's PA system is widely used in selecting projects; specific condition items include the reported pavement distress score, ride score, and load associated distress values. Among these condition items, the ride and distress scores are the most used indices. In each of the surveyed districts except the Paris District, staff reported that the TSD data were not used as a source for determining projects for the four-year plan; instead, the TSD routes were planned based on proposed projects. However, staff from the Dallas District indicated that the TSD graphs and video assist in identifying locations where distress and deflections are high. In the Paris District, the TSD data are used in conjunction with conventional data (e.g., FWD and ride data) to support project selection processes. One respondent noted that the TSD data provides more current and detailed pavement data that allows decisions to be made with greater certainty.

CHAPTER 3. COMPARISON OF TSD AND FWD DEFLECTION DATA COLLECTED ON SH 47 TEST SECTIONS

OVERVIEW OF SH 47 TEST SECTIONS

TSD data were collected in TxDOT's Bryan District in 2021 and 2022. Both of these data collection loops included a portion of SH 47 from FM 60 to SH 21. To determine the relationship between FWD and TSD data, nine homogeneous sections were defined along SH 47, each approximately 2,000 feet long. Figure 6 shows the five test sections in the southbound (SB) direction (in blue) and the four test sections in the northbound (NB) direction (in green).

Figure 6. Test Sections on SH 47.

Figure 7 shows a typical GPR display from the SB2 test section. This section is 2,000 feet long with a uniform pavement structure. The tick marks at the top of the color display show the locations where FWD data were collected. The TSD deflection reporting interval was 50 feet; the FWD data were collected at the same reporting interval for each section. This section was recently rehabilitated—the existing surface was removed, the top 10 inches of base were cement treated and a 3-inch-thick hot mix asphalt (HMA) surface layer was placed.

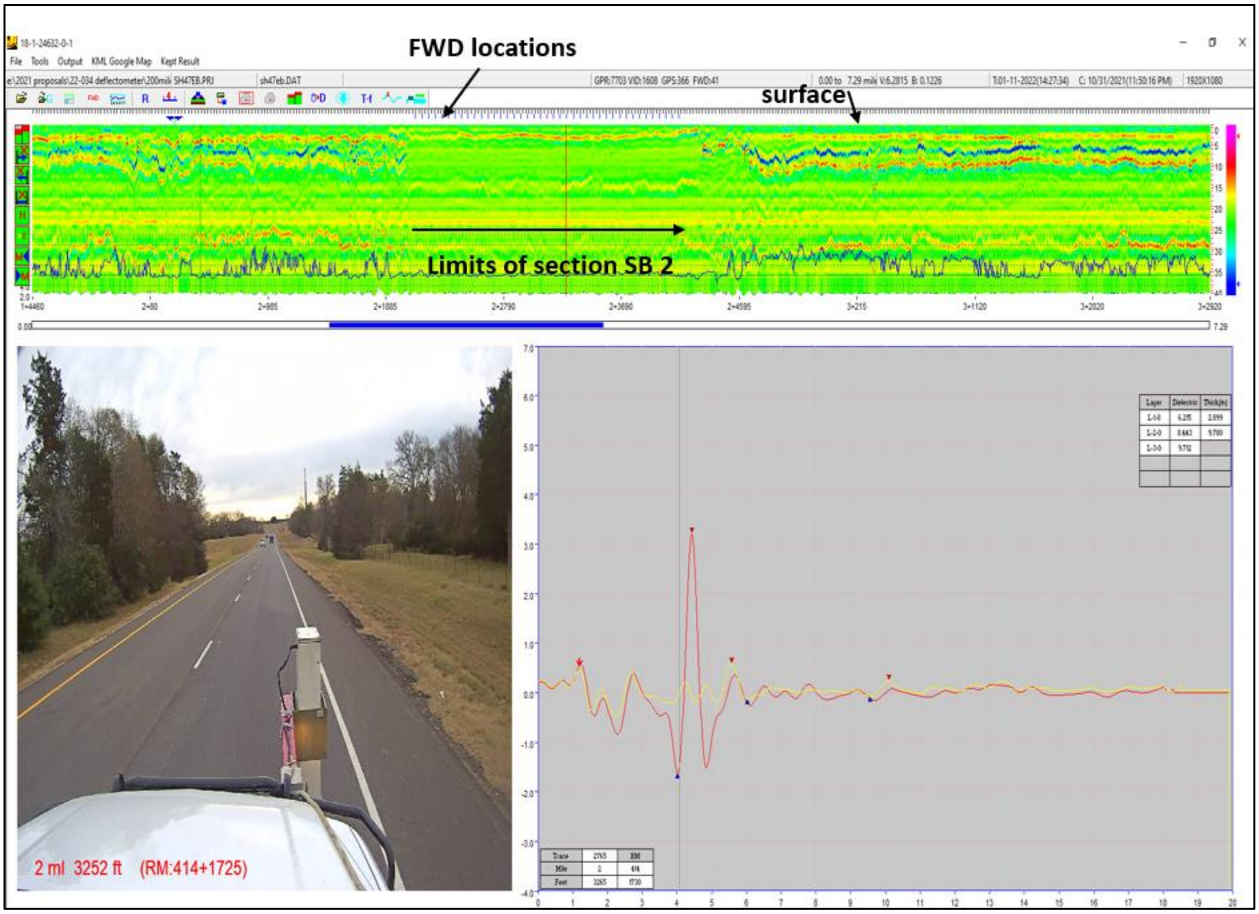


Figure 7. GPR Data Showing the Limits of Section SB2 on SH 47.

TEST SECTION PAVEMENT STRUCTURE CHARACTERISTICS

The pavement structure for each of the sections was determined using the construction plans for SH 47. The pavement surface thicknesses and, in some cases, the base thicknesses were determined using GPR data. Table 3 lists the pavement structure thickness (T) and backcalculated modulus (E) values from the MODULUS (Version 7.0) software for the nine test sections.

In the SB direction, sections 1, 2, and 4 are on straight flat pavements, while sections 3 and 5 are located on bridge approaches. In the NB direction, sections 2, 3, and 4 are on flat pavements, while section 1 is on a bridge approach. The SB2, SB4, NB1, and NB4 sections are known to contain cement-treated base (CTB) materials, while the HMA layer at the NB2 section had known delamination issues. As such, the SB2, SB4, NB1, and NB4 sections were considered to be strong test sections, while the SB3, SB5, and NB2 sections were considered to be weak test sections. Figure 8 summarizes the subsurface layer strengths for each section.

Table 3. SH 47 Test Section Pavement Structure Thicknesses and Backcalculated Moduli.

Section	T Surface (inches)	T Base (inches)	T Subbase (inches)	T Subgrade (inches)	E Surface (ksi)	E Base (ksi)	E Subbase (ksi)	E Subgrade (ksi)
SB1	7.5	12.5	8	120	330	72	44	14
SB2	2.8	10	12.5	120	450	621*	44	15.6
SB3	2.4	12.5	0	120	450	28		15.7
SB4	5.5	10	12.5	120	500	707*	37	9.2
SB5	5	6	8	120	400	18	27	7.5
NB1	2.2	8	8	120	450	800*	44	11
NB2	5.4	10	0	120	73**	40		12
NB3	7.6	12.5	8	120	260	37	40	13.9
NB4	5.7	10	12	120	500	800*	32	12.7

* Section with known CTB.
** Section with known delamination problems in HMA layer.

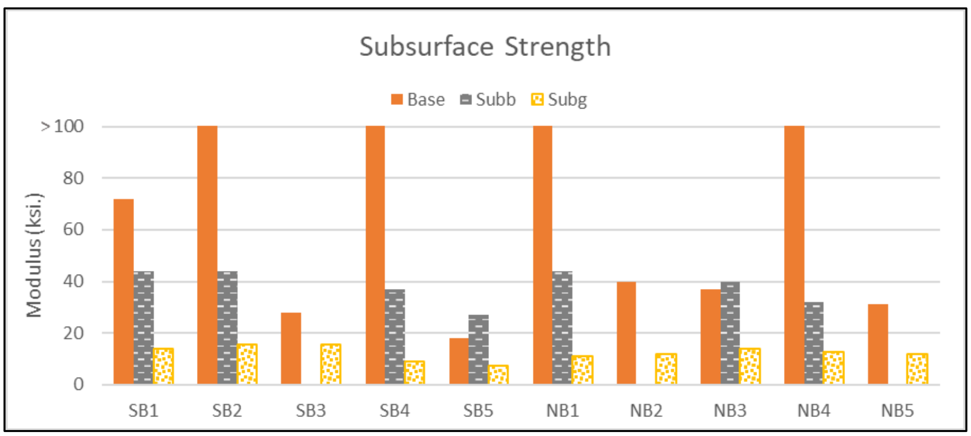


Figure 8. SH 47 Test Section Subsurface Layer Strength.

EVALUATION OF DATA COLLECTED IN 2021

Several commonly used indices are reported when analyzing FWD data. These indices include the following:

- Maximum deflection.
- Outer sensor deflection.
- Surface curvature index (SCI).
- Base curvature index (BCI).
- M_r.

These metrics are obtained or calculated directly from the deflection output generated by both the FWD and TSD devices. Table 4 displays the parameters and associated formulas used in the next two sections to compare the FWD and TSD deflection data collected for the SH 47 test sections in 2021 and 2022. Excluding the M_r for which the load was an input variable, each parameter was normalized to a 9,000-pound load.

Table 4. Parameters and Formulas for FWD and TSD Deflection Indices.

Index	Formula		Characterized Layer
	FWD	TSD	
Maximum deflection	W1	D0	Total pavement structure
Outer sensor deflection	W7	D72	Subgrade layer
SCI	W1 – W2	D0 – D8	Surface layer
BCI	W2 – W3	D12 – D24	Base layer
M_r	$0.33 * \left(\frac{(0.24 * P)}{d_r * r}\right)$		Subgrade layer

In the formula for M_r in Table 4, P is the load (pounds), D_r is the deflection at r inches from the load center (mils), and r is either 72 or 48 inches for the FWD or TSD data, respectively.

Figure 9 shows the maximum deflections reported by the FWD and TSD devices in 2021. In general, the TSD data followed the same trend as the FWD data, although the measured deflection values were higher in the FWD data than those reported by the TSD data. Both devices reported higher deflections for the weak SB3, SB5, and NB2 test sections. However, for the strong SB2, SB4, and NB4 test sections, errors in the TSD data produced gaps within the data.

Figure 10 shows similar trends in the outer deflections measured by the FWD and TSD devices in 2021. The measured deflection values were again higher in the FWD data than the TSD data, and errors in the TSD data produced gaps for the SB2, SB4, and NB4 test sections. Despite the similarities, the correlation between the FWD and TSD outer deflection data was not as strong as the correlation between the FWD and TSD maximum deflection data.

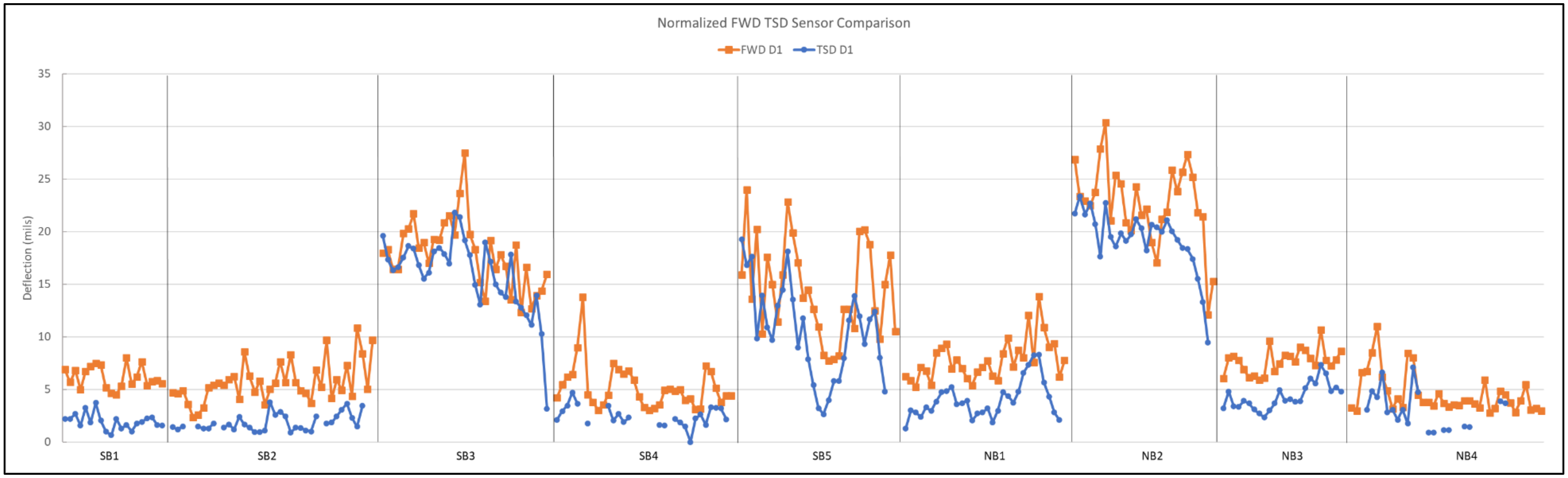


Figure 9. Comparison of FWD and TSD Normalized Maximum Deflections (2021).

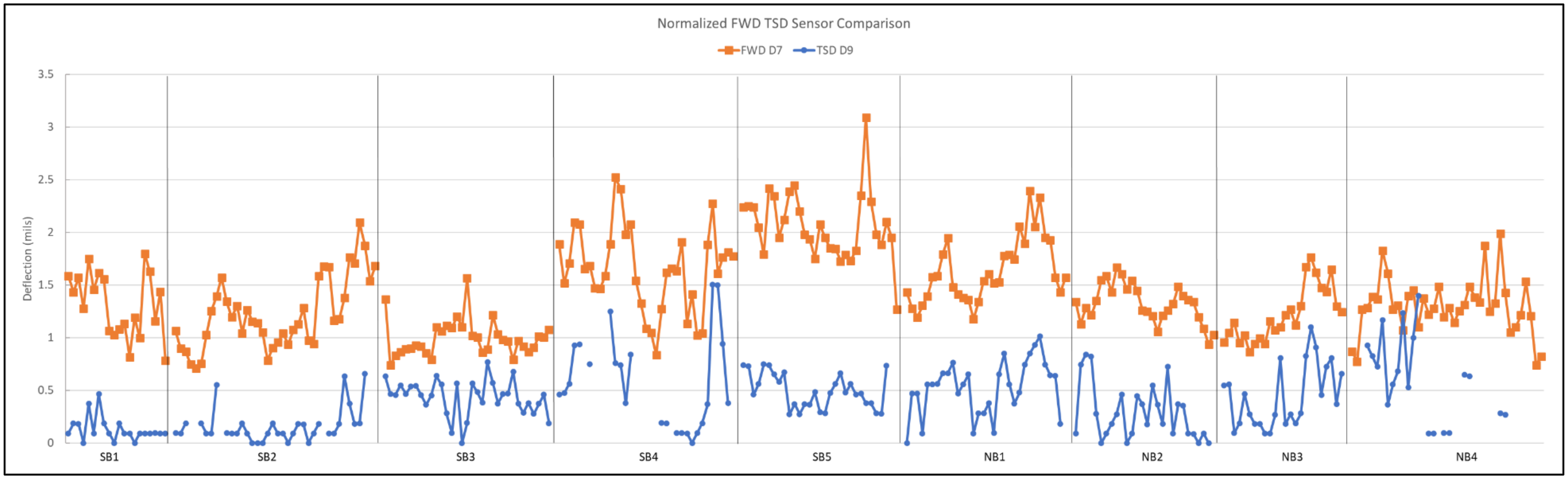
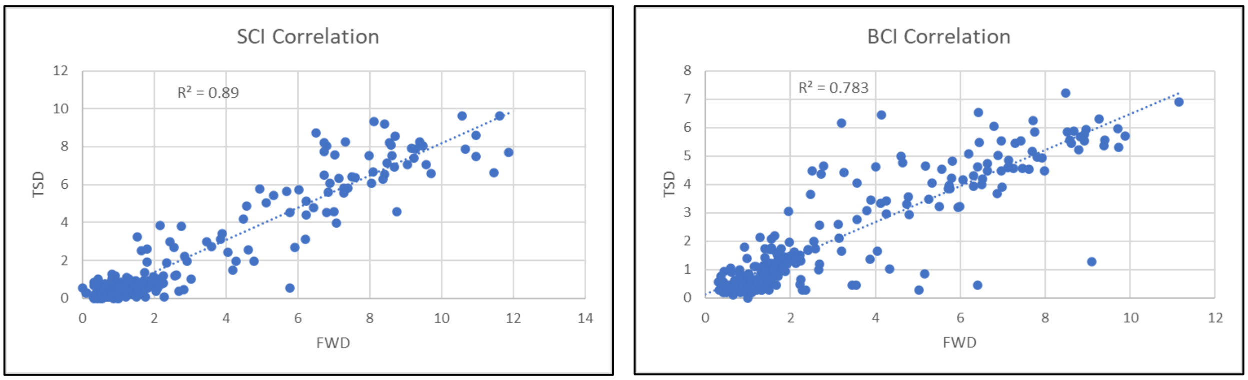


Figure 10. Comparison of FWD and TSD Normalized Outer Sensor Deflections (2021).

Figure 11 (a) and (b) display the correlation between the FWD and TSD data for the SCI and BCI, respectively. The correlation between the FWD and TSD data for both indices was very strong; however, the correlation was stronger for the SCI than the BCI. Figure 12 shows the average calculated M_r using both FWD and TSD data for each test section. The M_r calculated using the TSD data was much greater than the M_r calculated using the FWD data. However, the M_r calculated from TSD data was greater for test sections that were identified as strong than those test sections that were identified as weak.



(a) **(b)**

Figure 11. Correlation Between FWD and TSD Data (2021): (a) SCI and (b) BCI.

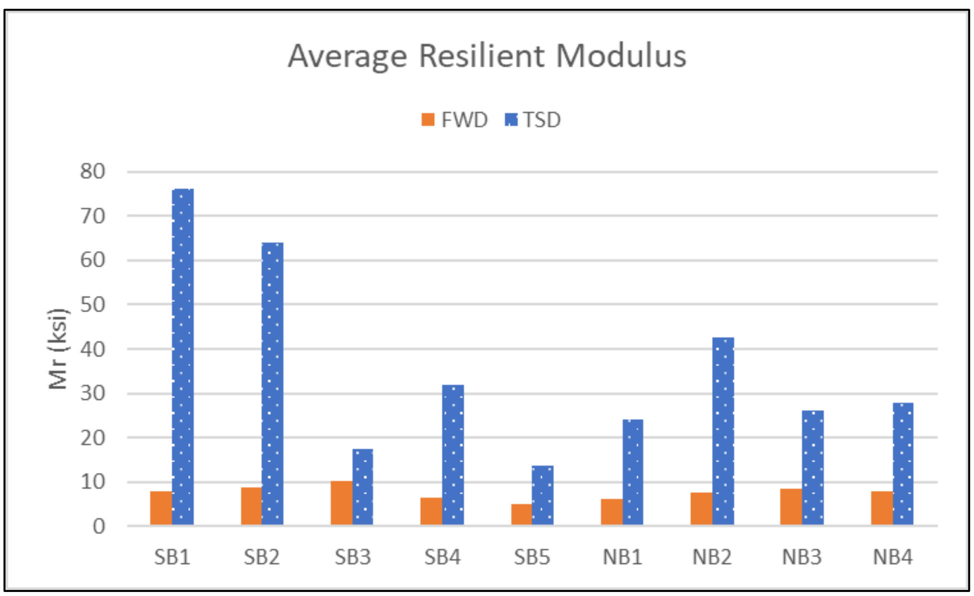


Figure 12. Comparison of FWD and TSD M_r Values (2021).

In total, 281 FWD and 238 TSD valid deflection bowls were measured along the test sections in 2021 and used to compare the output from the two deflection devices. Figure 13 shows the correlations between each deflection sensor for each of the nine test sections. Strong correlations were observed between the first TSD sensor and the first two FWD sensors, but no clear trend was observed for the outer sensors.

R^2 Values		2021 TSD Sensor (Location, inches)								
		1 (0)	2 (8)	3 (12)	4 (18)	5 (24)	6 (36)	7 (48)	8 (60)	9 (72)
FWD Sensor (Location, inches)	1 (0)	0.86	0.81	0.72	0.50	0.31	0.13	0.05	0.01	0.00
	2 (12)	0.76	0.76	0.71	0.54	0.35	0.15	0.07	0.03	0.00
	3 (24)	0.31	0.39	0.45	0.46	0.35	0.19	0.12	0.09	0.05
	4 (36)	0.05	0.10	0.16	0.23	0.19	0.12	0.10	0.10	0.09
	5 (48)	0.00	0.03	0.06	0.12	0.12	0.09	0.09	0.11	0.12
	6 (60)	0.00	0.01	0.03	0.08	0.08	0.07	0.08	0.11	0.12
	7 (72)	0.00	0.00	0.02	0.06	0.06	0.06	0.07	0.10	0.12

Figure 13. FWD and TSD Data Correlation Matrix (2021).

EVALUATION OF DATA COLLECTED IN 2022

Figure 14 and Figure 15 show the maximum and outer sensor deflections, respectively, measured by the FWD and TSD devices in 2022. As observed in the 2021 comparison, the TSD data trends generally agreed with the FWD trends. However, the correlation between the FWD and TSD maximum deflection data was much stronger in 2022 than in 2021, especially for the strong test sections. Additionally, the 2022 TSD data had fewer gaps in the deflection data than the 2021 TSD data.

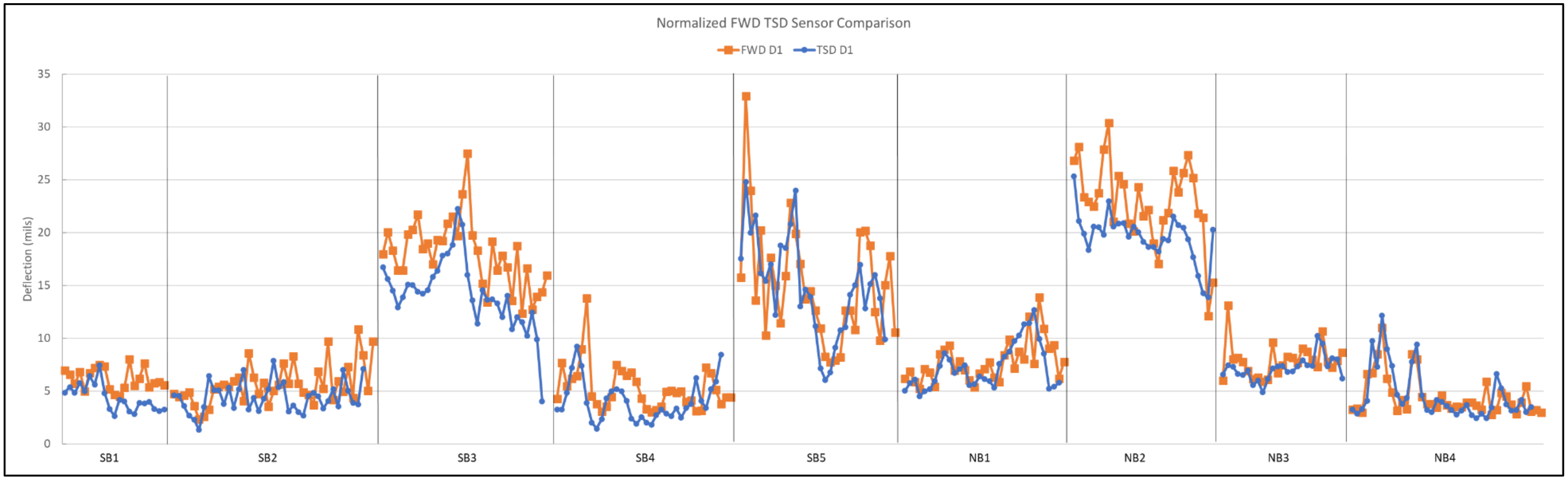


Figure 14. Comparison of FWD and TSD Normalized Maximum Deflections (2022).

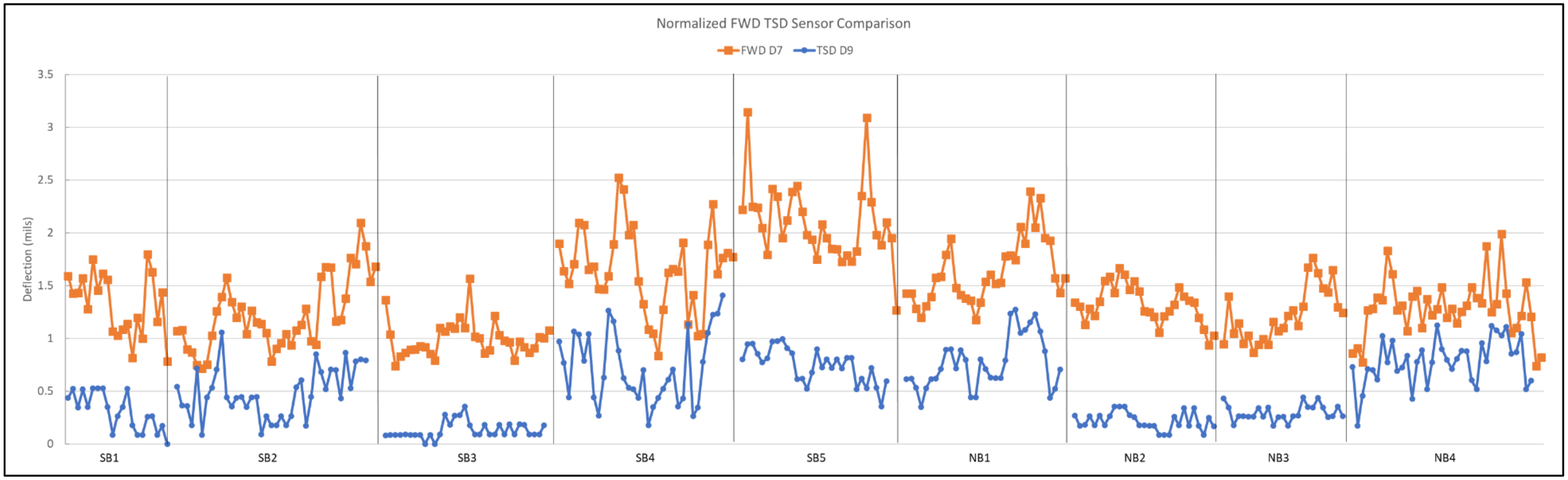
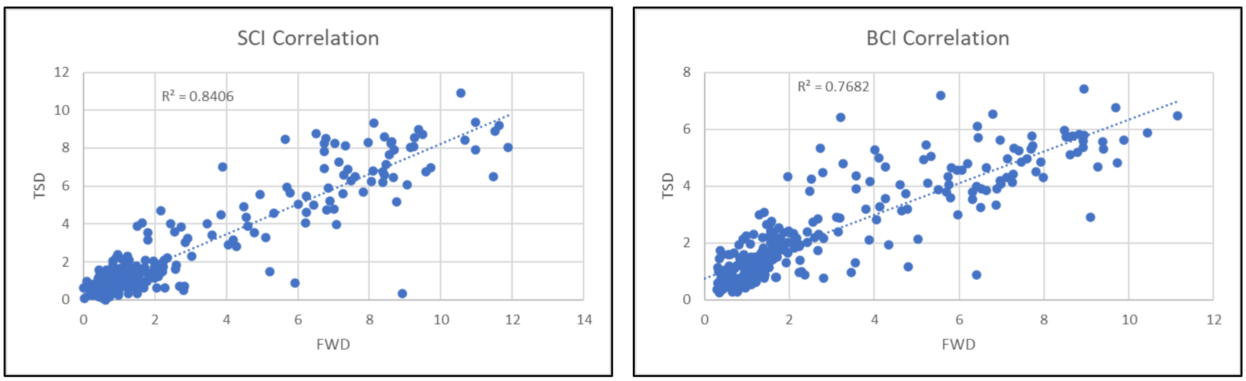


Figure 15. Comparison of FWD and TSD Normalized Outer Sensor Deflections (2022).

Figure 16(a) and (b) display the correlation between the FWD and TSD data for the SCI and BCI, respectively. As with the 2021 data, the correlation between the FWD and TSD data for both indices was strong, with a stronger correlation for the SCI than the BCI. Compared to the 2021 data, the 2022 TSD parameters showed marginally weaker correlations to the corresponding FWD parameters. Figure 17 shows the average calculated M_r using both FWD and TSD data for each test section. The M_r calculated using the TSD data was greater than the M_r calculated using the FWD data. Unlike the comparison of the 2021 data, the trends for the M_r calculated using the TSD data do not agree with the deflection trends. The SB3 section was considered a weak pavement section, but the M_r calculated from the 2022 TSD data was greater than any other section.



(a) **(b)**

Figure 16. Correlation Between FWD and TSD Data (2022): (a) SCI and (b) BCI.

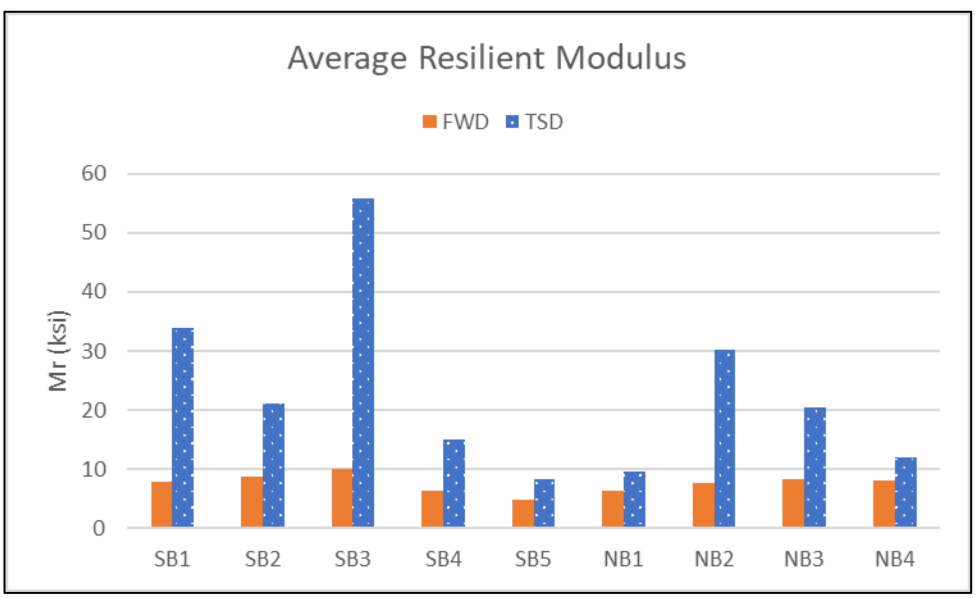


Figure 17. Comparison of FWD and TSD M_r Values (2022).

To compare the 2022 TSD data to the FWD data, 280 TSD and 290 FWD valid deflection bowls were recorded. Figure 18 shows the correlations between each deflection sensor for the two testing devices. The 2022 data exhibited a much stronger correlation between the FWD and TSD outer sensors compared to the 2021 data.

R^2 Values		2022 TSD Sensor (Location, Inches)								
		1 (0)	2 (8)	3 (12)	4 (18)	5 (24)	6 (36)	7 (48)	8 (60)	9 (72)
FWD Sensor (Location, inches)	1 (0)	0.81	0.67	0.52	0.25	0.07	0.00	0.04	0.09	0.14
	2 (12)	0.80	0.74	0.64	0.39	0.18	0.02	0.00	0.03	0.06
	3 (24)	0.46	0.59	0.65	0.62	0.50	0.23	0.11	0.05	0.01
	4 (36)	0.17	0.33	0.45	0.59	0.61	0.47	0.32	0.22	0.13
	5 (48)	0.07	0.19	0.31	0.49	0.58	0.54	0.42	0.33	0.23
	6 (60)	0.03	0.12	0.22	0.39	0.50	0.53	0.44	0.37	0.28
	7 (72)	0.02	0.09	0.17	0.33	0.44	0.49	0.43	0.37	0.30

Figure 18. FWD and TSD Data Correlation Matrix (2022).

CHAPTER 4. LESSONS LEARNED FROM BRYAN TSD DATA COLLECTION

OVERVIEW OF PAVEMENT TYPES TESTED

TxDOT defines the following 10 categories of pavement types within the PA system:

1. Continuously reinforced concrete pavement (CRCP).
2. Jointed reinforced concrete pavement (JRCP).
3. Jointed plain concrete pavement (JCP).
4. Thick asphaltic concrete pavement (> 5.5 inches).
5. Intermediate thickness asphaltic concrete pavement (2.5–5.5 inches).
6. Thin surfaced flexible base pavement (<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).

Table 5 lists the roadways, distance from origin (DFO) limits, pavement types, and number of miles for the 2021 and 2022 TSD loops in TxDOT’s Bryan District. Figure 19 provides a visual summary of the tested pavement types, nearly all of which were type 5 or 10 flexible pavements.

Table 5. Pavement Types Tested in TxDOT's Bryan District (2021 and 2022).

Roadway	From DFO	To DFO	Pavement Type	Number of Miles
2021 TSD Loop				
FM 39	38.7	70.3	5	16
			10	15.6
FM 1696	0.0	9.1	5	0.5
			10	8.7
SH 7	78.4	69.5	5	8.5
SH 21	116.2	107.7	5	8.5
			2	1.6
SH 47	0.1	7.3	5	7.2
SH 75	43.0	73.4	5	30.4
SH 90	12.7	0.0	5	12.7
US 79	228.5	148.0	1	1.9
			5	39.6
			7	0.5
			8	5.5
			10	33.1
US 190	427.2	392.8	5	34.4
Total: 225 miles				
2022 TSD Loop				
Roadway	**From DFO**	**To DFO**	**Pavement Type**	**Number of Miles**
FM 1791	0.0	2.6	5	2.6
FM 50	52.8	18.1	5	34.7
SH 105	26.1	3.1	1	0.5
			5	15.6
			10	6.4
SH 30	47.4	25.2	1	0.5
			5	22.1
SH 47	0.1	7.1	5	7.0
SH 75	63.2	98.6	5	4.0
			8	15.3
			10	15.5
SH 90	7.2	42.0	5	4
			8	15.3
			10	15.5
OSR	0.0	47.0	1	0.1
			5	28.9
			10	18.0
Total: 206 miles				

Figure 19. Pavement Types Tested in TxDOT's Bryan District (2021 and 2022).

POTENTIAL FOR INVALID DEFLECTION DATA

The reason flexible pavements were preferred over rigid pavements is due to the frequency of invalid deflection bowls for rigid pavements. Figure 20 displays the percentage of invalid deflection data for each of the tested pavement types collected during both TSD loops. Rigid pavement types 1 and 2 had the lowest return among all tested pavement types, while the flexible pavements that were tested had high rates of return. Throughout the data collection process, the TSD system flags irregular or unexpected pavement responses. For each invalid deflection bowl, the TSD system produces a No Model Fit message. The *iPAVe Comprehensive Structural and Functional Pavement Survey Methodology Handbook* [2] explains this message as follows:

> *Sensor drop off occurs where resolution of the measurement exceeds the limits of measurability (i.e., a very low deflection becomes a zero deflection). As a very strong or rigid pavement does not deflect in the same or uniform way a flexible pavement does (e.g., slab tilt and/or irregular load transfer) and it is at a greatly reduced magnitude (sub 100 microns), it is likely to give a zero, negligible, or negative defection velocity reading on multiple lasers. Hence, there is no valid result. Rigid and very strong pavements and bridges are areas where this will most commonly occur.*
>
> *It is not uncommon to have "No model fit TD0–TD900" and "Low sensor reading" in the comment column prior to and after "Sensor drop-off" locations, where the resolution of the measurement is approaching the limits of measurability.*

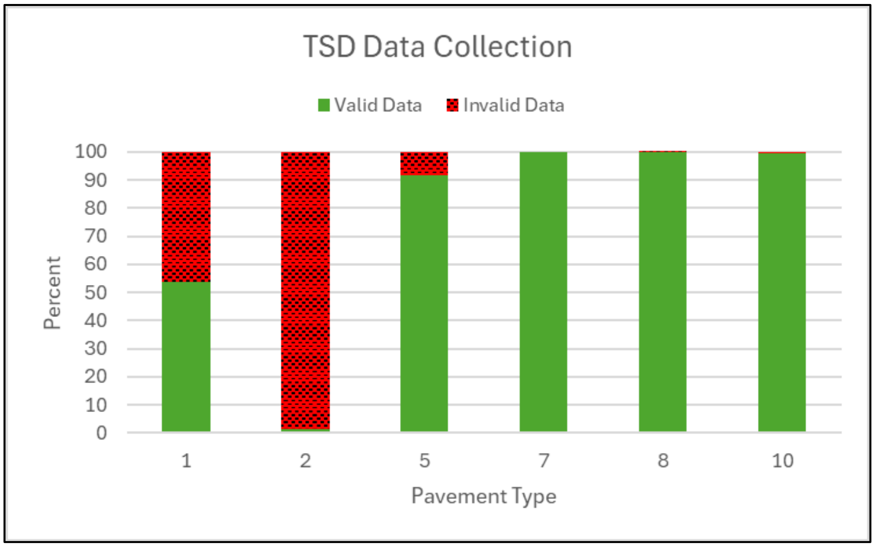


Figure 20. Valid and Invalid TSD Deflection Data per Pavement Type (2021 and 2022 Data Collection).

FINAL CORRELATION MATRIX

Figure 21 shows the final correlation matrix between the FWD and TSD deflection sensors generated from 326 valid deflection bowls collected in 2022 for each of the nine SH 47 test sections, as well as an additional project on FM 99 collected in the Corpus Christi District in 2023. The FWD data were collected around the same time as the TSD data at these locations, making them good candidates for inclusion within a larger dataset for correlation measurements. Note that the 2021 data for the SH 47 test sections were not included in this correlation because the 2021 data showed poor correlation with FWD and a high frequency of invalid deflection bowls compared to the 2022 data. The resulting correlation matrix shows strong correlation between the seven FWD sensors and the first seven TSD sensors. The correlation between the sensors decreased as the sensor distance from the load center increased.

R^2 Values		TSD Sensor (Location, inches)								
		W1 (0)	W2 (8)	W3 (12)	W4 (18)	W5 (24)	W6 (36)	W7 (48)	W8 (60)	W9 (72)
FWD Sensor (Location, inches)	W1 (0)	0.80	0.72	0.62	0.43	0.28	0.11	0.02	0.00	0.00
	W2 (12)	0.75	0.74	0.67	0.52	0.36	0.17	0.05	0.01	0.00
	W3 (24)	0.56	0.66	0.71	0.69	0.61	0.43	0.26	0.16	0.09
	W4 (36)	0.32	0.47	0.56	0.65	0.66	0.56	0.43	0.33	0.23
	W5 (48)	0.21	0.34	0.45	0.57	0.62	0.60	0.51	0.43	0.33
	W6 (60)	0.16	0.28	0.38	0.51	0.57	0.57	0.52	0.45	0.37
	W7 (72)	0.17	0.29	0.38	0.50	0.57	0.58	0.53	0.46	0.39

Figure 21. Final FWD and TSD Data Correlation Matrix.

CHAPTER 5. APPLICATION OF THE HAWKEYE SYSTEM TO SELECT REHABILITATION FUNDING LEVELS

This chapter describes how to use the existing Hawkeye system from ARRB Systems to generate appropriate funding level recommendations at the network level for any pavement section based on TSD condition and deflection data. This process includes the generation of filters that assign each pavement section to one of the following four cases and treatments/funding levels:

1. Structurally sound and good distress score (do nothing or perform maintenance if required [i.e., preventative maintenance]).
2. Structurally sound and poor distress score (indicates an upper layer problem, perform a mill/thin overlay if required [i.e., light rehabilitation]).
3. Structurally weak with good distress score (indicates a problem that maintenance may have temporarily covered, investigate and perform medium rehabilitation if required).
4. Structurally weak with poor distress score (perform heavy rehabilitation).

The filter outputs from the Hawkeye system were compared to the decisions currently being made by districts. These filters should be reviewed and modified by district pavement engineers to meet their local conditions and different pavement types.

TREATMENT FUNDING LEVELS DEFINED BY TXDOT

At the network level, TxDOT defines the following four categories of treatments/funding levels:

1. *Preventative maintenance* (PM) is used to reduce the rate of deterioration and retard failures of pavements still in good condition, extending their service life. Structural capacity is not increased, and low severity non-load related distresses are corrected.
2. *Light rehabilitation* (LRhb) is mainly composed of nonstructural improvements to address surface distresses related to aging and environmental effects. Structural capacity is not significantly increased, but ride quality is expected to improve.
3. *Medium rehabilitation* (MRhb) is a structural improvement that extends the service life of an existing pavement and increases its load-carrying capacity. Treatments under this category also restore functional characteristics, considerably improving the ride quality.
4. *Heavy rehabilitation* (HRhb) is the partial or complete removal and replacement of the existing pavement structure to restore functional and structural conditions to at least the original state. Treatments under this category are performed on pavement sections with extensive structural distresses.

The TSD data, along with a combination of structural deflection data (primarily max surface deflection) and surface condition data (e.g., cracking, rutting, and roughness) can be used within the Hawkeye system to assist in selecting the appropriate funding level and identifying sections that should be investigated before including them in the four-year plans. Eventually, when the deflection data are incorporated into TxDOT's PA system, the same analysis will be performed within the PA system.

Recall that when a network is tested with the TSD, a range of different pavement thicknesses are included. For flexible pavements, this range extends from low-volume FM roadways with two-course surface treatments to high-volume SH or IH roadways with thick (often 8 to 12 inches) HMA pavements. Clearly, the trigger levels within the filters need to be modified based on the pavement types being evaluated—this work is ongoing. Currently, the Hawkeye system does not include layer thickness data. This omission will be addressed when the TSD data are incorporated into TxDOT's PA system or when the results from GPR surveys are included.

The development of the Query filter is a very innovative feature available within the Hawkeye system. It is activated using the filter button and has both preset and user defined filters. When applied, the areas of the network that meet the distress conditions specified are identified in a graphical map form.

The linkage between the four cases defined in the Hawkeye system and the four treatments/funding levels defined by TxDOT are explored in the remainder of this chapter. For each case, a set of filters that combine distress and deflection measurements was recommended. These filters were compared to the recommendations made by senior TxDOT pavement engineers regarding appropriate maintenance and rehabilitation treatments.

The recommendations presented in this chapter should be considered tentative but represent a good starting point that can be further improved upon with district staff input. The final recommendations will eventually be incorporated into TxDOT's PA system in map form. It is proposed that the TSD data for each district be classified as one of the four cases and that these rankings be provided to district staff as they are reviewing sections for inclusion in their four-year plans. Sections that are structurally weak but visually good will be of particular interest. Such sections may need further evaluation before selecting the optimal strategy.

RECOMMENDED FILTERS FOR CASE 1: GOOD SURFACE CONDITION–STRUCTURALLY STRONG

The recommended filter displayed in Figure 22 for pavements with good surface condition and are structurally strong includes low surface deflections (≤ 20 mils), low rutting (≤ 0.2 in) and cracking (≤ 5 percent), and a smooth surface expressed as the international roughness index (IRI) (≤ 95 in/mile). For roadway sections selected for this category, PM or LRhb treatments are recommended. Other factors such as skid resistance or age of last surface will influence the final funding levels and prioritizations. Figure 23 provides an example roadway section in this classification; consistent with the district's assessment, most of IH 37 in TxDOT's Corpus Christi District falls within this category.

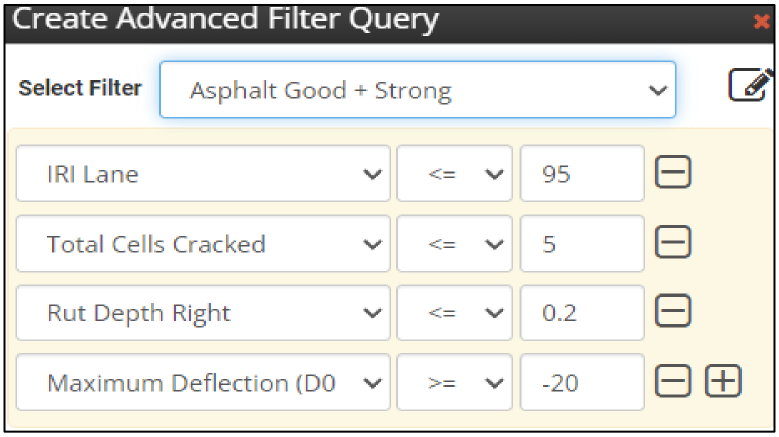


Figure 22. Proposed Filters Combining Deflection and Condition for Case 1.

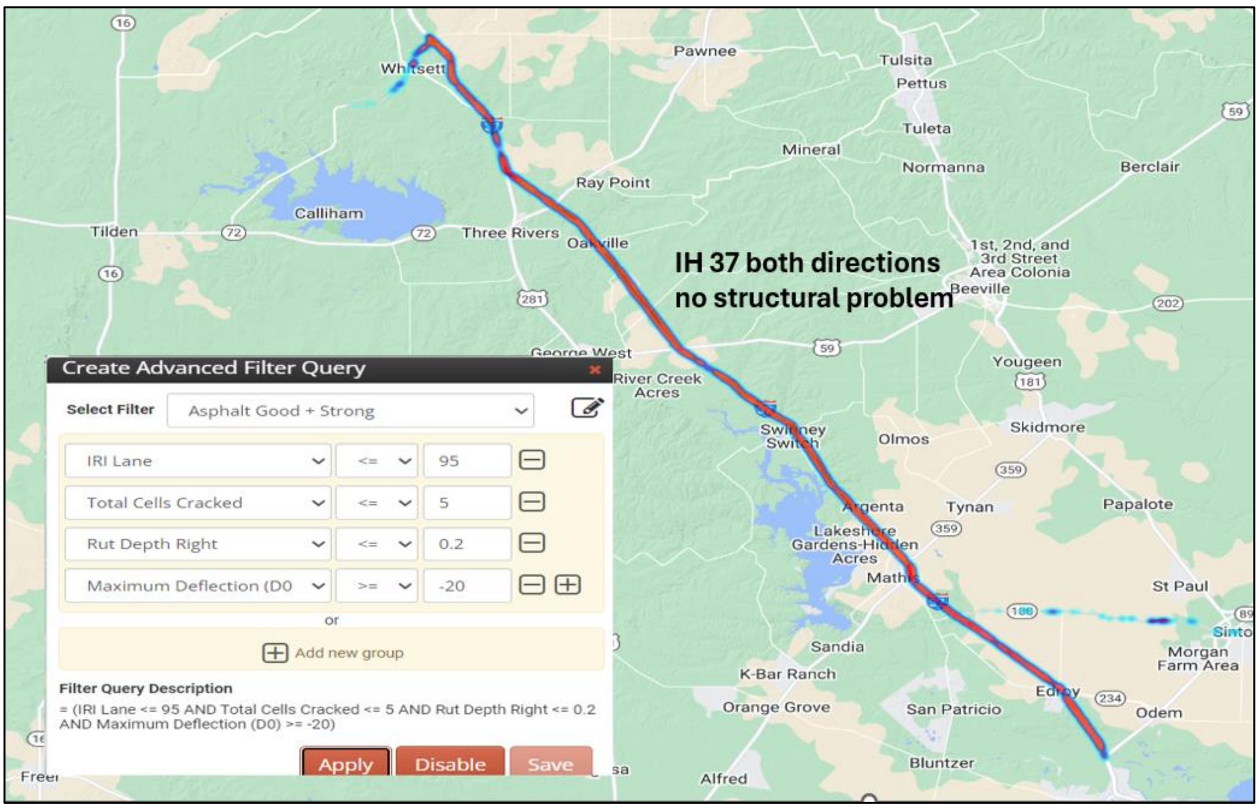


Figure 23. Good Surface Condition–Structurally Strong (Case 1) Example: IH 37 in TxDOT's Corpus Christi District.

RECOMMENDED FILTERS FOR CASE 2: POOR SURFACE CONDITION–STRUCTURALLY STRONG

The recommended filters for case 2 include low surface deflections (≤ 20 mils) and high rutting (≥ 0.41 inch), roughness expressed as IRI (≥ 171 in/mile), or total cells cracked (≥ 20 percent). For case 2 roadway sections, LRhb treatments requiring an overlay with or without milling are primarily recommended. Figure 24 provides an example roadway section in this classification;

for SH 11 in TxDOT’s Atlanta District, HMA was placed over a JCP, resulting in low deflections but reflection crack damage. In this case, the normal treatment will be a mill and placement of a high-performance overlay. Alternative explanations for pavements that fall into this category include HMA placed over a stiff CTB, leading to block surface cracking or HMA placed over another HMA layer without sufficient bonding (debonding).

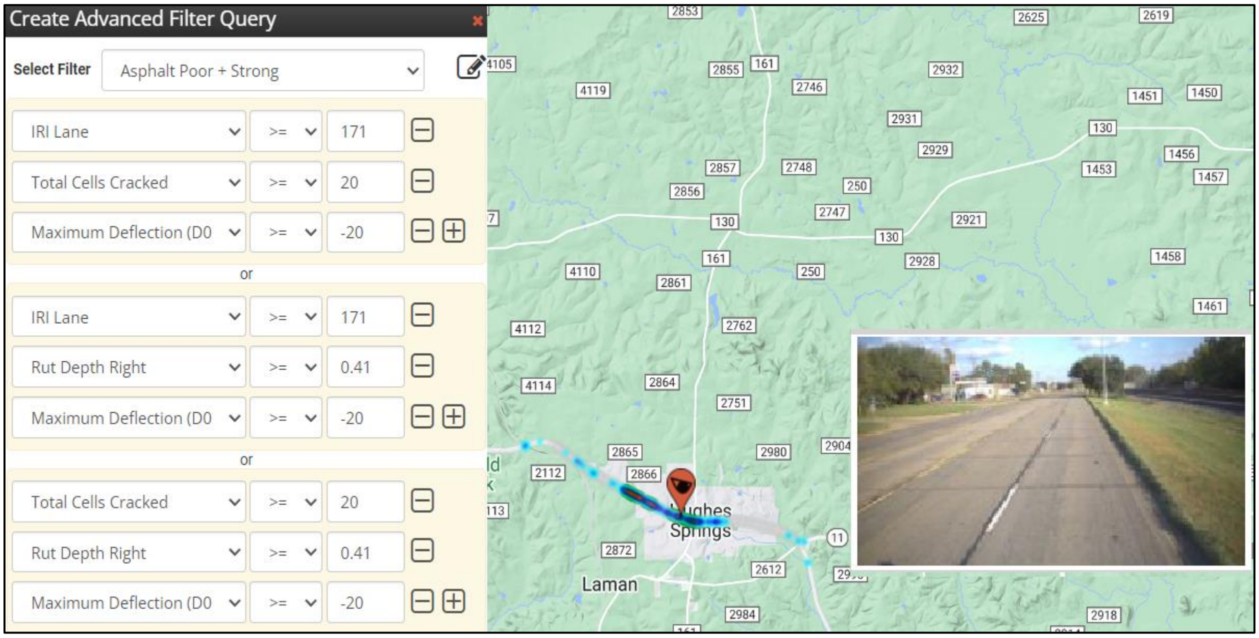


Figure 24. Poor Surface Condition–Structurally Strong (Case 2) Example: SH 11 in TxDOT’s Atlanta District.

RECOMMENDED FILTERS FOR CASE 3: GOOD SURFACE CONDITION–STRUCTURALLY WEAK

Case 3 is fairly common among Texas roadways; TxDOT’s active maintenance program temporarily improves the pavement condition, but the structural condition remains weak. The recommended filters for case 3 include high surface deflections (> 30 mils), but all other condition criteria are good, including cracking (< 5 percent), rut depth (< 0.2 inches), and IRI (< 95). For case 3 roadway sections, MRhb or HRhb treatments are mostly recommended. Figure 25 provides four example sections in TxDOT’s Atlanta District that meet these criteria.

To convert the extensive TSD data into useful information, it is proposed that a list of all case 3 sections including their limits, global positioning system (GPS) coordinates, and lengths be generated and provided to the district staff (Table 6). Existing deflections and distresses for each section will be separately provided; Figure 26 shows the important distress types for SH 11. This report should spur project-level assessments that include at least a GPR survey and potentially field cores. The purpose of the field investigation is to estimate the remaining life for the sections, to determine if and when to include them in the four-year plans, and, given their weak structural classification, to identify required strategies for developing a long lasting pavement.

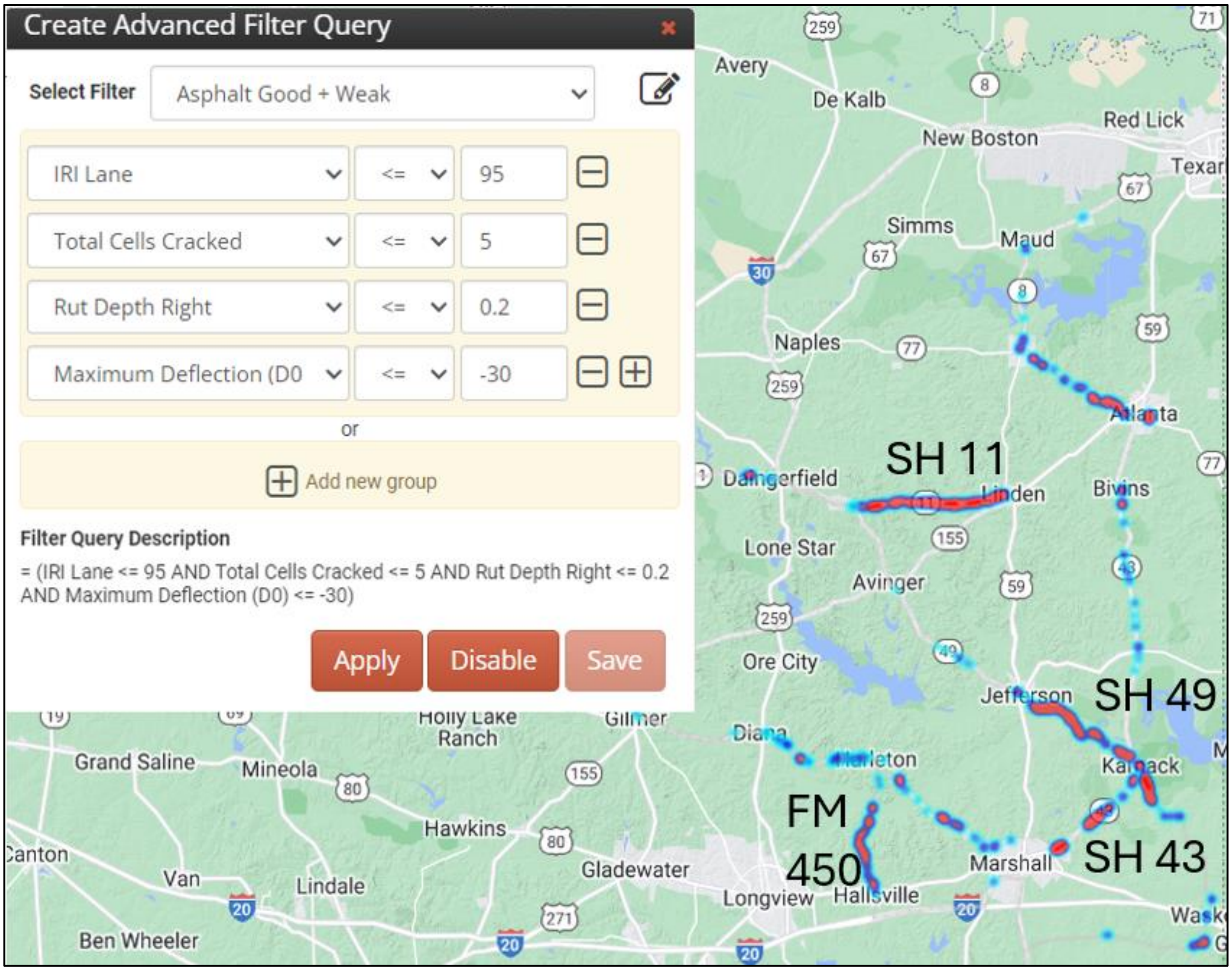


Figure 25. Good Surface Condition–Structurally Weak (Case 3) Example: Various Sections in TxDOT's Atlanta District.

Table 6. Example Report for Good Surface Condition–Structurally Weak (Case 3) Sections in TxDOT's Atlanta District.

	Roadway	Limits	GPS Coordinates	Length (miles)	Comment
1	SH 11	CR 2920 to Linden	33.00171–94.52944 33.01123–94.37772	8.4	Very high deflection (> 40 mils), recent seal–no cracking, good ride
2	SH 49	Jefferson to Kanack			
3	SH 43				
4	FM 450				

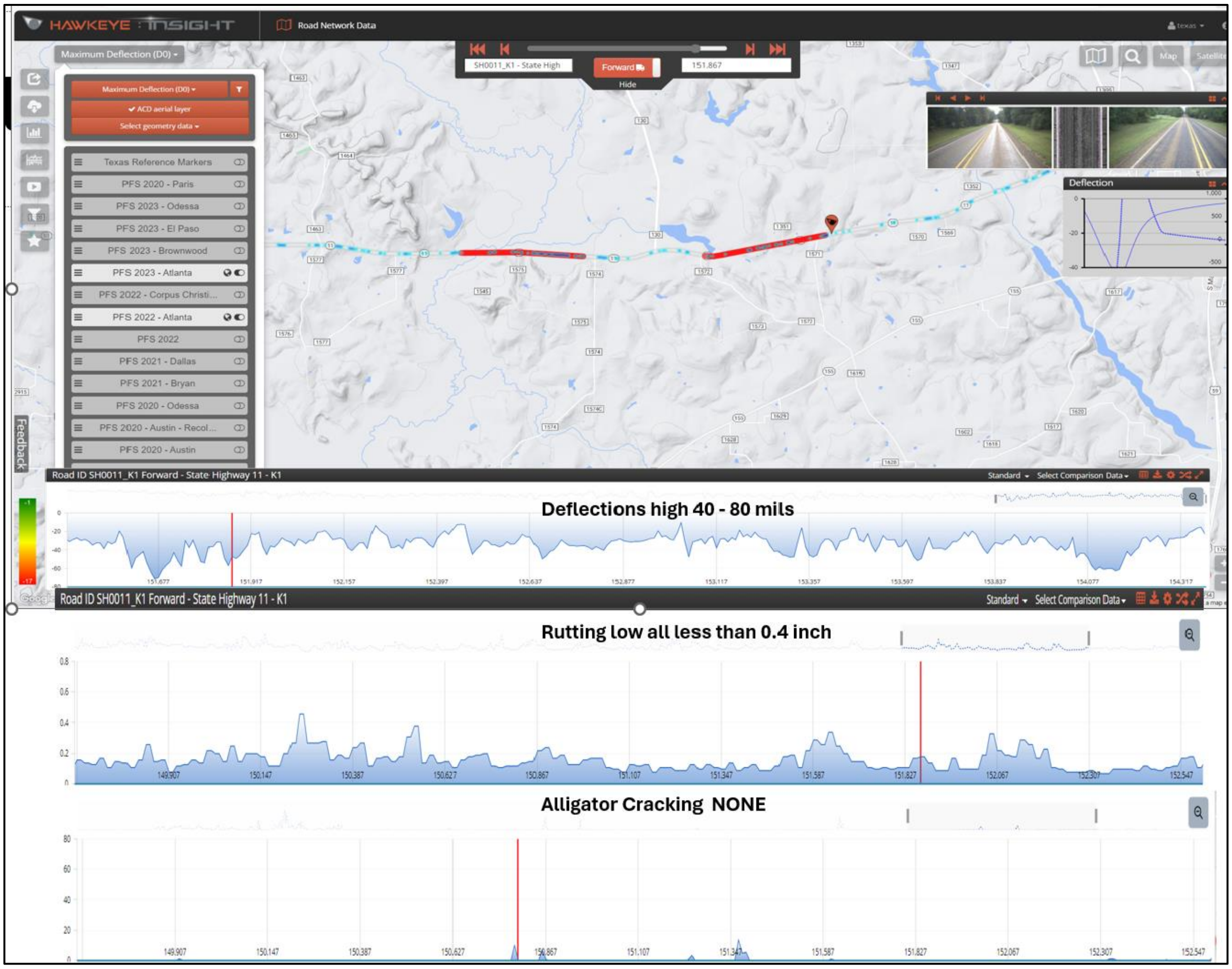


Figure 26. Example Condition Report for Good Surface Condition–Structurally Weak (Case 3) Sections in TxDOT's Atlanta District.

For the high deflection section on SH 11, a review of the TSD values relating to subgrade strength was performed and the SCI Subgrade parameter was found to be > 4 mils in many places. A GPR survey was also completed; Figure 27 shows the typical GPR output and a photo of the project. The high deflections on SH 11 were attributed to the following conditions:

- The HMA thickness is thin (< 3 inches in many places).
- Stripping is present in the HMA layer.
- The subgrade for the section is weak.

The good condition reported in the TSD data was attributable to the quality seal coat placed on the project. For this section of SH 11, MRhb or HRhb treatments are recommended, but the remaining life must first be determined.

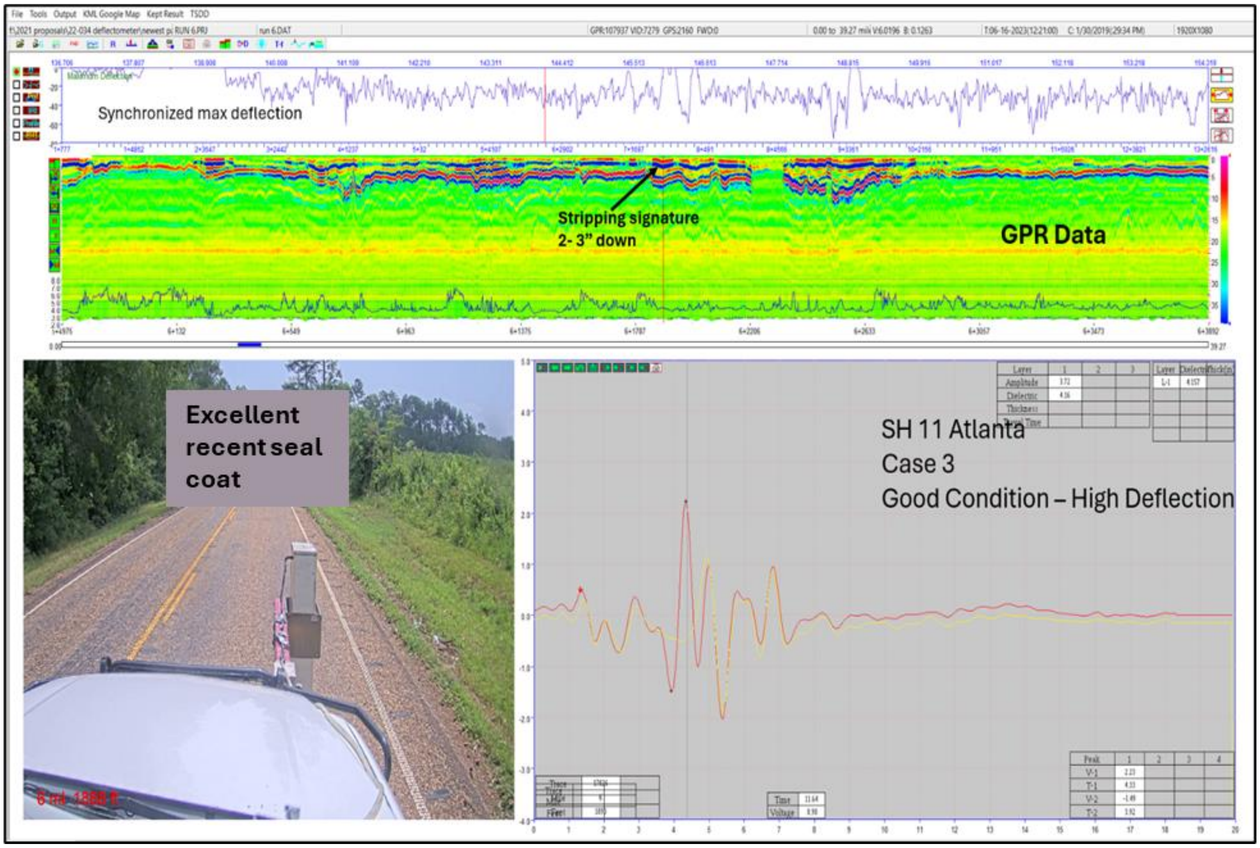


Figure 27. GPR Output for the High-Deflection Section on SH 11 in TxDOT's Atlanta District.

RECOMMENDED FILTERS FOR CASE 4: POOR SURFACE CONDITION–STRUCTURALLY WEAK

The recommended filters for case 4 include high surface deflections (> 20 mils) and poor surface conditions, including total cells cracked (> 20 percent), IRI (> 171), and rut depth (> 0.41 inches). For roadway sections that fall into this category, MRhb to HRhb treatments are recommended; however, a full structural evaluation with additional nondestructive testing and field coring and auguring is required to select the optimum rehabilitation strategy. A report similar to that shown in Table 6 should be generated and provided to the district pavement engineer for all case 4 sections.

Figure 28 and Figure 29 show example roadway sections that fall into this category in TxDOT's Corpus Christi and Atlanta Districts, respectively. District staff were aware of the poor condition of the IH 37 frontage road, and one segment has already been reconstructed using full-depth reclamation (FDR). Based on the TSD data collected on FM 99 as part of this project, a full forensics investigation was requested (described later in this report).

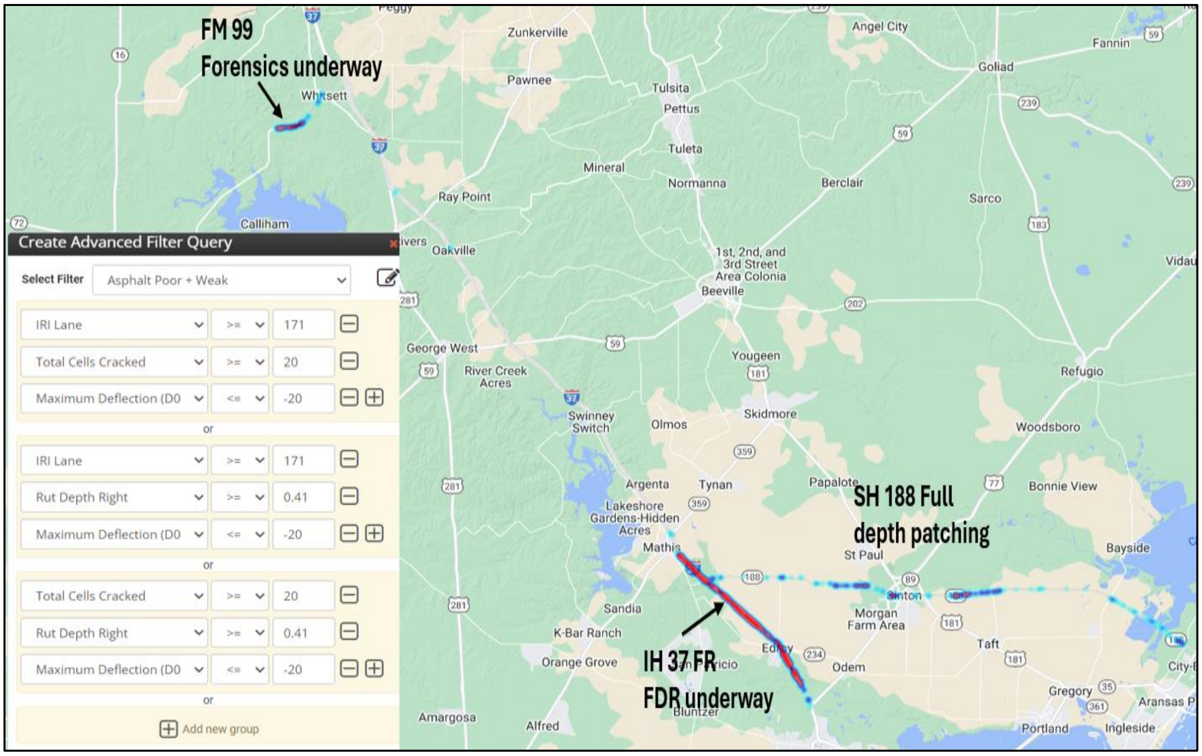


Figure 28. Poor Surface Conditions–Structurally Weak (Case 4) Example: Various Sections in TxDOT's Corpus Christi District.

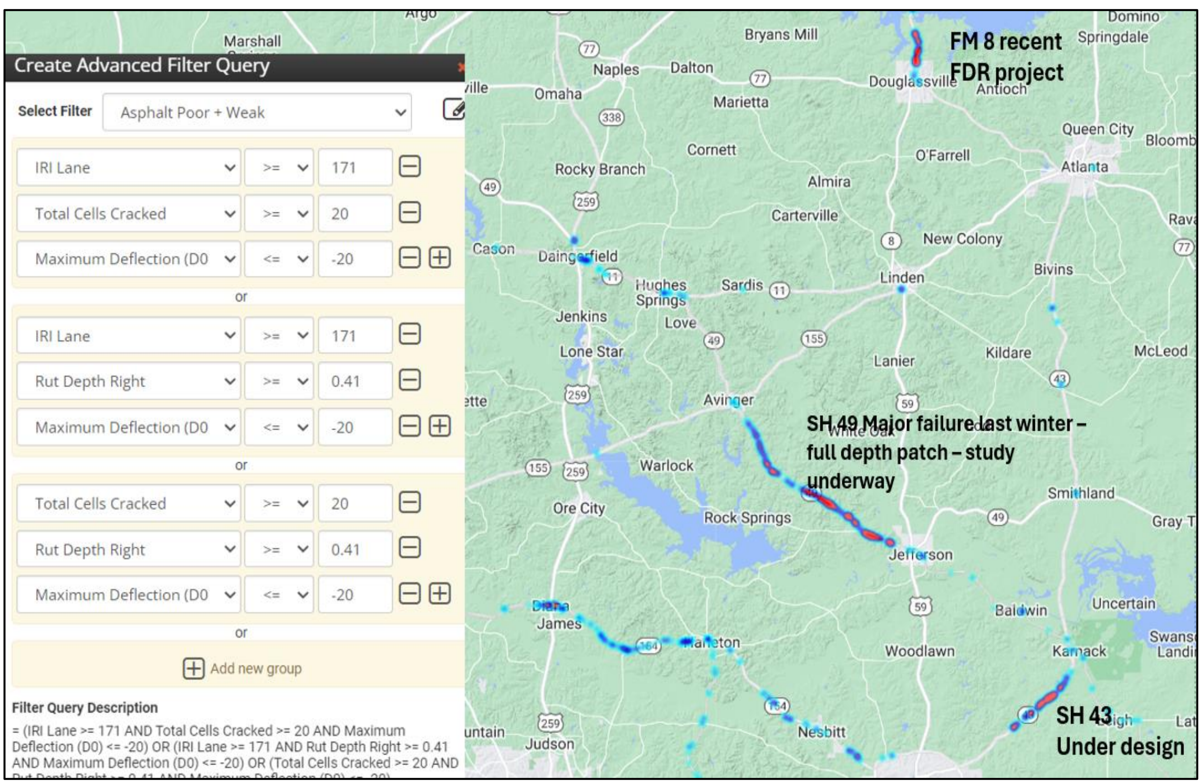


Figure 29. Poor Surface Conditions–Structurally Weak (Case 4) Example: Various Sections in TxDOT's Atlanta District.

Case 4 roadway sections require a full project-level evaluation. The data provided in the ARRB System's Hawkeye system can be used to define project limits; Figure 30 provides an example Hawkeye system screenshot showing the limits for a section on SH 43 in TxDOT's Atlanta District.

Figure 31 shows the case 4 sections requiring full reconstruction on FM 39 in TxDOT's Bryan District. This assessment matches the district's current work plan. The section from Normangee to North Zulch is currently being reconstructed as part of an FDR project. The northern and southern sections are currently under evaluation.

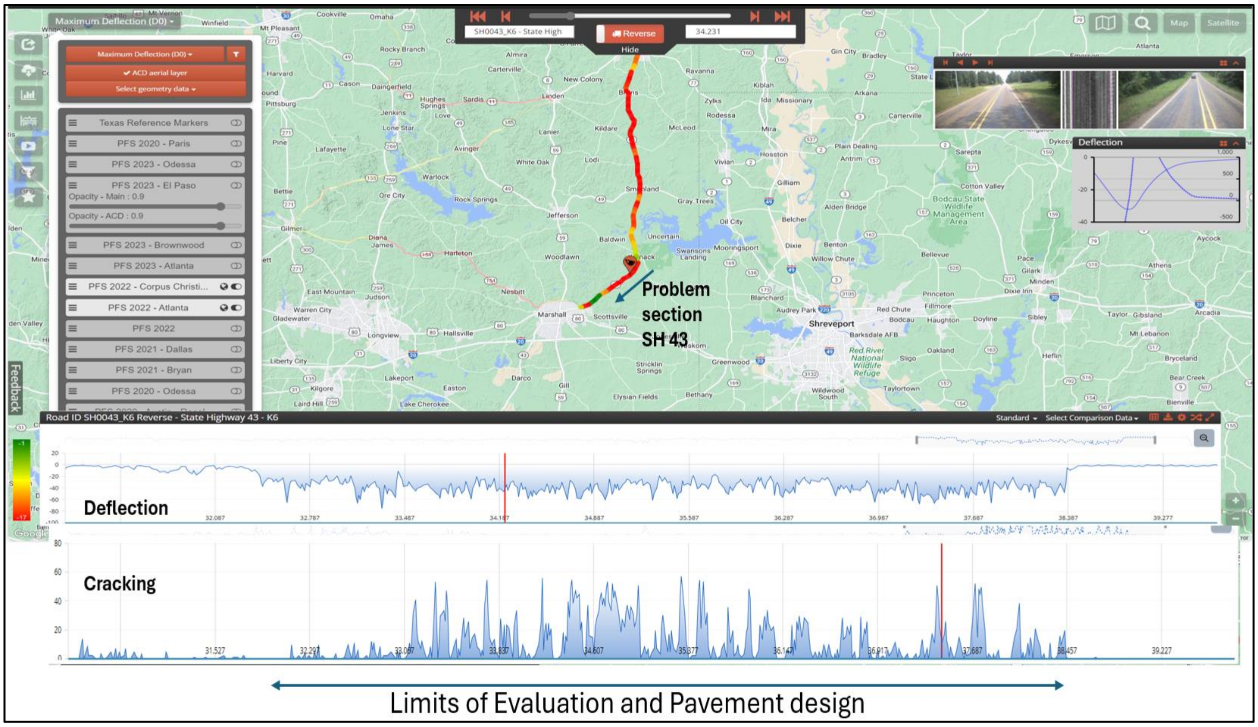


Figure 30. Example Hawkeye System Screenshot Showing Limits of Case 4 Section in TxDOT's Atlanta District.

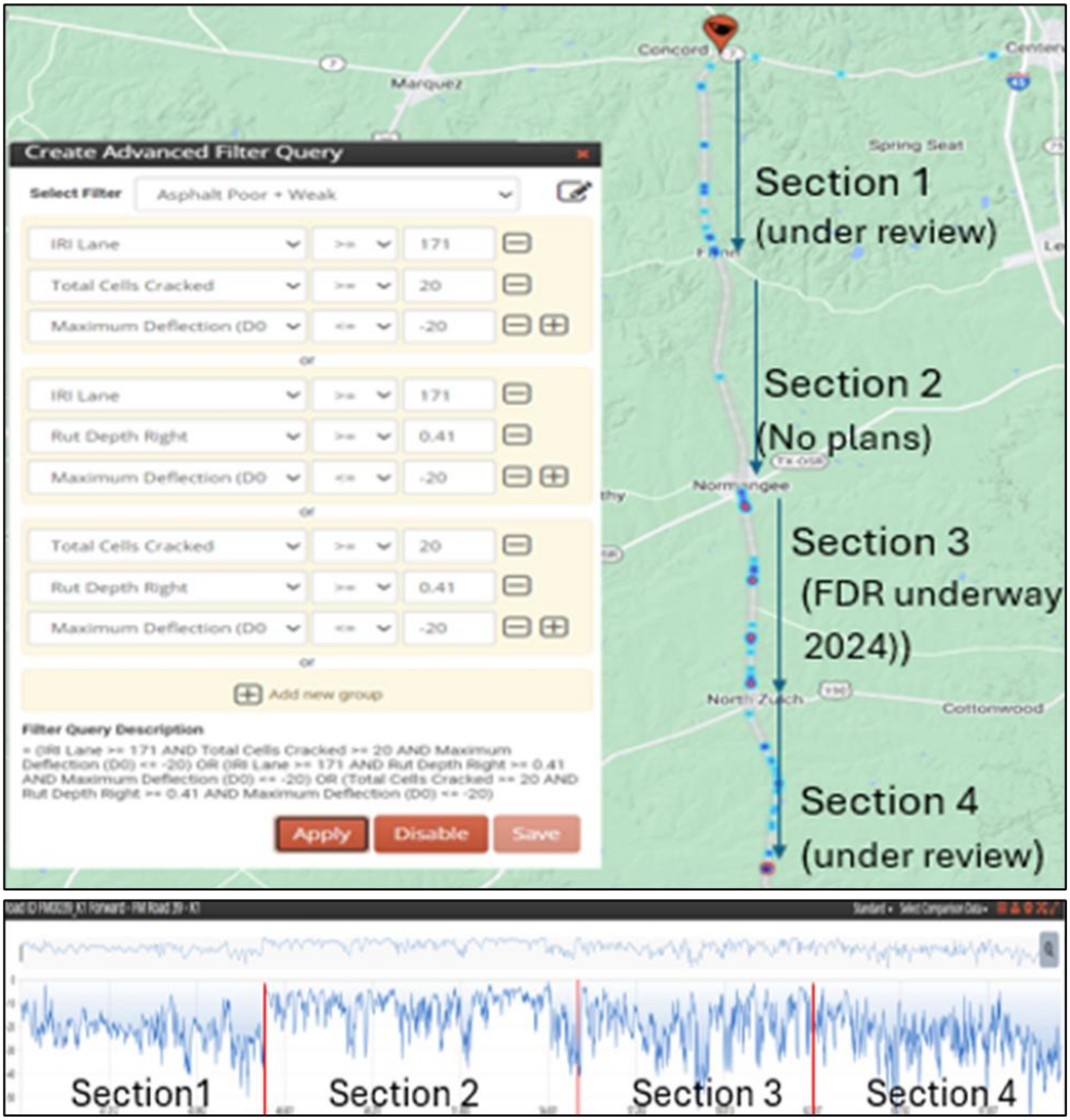


Figure 31. Case 4 Sections Identified on FM 39 in TxDOT's Bryan District with Maximum Deflection Plots.

CHAPTER 6. APPLICATION OF TXDOT'S PA SYSTEM FOR NETWORK-LEVEL ANALYSES

The TSD data being collected is currently being incorporated into TxDOT's PA system. This chapter describes efforts to develop a structural strength index (SSI) that ranges from 0 to 100 with 100 being structurally strong and to develop a remaining life estimation procedure that can be applied at the network level based on the TSD deflection data

INCORPORATION OF TSD DATA INTO TXDOT'S PA SYSTEM FOR NETWORK-LEVEL ANALYSIS

Three methods were previously identified for incorporating the TSD structural strength data into TxDOT's PA system at the network level to assist district staff in prioritizing upcoming projects and selecting optimal treatments/funding levels. Table 7 lists the strengths and weaknesses of each method and indicates the current level of implementation for each. The SN_{eff}/SN_{req} method has already been developed and implemented within the PA system. Recommendations for developing SSI and remaining life estimates based on TSD deflection data are described later in this chapter.

Table 7. Methods for Incorporating TSD Structural Strength Data into TxDOT's PA System.

Method	Strengths	Weaknesses
SN_{eff}/SN_{req}	• Already implemented in the PA system by TxDOT's Maintenance Division—no further development is needed. • Includes a subgrade modulus estimated using American Association of State Highway and Transportation Officials' method. • Uses the PA system's 18-kip ESAL estimates. • Similar systems are under development in other agencies.	• Requires total pavement thickness, which is often not available and can be variable. • Current method of obtaining thickness is based on the PA system's 18-kip ESAL estimates, which have been found to be inaccurate. • Structural numbers are not used or understood by TxDOT designers.
Modify current SSI estimation procedure for TSD data	• Modifies SSI estimates based on FWD deflection bowl parameters (SCI and W7). • Relies on the PA system's existing pavement type classifications. • Supports use of TSD deflection data, which will be combined with existing pavement condition scores to identify required rehabilitation category.	• Linkage between strength index and treatment level needs to be defined. • First generation from TxDOT Project 0-7107 needs to be pilot tested.
Develop remaining life estimation procedure for TSD data	• Remaining life and layer strength classification is already implemented in TxDOT's Flexible Pavement Design System at the project-level and is widely used and understood by TxDOT's pavement designers. • Pilot tested in TxDOT Project 0-7107 but needs further evaluation.	• Needs to be pilot tested using PA system data for further evaluation. • Requires 18-kip ESAL estimates, which are thought to be inaccurate at the network level.

Pavement Thicknesses

One issue that needs to be addressed is the lack of pavement type and pavement thickness information within TxDOT's PA system. Recent efforts focused on the use of traffic data within the PA system have found that traffic estimates using network-level traffic data are substantially less than traffic estimates at the project-level. Table 8 notes the discrepancies in various traffic estimates—including average daily traffic (ADT), percent trucks, and 18-kip ESALs—from TxDOT's PA system and from TxDOT's Transportation Planning and Programming (TPP) Division for FM 39 and SH 47 in the Bryan District.

Regarding pavement type, use of the PA system's pavement classification codes may provide the most accurate method for identifying existing pavement types (Figure 32). TxDOT should ensure that these categories are current.

These same pavement classification codes can be used to determine pavement thicknesses. Recent studies have shown that the thicknesses determined using the pavement classification codes in Figure 32 are substantially better than estimates based on network-level 18-kip ESAL traffic. These estimates are judged to be the best available pavement layer data within the PA system; this information is critical in providing the basis for developing meaningful repair recommendations. If HMA thickness is a required input to the system, then the thickness at the top of the allowable range should be used (i.e., for pavement type 05, use 5.5 inches and for pavement type 04, use 8 inches).

Table 8. Traffic Estimation Discrepancies Between PA and TPP.

Highway	ADT 2023–2043	Percent Trucks	20-year 18-kip ESALs from TPP (million ESALs)	18-kip ESALs in PA System (million ESALs)	Difference Factor
FM 39	1,928–2,699	10.5%	1.1 M	0.42 M	2.6
SH 47	8,744–12,242	7.5%	3.55 M	1.04 M	3.4

Codes	Description
01	Continuously Reinforced Concrete Pavement
02	Jointed Reinforced Concrete Pavement
03	Jointed Plain Concrete Pavement
04	Thick Asphaltice Concrete Pavement (greater than 5-1/2")
05	Intermediate Thickness Asphaltic Concrete Pavement (2-1/2" to 5-1/2")
06	Thin Surfaced Flexible Base Pavement (less than 2-1/2")
07	Asphalt Surfaceing with Heavily Stabilized Base
08	Overlaid and/or Widened Old Concrete Pavement
09	Overlaid and/or Widened Old Flexible Pavement
10	Thin Surface Flexible Base Pavement (Surface Treatment-Seal Coat Combination)

Figure 32. Pavement Classification Codes in TxDOT's PA System.

Traffic Levels

To implement network-level decision tools, it is also appropriate to provide low, medium, and high categories for traffic and ride and quality levels. Table 9 lists the traffic level definitions for asphalt, jointed concrete, and continuously reinforced concrete pavements. Three levels of traffic were defined for asphalt pavements; two levels of traffic were defined for JCP and CRCP.

Table 9. Traffic Level Definitions for Asphalt and Concrete Pavements.

Pavement	Traffic Level	ADT/Lane
Asphalt	Low	< 1,000
	Medium	1,000–5,000
	High	> 5,000
JCP	Low	< 7,500
	High	≥ 7,500
CRCP	Low	< 7,500
	High	≥ 7,500

Ride Quality Levels

Table 10 lists the ride quality level definitions for asphalt pavements based on the ride score (RS) and IRI.

Table 10. Ride Quality Level Definitions for Asphalt Pavements.

Pavement	Ride Quality Index		Ride Quality Level
	RS	**IRI (inches/mile)**	
Pavement Types 04, 05, 07, and 08	< 3.0	> 141	Low
	3.0 ≤ RS ≤ 3.5	109 < IRI ≤ 141	Medium
	> 3.5	≤ 109	High
Pavement Types 06, 09, and 10	**Ride Quality Index**		**Ride Quality Level**
	RS	**IRI (inches/mile)**	
	< 2.5	> 178	Low
	2.5 ≤ RS ≤ 3.0	141 < IRI ≤ 178	Medium
	> 3.0	≤ 141	High

DEVELOPMENT OF AN SSI BASED ON TSD DATA

To make use of the TSD deflection data at the network level within TxDOT's PA system, the measured TSD deflections—corrected for temperature[1]—are being incorporated into the PA system allowing for both the pavement strength and the pavement condition index to be used to select a pavement maintenance and rehabilitation treatment category. One challenge in this effort is that the TSD deflection data are reported in intervals of 50 feet, while the PA system has a basic length unit of 0.5 mile. Therefore, every half-mile section in the PA system correlates to

[1] The temperature correction scheme described in slide 27 of TxDOT Implementation of Structural Strength Data for Network-Level Pavement Management 10-14-2020 presentation looks very reasonable, where no corrections are recommended for thin pavements.

10 sets of TSD deflection data. Both the mean deflection bowl and a deflection category will eventually be incorporated into TxDOT's PA system.

Table 11, Table 12, and Table 13 list the proposed SSI based on TSD deflection parameters for pavement types 04, 05, 07, and 08; pavement types 06 and 09; and pavement type 10; respectively. The SSI ranges from 10 to 100 with 100 being very strong.

It is assumed that the TSD deflection one standard deviation above the mean (or maximum for the 0.5-mile section) will be used. This assumption is tentative; final decisions regarding which parameters to include in the PA system are pending.

The SSI is based on two deflection indices calculated from the TSD: W36−W60 and W0−W8. These indices are calculated by taking the difference between reported deflections from the TSD sensor located 36 and 60 inches from the load, and 0 and 8 inches from the load, respectively. The criteria for TSD W36–W60 are based on a regression analysis discussed later in this report generated using FWD and TSD deflection data collected on FM 99 that related the backcalculated subgrade modulus to raw TSD deflection data. This preliminary equation relating the subgrade modulus to the TSD deflection data appears to be reasonable; for a weak subgrade, $E < 10$ ksi and for a strong subgrade, $E > 16$ ksi.

Table 14 identifies the proposed level of treatment for flexible pavements based on TxDOT's PA system condition scores and the TSD-based SSIs. Note that the load vs. no load associated distress calculation has been replaced with the SSI.

Table 11. Proposed SSI for Pavement Types 04, 05, 07, and 08.

Subgrade Modulus (ksi) = 22.3 – 3.7 × (W36–W60)		
TSD W36–W60 Subgrade Support (mils)	**TSD W0–W8 SCI (mils)**	**SSI**
< 1.7	< 10	100
	10–15.9	80
	16–20.9	60
	21–25.9	40
	26–30	30
	>30	20
1.7–3.5	< 10	90
	10–15.9	70
	16–20.9	50
	21–25.9	35
	26–30	25
	>30	15
> 3.5	< 10	80
	10–15.9	55
	16–20.9	40
	21–25.9	30
	26–30	20
	>30	10

Table 12. Proposed SSI for Pavement Types 06 and 09.

Subgrade Modulus (ksi) = 22.3 – 3.7 × (W36–W60)		
TSD W36–W60 Subgrade Support (mils)	**TSD W0–W8 SCI (mils)**	**SSI (mils)**
< 1.7	< 15	100
	15–20.9	80
	21–25.9	60
	26–30.9	40
	31–35	30
	> 35	20
1.7–3.5	< 15	90
	15–20.9	70
	21–25.9	50
	26–30.9	35
	31–35	25
	> 35	15
> 3.5	< 15	80
	15–20.9	55
	21–25.9	40
	26–30.9	30
	31–35	20
	> 35	10

Table 13. Proposed SSI for Pavement Type 10.

Subgrade Modulus (ksi) = 22.3 – 3.7 × (W36–W60)		
TSD W36–W60 Subgrade Support (mils)	**TSD W0–W8 SCI (mils)**	**SSI**
< 1.7	< 20	100
	20–25.9	80
	26–30.9	60
	31–35.9	40
	36–40	30
	> 40	20
1.7–3.5	< 20	90
	20–25.9	70
	26–30.9	50
	31–35.9	35
	36–40	25
	> 40	15
> 3.5	< 20	80
	20–25.9	55
	26–30.9	40
	31–35.9	30
	36–40	20
	> 40	10

Table 14. Treatment Levels for Flexible Pavements Based on TxDOT's PA System Condition Scores and the TSD-based SSI.

PA System Condition Score	TSD-based SSI	Ride	PM	LRhb	MRhb	HRhb	Do Nothing
85–100	< 60%	L		X*			
		M	X	X			
		H	X				
	> 60%	L		X*			
		M	X				X
		H					X
60–84	< 60%	L				X	
		M			X	X	
		H		X			
	> 60%	L			X		
		M		X	X		
		H	X	X			
< 60	< 60%	L			X	X	
		M			X	X	
		H		X		X	
	> 60%	L		X			
		M		X			
		H	X	X			

*Must identify the cause of low ride quality; could be a poor/swelling subgrade issue.

DEVELOPMENT OF A REMAINING LIFE ESTIMATION PROCEDURE BASED ON TSD DATA

To further examine the data collected using TSD and compare it to FWD, the remaining life of a pavement was calculated using both data sources and existing procedures. Because the pavement structures and material strengths were known with a high level of certainty, the test sections identified on SH 47 in TxDOT's Bryan District were used for this evaluation. This section describes the remaining life evaluation inputs, procedure, and results generated from the FWD and TSD data for these test sections.

Pavement Conditions

TxDOT has implemented a remaining life classification scheme to support project selection and funding allocation decisions. The remaining life classification function within the MODULUS software requires several pavement, environmental, and condition metrics as inputs, including surface thickness, average rut depth, alligator cracking, and 20-year 18-kip ESALs (Figure 33).

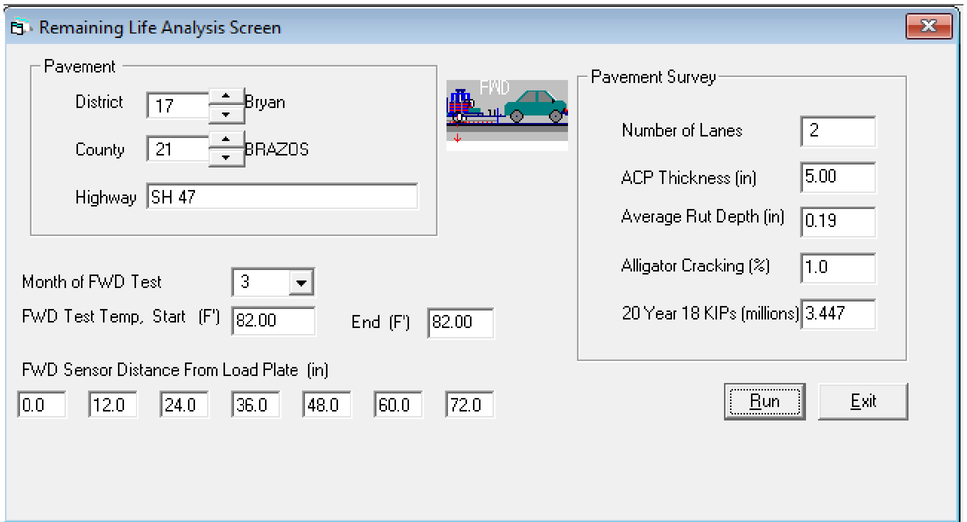


Figure 33. Screenshot of the MODULUS Software's Remaining Life Input Screen.

Table 15 displays the pavement information used to calculate remaining life estimates for each test section on SH 47. The surface thickness was measured using GPR, the rutting and cracking values were taken from the PA system's condition survey, and the traffic estimates were calculated using the daily traffic and percent truck values from TxDOT's TPP Division.

Table 15. SH 47 Test Section Condition Data.

Section	Surface Thickness (inches)	Average Rut Depth (inches)	Cracking (%)	20-year 18-kip ESALs (million ESALs)
NB1	2.2	0.13	3.3	3.447
NB2	5.4	0.15	2.37	9.912
NB3	7.6	0.15	0.25	9.912
NB4	5.7	0.15	0.25	9.912
SB1	7.5	0.11	0.75	9.912
SB2	2.8	0.17	1.5	9.912
SB3	2.5	0.17	1.5	9.912
SB4	5.5	0.19	1.0	3.447
SB5	5.0	0.19	1.0	3.447

Deflections

The MODULUS software requires a .fwd file to read the measured deflections into the program. For FWD testing, deflections are measured every 12 inches from the center of the load up to 72 inches away from the load for a total of seven data points for each deflection bowl. To calculate remaining life, the MODULUS software uses the deflection values from the W1, W2, and W7 sensors. For TSD testing, two additional sensors are positioned 8 and 18 inches away from the load center. Because of this discrepancy, five test cases were developed to compare the remaining life outputs based on the FWD and TSD data (Table 16). Case (a) reflects the output from the FWD sensors. Case (b) mirrors the strong correlation between the TSD and FWD 2022 deflection data. Case (c) uses equivalent sensor spacing as FWD. Cases (d) and (e) adjust the outer sensor spacing, which influences the rut remaining life.

Table 16. FWD and TSD Deflection Sensor Configurations for Remaining Life Analysis.

Data Source	Case	Sensor Distance from Load Center		
FWD	(a)	0	12	72
TSD	(b)	0	8	48
	(c)	0	12	72
	(d)	0	12	48
	(e)	0	12	36

RESULTS AND DISCUSSION

Figure 34 provides an example of the remaining life output from the MODULUS software, which contains roadway and testing information as well as estimated pavement layer strength classifications and remaining life. The remaining life is divided into two categories: cracking and rutting. This section describes the results for the layer strength classifications, followed by the results for the cracking and rutting remaining life categories.

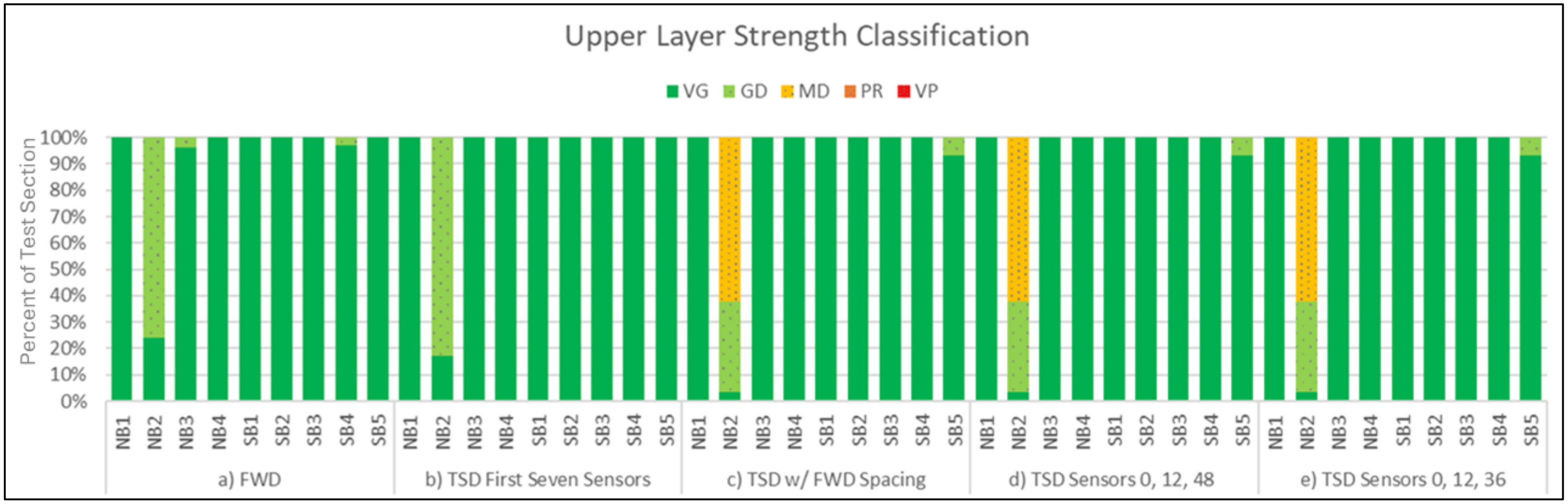
```
                              ****************
                              * R E L A P S *
                              ****************

         TTI FLEXIBLE PAVEMENT DEFLECTION BASIN ANALYSIS PROGRAM

-------------------------------------------------------------------------------
  FWD TESTED FILE NAME :
-------------------------------------------------------------------------------
  DISTRICT              :    17--Bryan              ASPH. THICKNESS  :  2.20
  COUNTY                :    21--BRAZOS             MONTH TESTED     :  FEB
  HIGHWAY               :    SH                     DESIGN LOAD (lbs):  9000
  TEMPERATURE("F) start:     82.0 End:  82.0        20 year 18 KIP(m):     3.45
  AVERAGE RUT DEPTH(in):      0.1                   LANES            :    2
  ALLIGATOR CRACKING   :      3.3 %                 SENSORS: 0 12 24 36 48 60 72
-------------------------------------------------------------------------------
                                                  ASPH DESIGN   LAYER     REMAINING
         ** NORMALIZED DEFLECTION (mils) **  TEMP  SCI   STRENGTHS  LIFE (yrs)
   STATION    W1      W2      W3      W4      W7  DEF F  MILS UPR LWR SGR  RUT    CRK
-------------------------------------------------------------------------------
     0.000   6.19    4.99    3.86    3.07    1.43  82.0  1.20  VG  VG  MD  10+    10+
    50.000   6.89    5.76    4.29    3.20    1.43  82.0  1.12  VG  VG  MD  10+    10+
   102.000   5.87    5.11    3.64    2.76    1.28  82.0  0.76  VG  VG  GD  10+    10+
   149.000   5.25    4.21    3.21    2.53    1.19  82.0  1.04  VG  VG  GD  10+    10+
   199.000   7.13    5.91    4.40    3.21    1.30  82.0  1.21  VG  VG  GD  10+    10+
   250.000   6.78    5.64    4.14    3.10    1.39  82.0  1.13  VG  VG  GD  10+    10+
   299.000   5.42    4.77    3.93    3.19    1.57  82.0  0.65  VG  VG  MD  10+    10+
   353.000   8.50    7.15    5.32    3.92    1.59  82.0  1.35  VG  VG  MD  10+    10+
   398.000   8.96    7.60    5.89    4.28    1.79  82.0  1.36  VG  VG  MD  10+    10+
   455.000   9.32    7.97    6.14    4.66    1.95  82.0  1.35  VG  VG  PR  10+    10+
   503.000   6.96    6.07    4.66    3.53    1.48  82.0  0.89  VG  VG  MD  10+    10+
   548.000   7.83    6.08    4.43    3.32    1.41  82.0  1.75  VG  VG  MD  10+    10+
   601.000   7.02    6.08    4.26    3.17    1.38  82.0  0.94  VG  VG  GD  10+    10+
   652.000   6.04    5.03    3.85    2.99    1.36  82.0  1.01  VG  VG  GD  10+    10+
   700.000   5.40    4.48    3.28    2.52    1.18  82.0  0.92  VG  VG  GD  10+    10+
   749.000   6.69    5.63    3.92    2.94    1.34  82.0  1.06  VG  VG  GD  10+    10+
   799.000   7.10    5.82    4.32    3.32    1.54  82.0  1.28  VG  VG  MD  10+    10+
   851.000   7.72    6.12    4.55    3.50    1.61  82.0  1.60  VG  VG  MD  10+    10+
   904.000   6.27    5.49    4.16    3.24    1.52  82.0  0.78  VG  VG  MD  10+    10+
   950.000   5.86    5.01    3.94    3.13    1.53  82.0  0.85  VG  VG  MD  10+    10+
  1003.000   8.42    7.10    5.15    3.77    1.78  82.0  1.32  VG  VG  MD  10+    10+
  1055.000   9.91    7.82    5.57    4.09    1.79  82.0  2.10  VG  VG  MD  10+    10+
  1101.000   7.17    5.97    4.61    3.63    1.75  82.0  1.19  VG  VG  MD  10+    10+
  1150.000   8.76    7.58    5.72    4.39    2.06  82.0  1.18  VG  VG  PR  10+    10+
  1201.000   8.04    6.56    5.01    3.92    1.90  82.0  1.48  VG  VG  PR  10+    10+
  1251.000  12.08    9.96    7.41    5.62    2.40  82.0  2.11  VG  VG  VP  10+    10+
  1301.000   7.59    6.68    5.39    4.35    2.05  82.0  0.91  VG  VG  PR  10+    10+
  1353.000  13.86   11.29    8.13    5.90    2.33  82.0  2.58  VG  VG  VP  10+    10+
  1403.000  10.90    8.95    6.52    4.84    1.95  82.0  1.95  VG  VG  PR  10+    10+
  1449.000   9.04    7.67    5.76    4.35    1.93  82.0  1.37  VG  VG  PR  10+    10+
  1499.000   9.37    7.82    5.57    3.85    1.57  82.0  1.55  VG  VG  MD  10+    10+
  1550.000   6.20    5.18    3.88    2.99    1.43  82.0  1.02  VG  VG  MD  10+    10+
  1601.000   7.77    6.45    4.57    3.38    1.57  82.0  1.33  VG  VG  MD  10+    10+
-------------------------------------------------------------------------------
     MEAN:   7.77    6.48    4.83    3.66    1.63        1.28  VG  VG  MD
  STD DEV:   1.94    1.57    1.13    0.80    0.31        0.43
  COF VAR:  24.98   24.16   23.34   21.97   18.86       33.52
-------------------------------------------------------------------------------
*  0~2:Failed    2~5:Problem    5~10:OK for Now    10+:Good
```

Figure 34. Screenshot of the MODULUS Software's Remaining Life Output.

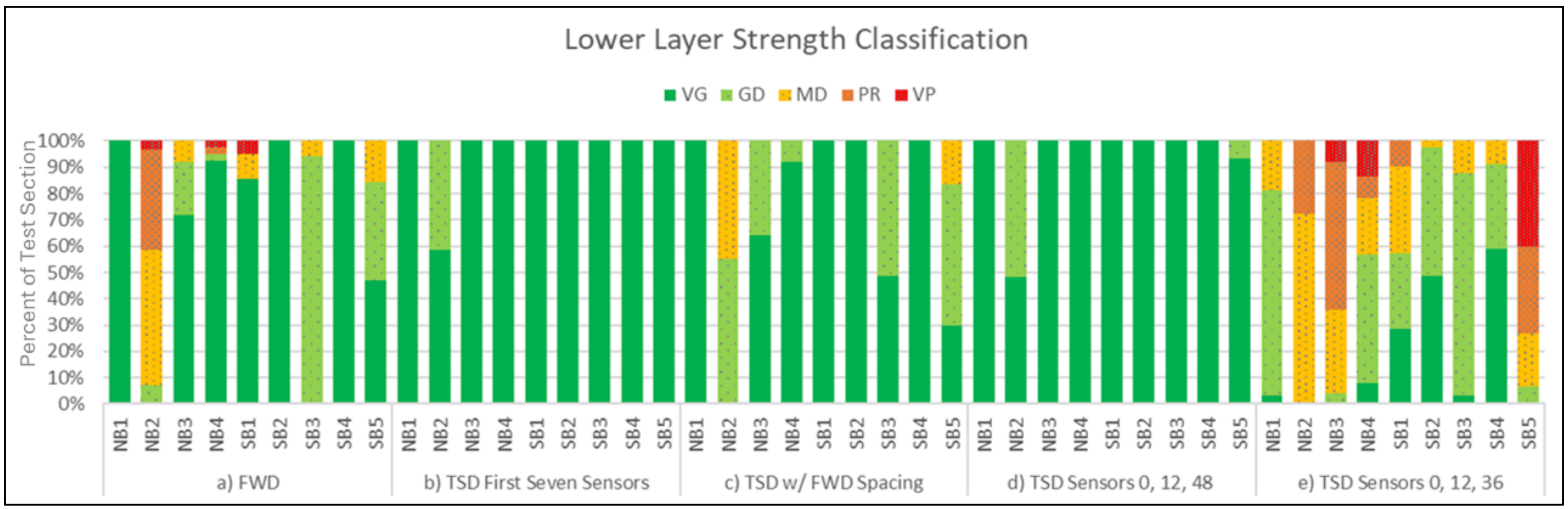
Layer strength is categorized into one of five classifications in accordance with Table 17. Figure 35 (a), (b) and (c) show the upper, lower, and subgrade strength classification results, respectively, for cases (a)–(e). The TSD upper layer classifications agreed well with the classifications reported from the FWD data. Case (b) provided the best fit with the FWD data, while cases (c), (d), and (e) all underestimated the layer strength. This trend was not observed in the lower layer strength classification. Cases (b), (c), and (d) overestimated the layer strength compared to the FWD data, while case (e) underestimated the layer strength. The TSD subgrade layer strength classification results for cases (b), (d), and (e) matched well with the results reported from the FWD data. Case (c) overestimated the subgrade strength compared to the other cases.

Table 17. Layer Strength Classification Criteria in the MODULUS Software Based on a FWD 9,000-pound Load.

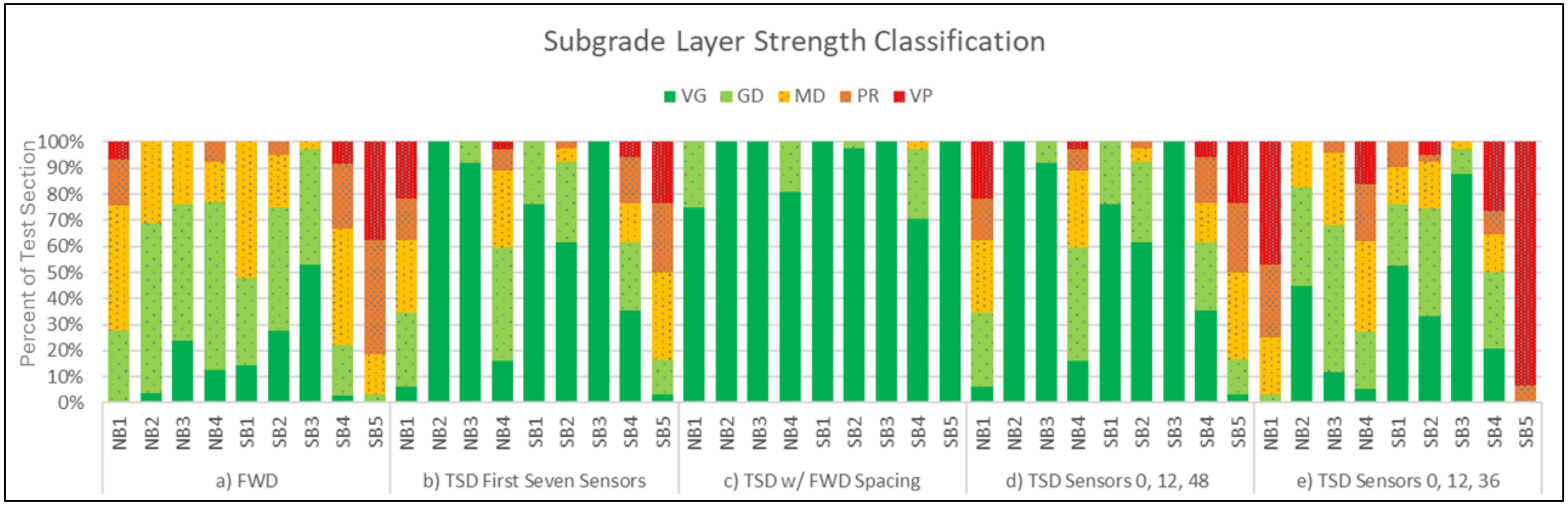
Remaining Life Estimate					
Index	**Condition**	**Asphalt Thickness** > 5 inches (mils)	2.5–5 inches (mils)	1–2.5 inches (mils)	< 1 inch (mils)
SCI (Upper 8 inches)	VG	< 4	< 6	< 12	< 16
	GD	4–6	6–10	12–18	16–24
	MD	6–8	10–15	18–24	14–32
	PR	8–10	15–20	24–30	32–40
	VP	> 10	> 20	> 30	> 40
BCI (8–16 inches)	VG	< 2	< 3	< 4	< 8
	GD	2–3	3–5	4–8	8–12
	MD	3–4	5–9	8–12	12–16
	PR	4–5	8–10	12–16	16–20
	VP	> 5	> 10	> 16	> 20
W7 (48 inches down)	VG	< 1.0	< 1.0	< 1.0	< 1.0
	GD	1.0–1.4	1.0–1.4	1.0–1.4	1.0–1.4
	MD	1.4–1.8	1.4–1.8	1.4–1.8	1.4–1.8
	PR	1.8–2.2	1.8–2.2	1.8–2.2	1.8–2.2
	VP	> 2.2	> 2.2	> 2.2	> 2.2
VG = Very Good, GD = Good, MD = Moderate, PR = Poor, VP = Very Poor					


Upper Layer Strength Classification
VG GD MD PR VP
Percent of Test Section
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NB1 NB2 NB3 NB4 SB1 SB2 SB3 SB4 SB5
a) FWD
b) TSD First Seven Sensors
c) TSD w/ FWD Spacing
d) TSD Sensors 0, 12, 48
e) TSD Sensors 0, 12, 36

(a)


Lower Layer Strength Classification
VG GD MD PR VP
Percent of Test Section
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NB1 NB2 NB3 NB4 SB1 SB2 SB3 SB4 SB5
a) FWD
b) TSD First Seven Sensors
c) TSD w/ FWD Spacing
d) TSD Sensors 0, 12, 48
e) TSD Sensors 0, 12, 36

(b)

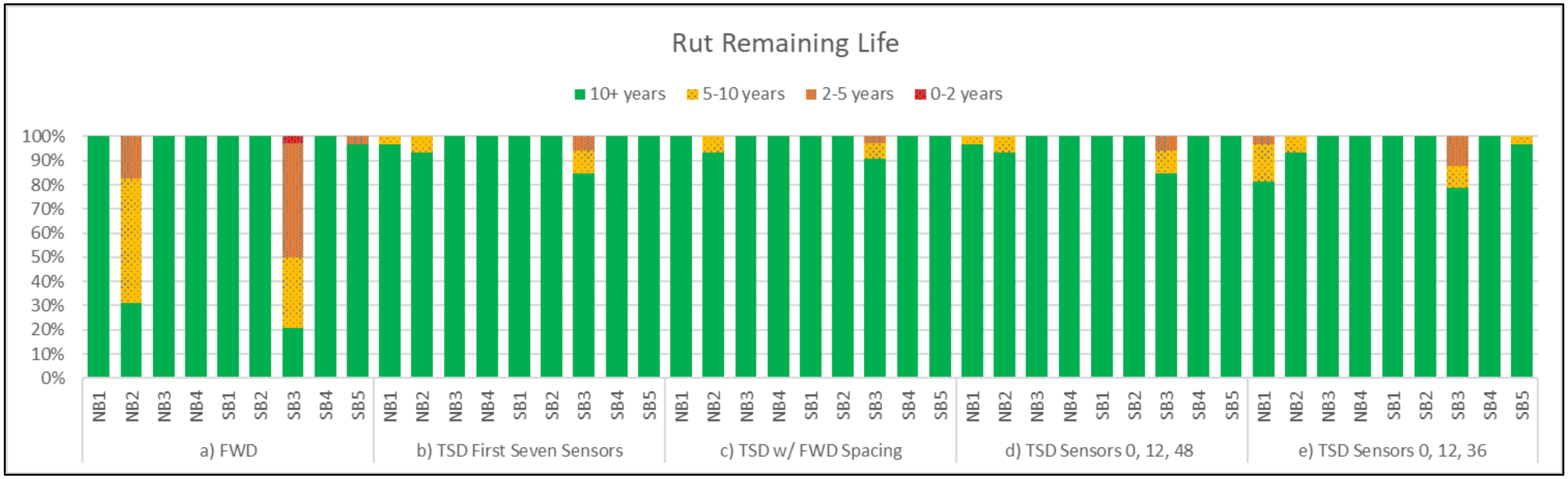


(c)

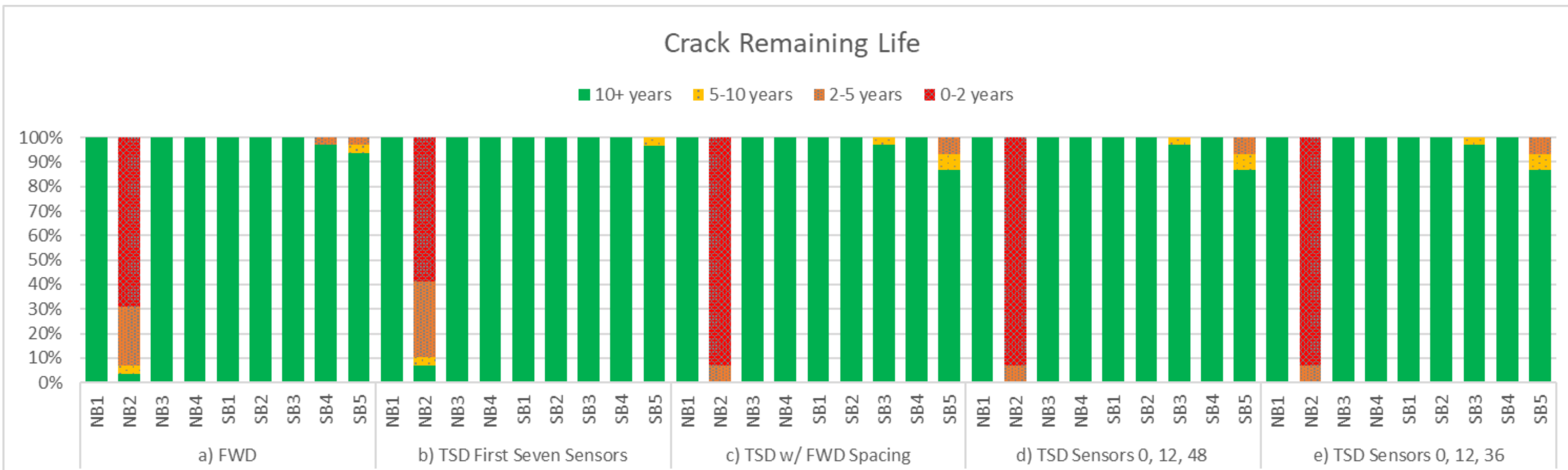
Figure 35. Strength Classification Results for Cases (a)–(e): (a) Upper Layer, (b) Lower Layer, and (c) Subgrade Layer.

The MODULUS software estimates the remaining life of a pavement until rutting and cracking failures occur. The estimation results are grouped into four categorial ranges: 0–2 years, 2–5 years, 5–10 years, and 10+ years. These categorical ranges are used to accurately prioritize TxDOT projects and allocate funds. The remaining life until rutting failure (referred to in this report as *rut remaining life*) is dependent upon the strength of the subsurface pavement layers, while the remaining life until cracking failure (referred to in this report as *crack remaining life*) is dependent upon the SCI. Figure 36 (a) and (b) display the rut and crack remaining life results, respectively, for cases (a)–(e). In general, all five cases were in good agreement for pavement sections that had estimated rut and crack remaining lives of 10+ years across 100 percent of the data points.

When less than 100 percent of the data points produced estimated rut and crack remaining lives of 10+ years for select pavement sections, the rut remaining life calculated from the TSD data was much greater than remaining life calculated from the FWD data. For example, FWD estimates indicated that the NB2 and SB3 sections were at risk of rut failure within the next 10 years, but the TSD estimates indicated no risk of rut failure among any of the test sections. The differences in the rut remaining life estimates for each of the TSD cases (b)–(e) were minimal, despite the differences in outer sensor spacing. The crack remaining life estimates for each of the TSD cases (b)–(e) matched well with the estimates based on the FWD data. Case (b) best matched the FWD estimates, but the difference between using the D8 and D12 sensor to estimate crack remaining life was minimal.



(a)



(b)

Figure 36. Remaining Life Results: (a) Rut and (b) Crack.

CHAPTER 7. MERGING GPR AND TSD DATA

A major issue when processing the TSD data is the lack of pavement layer information, which is critical to understanding the variations in deflections and distress levels that are measured by the TSD device. Historically, TxDOT has addressed this issue through the use of GPR for project-level pavement design evaluations. ARRB Systems also recognized this limitation and have installed a 3D radar unit on the TSD. For the recent TSD data collection efforts in TxDOT's Atlanta, Bryan, Brownwood, and Corpus Districts, the TTI GPR vehicle directly followed the TSD equipment to collect pavement layer data.

TxDOT has actively been collecting and using GPR for the past 25 years to assist in evaluating subsurface conditions. TxDOT has five operational GPR units capable of collecting data at highway speeds. The data collection and processing software systems were developed by TTI. Because both the TSD data and TxDOT's GPR system incorporate GPS coordinates, the two datasets can be merged. This work has been completed by Dr. Wenting Liu at TTI, and a new version of PaveCheck has been developed for prototype evaluation. The data input field has a line entry to merge the two datasets. Most of TxDOT's district staff are already familiar with the PaveCheck data processing system. Figure 37 shows a screenshot of the latest PaveCheck software input screen, an image of the new software logo, and a photo of a TxDOT GPR unit. The line entry to merge the TDS and GPR datasets is highlighted with a red arrow.

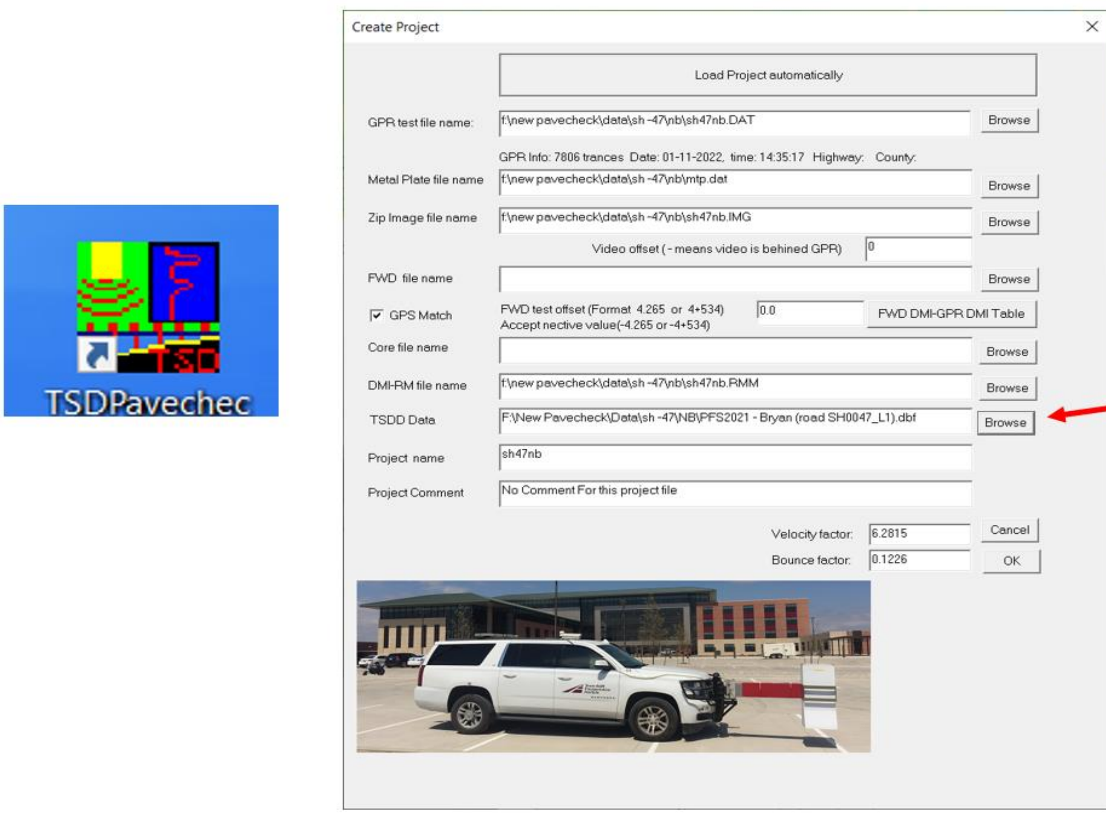


Figure 37. Screenshot of the Updated PaveCheck Software's File Input Screen and Logo.

Examples of the combined TSD/GPR data display in the updated PaveCheck software are exhibited in this section. The overall goal was to show both pavement layer information from the GPR and any additional data items from the TSD device. TxDOT's top priorities were to merge the visual and layer thickness information with structural strength data to classify projects in terms of required treatment levels, and to identify structurally deficient segments for prioritized repair work.

Within each of the selection menu items displayed in Figure 38, the user can choose between several indices. For example, under Deflection, the user can choose to display SCI (D8–D0), SCI (D12–D0), SCI (D36–D60), or D0. Similarly, under Rutting, the user can choose from Rut Depth Right Wheel Path, Rut Depth Left Wheel Path, or Average Rut Depth.

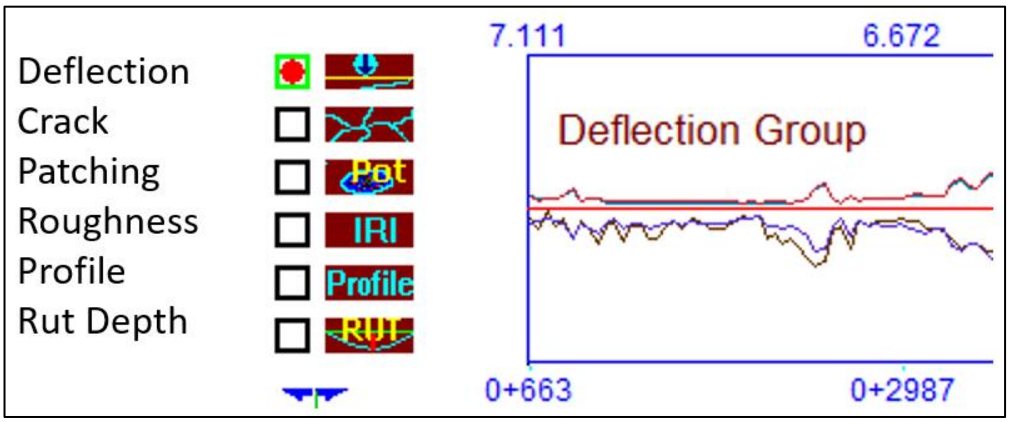


Figure 38. Screenshot of the TSD Selection Menu in PaveCheck.

Figure 39 shows the merged TSD and GPR data for NB SH 47 in TxDOT's Bryan District. The upper plot shows the TSD data of SCI (D0–D8) for the entire 7-mile-long project and the lower plot shows the GPR data. Note that this figure reflects the first generation display of the merged datasets and is intended to be modified based on input from TxDOT. Each of the reported deflection parameters identified the same weak section. Bold vertical red lines define the limits of the high deflection section in both the TSD and GPR data plots. The lower left photo was taken at 2 miles + 2,500 feet (designated by a thin vertical red line in the TSD and GPR data plots). This location reflects a bridge overpass that was constructed 6–7 years ago. The HMA thickness for much of SH 47 is nearly 8 inches, but on this bridge overpass, the HMA thickness is much less. On the leading approach, the HMA is 2–3 inches thick, and on the following approach, the bridge is 4–6 inches thick. The key issue here is that the deflection for the entire overpass is substantially higher than the rest of SH 47. The lower left photo was taken at the time of data collection and shows the fine cracking that was observed. The lower right photo was taken 6 months after data collection (merged into this figure) and shows the major fatigue damage that has occurred during this time.

Figure 39. Merged TSD and GPR Data for NB SH 47 in TxDOT's Bryan District Showing a High Deflection Section and Rapid Deterioration.

Figure 40 shows the merged TSD and GPR data for FM 39, which is of interest to TxDOT's Bryan District. The upper plot shows the TSD maximum deflection data. The GPR data were collected on a segment close to the transition from section 1 to 2 (Location A). The two arrowed locations show the transition from section 1 to 2 in both the TSD deflection and GPR data. The GPR data show a clear change in pavement structure at this location, and also a transition from high to low deflections. Chuck Reed, TxDOT district pavement engineer, provided the section breaks. Overall, the data indicated that the roadway is in poor condition and needs to be rehabilitated and widened. The entire roadway segment has no hot mix surfacing, only multiple chip seals. Section 3 was judged by district staff to be in the worse structural and visual condition and is already scheduled for full reconstruction (FDR treatment with foamed asphalt). District staff are, however, seeking guidance regarding the other three sections. Based on the data, the following tentative conclusions can be drawn:

- Based on the GPR data, section 1 is essentially a road constructed over a road, with 6 inches of new base placed over an existing roadbed. From the in-field video, multiple maintenance repairs are either underway or have been recently completed. Deflections for this section are high, and a subsequent review of the rut depths for this section found that several locations have over 1-inch-deep ruts.
- Section 2 appears to have a thin surface coat over most likely a treated base or a very good flexible base. The deflections for all of section 2 were significantly less than the deflections for the other three sections. Section 2 was found to be in the best condition and relatively structurally sound.
- Section 4 had a very similar visual condition and deflection profile as section 3. Based on the data presented, section 4 will likely require the same FDR treatment as section 3.

The remaining data items are pending review but based on the limited data discussed here, district staff should consider the following prioritization for the three sections of interest: section 4 (highest), section 1 (second highest), and section 2 (lowest).

Again, using the merged TSD and GPR data, Figure 41 shows the right wheel path rut measurements from a location in the middle of section 1 on FM 39 in TxDOT's Bryan District. At the location marked with a red arrow, a rut depth of more than 1.25 inches was reported. TTI researchers inspected this location and confirmed that deep ruts are present (lower right photo). A second location with similar measurements showing a rut depth of more than 1 inch was also validated, demonstrating that the rut measurements provided by the TSD device were reasonable. The validation of TSD rutting and ride measurements have been performed on several sections.

Similar validations were attempted for the crack predictions, but these efforts were not as successful. The entire FM 39 roadway segment has chip seals in various conditions; cracking measurements for chip seal pavements remain a challenge with TSD equipment. However, cracking measurements on roadways with HMA surfaces appear reasonable.

Figure 40. Merged TSD and GPR Data for FM 39 in TxDOT's Bryan District Showing Maximum Deflections and the Transition Between Sections 1 and 2 (Location A).

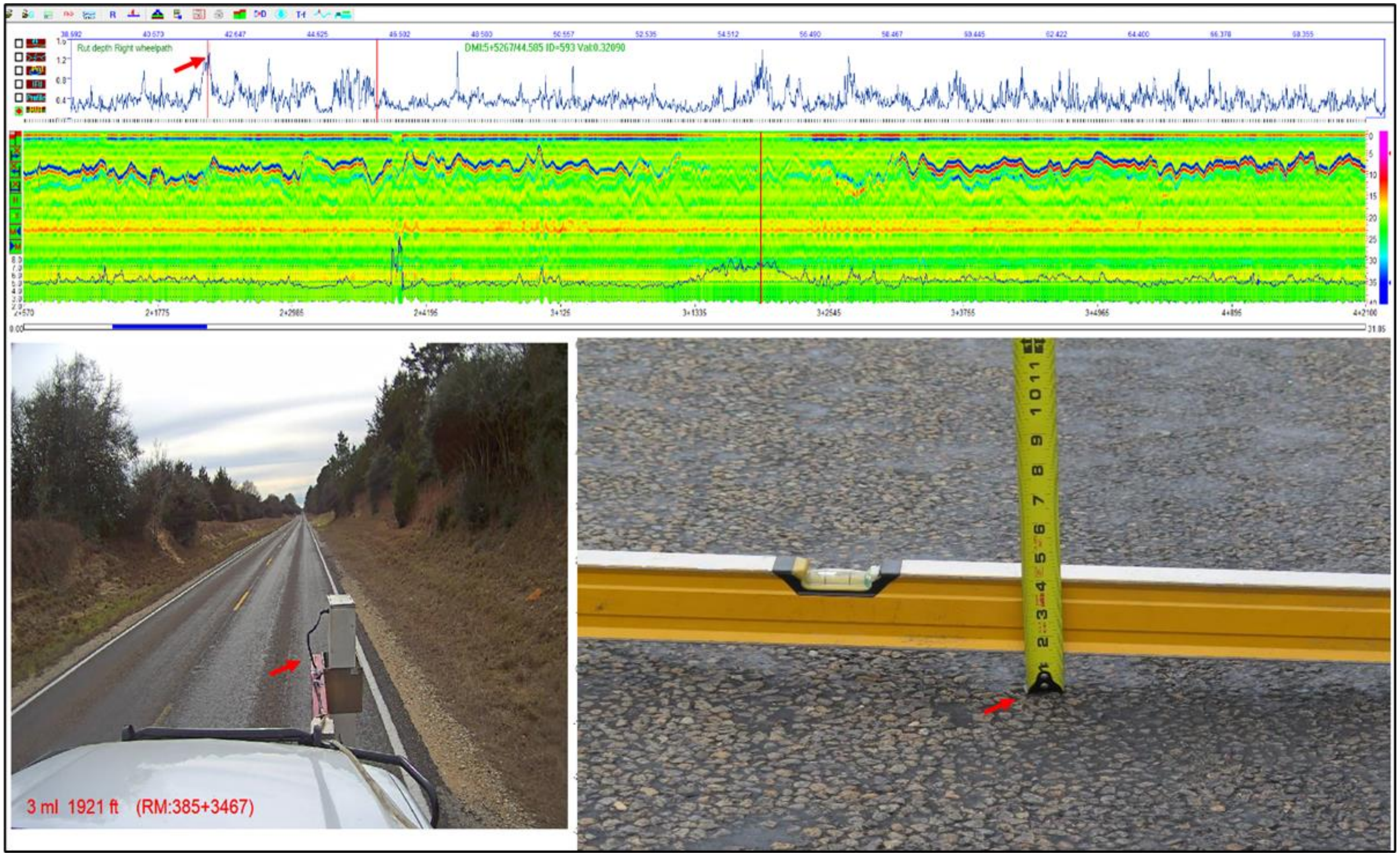


Figure 41. Merged TSD and GPR Data for Section 1 on FM 39 in TxDOT's Bryan District Showing Validation of High Rutting Locations.

CHAPTER 8. APPLICATION OF THE 3D-MOVE SIMULATION SOFTWARE TO COMPUTE PAVEMENT RESPONSES

The literature review completed in Task 2 revealed that several projects examining the scope and viability of TSD devices had applied the 3D-Move simulation software as part of their efforts. The 3D-Move software is a free program developed by the University of Nevada-Reno that uses a continuum-based finite-layer approach to compute pavement responses [7]. By using this approach, the program can account for complicated surface loads caused by multiple loads and asymmetrical contact stress distributions. For the purpose of this project, various load cases were simulated using the 3D-Move software to determine whether its output is accurate enough to reliably model pavement response under TSD loading (i.e., the TSD deflection data can be validated and an experimental backcalculation procedure can be developed to ascertain layer moduli values from the TSD deflection data). The purpose of this chapter is to:

- Define the 3D-Move software inputs and explain the process for modeling three different load cases: (1) FWD device, (2) semi-truck and trailer, and (3) TSD device.
- Compare and validate the results of the 3D-Move simulations to field measurements.
- Demonstrate how the 3D-Move software may be utilized in an experimental backcalculation procedure using TSD deflection data.

3D-MOVE SOFTWARE INPUTS

The inputs for the 3D-Move software are organized into the following four main categories:

1. Project information.
2. Vehicle characteristics.
3. Pavement structure.
4. Response points.

Figure 42 shows a screenshot of the 3D-Move software user interface that includes the input options. Upon opening the program, the user is prompted to select either a static or dynamic response as the analysis type. If the static response option is selected, the software will simulate the deflections beneath a static load for a given pavement structure. The user will later define the coordinate location(s) or *response points* where the deflections are to be recorded. If the dynamic response option is selected, the user is asked to input the vehicle speed in miles per hour, and the software will simulate the moving load and deflection responses at the desired response points. The user may also select the extended pavement analysis option to evaluate pavement performance.

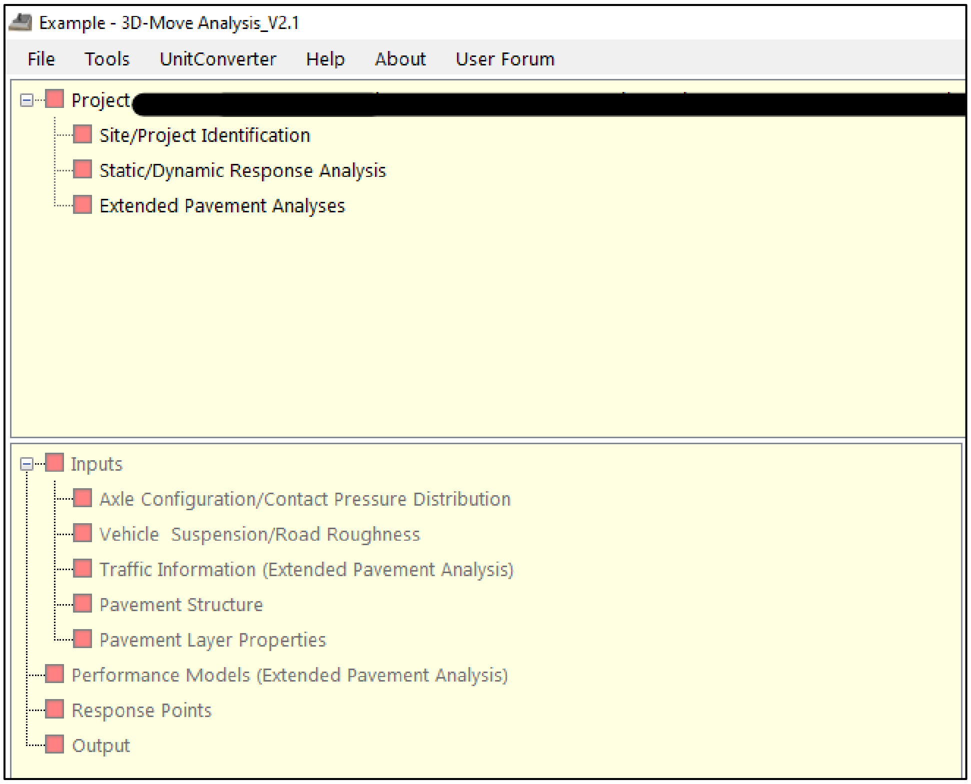


Figure 42. Screenshot of 3D-Move Software's User Interface with Input Options.

The next set of inputs in the 3D-Move software pertains to vehicle characteristics. Clicking Axle Configuration/Contact Distribution opens a series of options that the user must choose from (Figure 43). Each option listed in the dialogue box requires a unique set of inputs regarding tire types and imprints on the pavement, loads, and vehicle dimensions. For this project, Option B was used to model the FWD and TSD load cases (load case 1 and 3), while option D was used to model the semi-truck and trailer load case (load case 2).

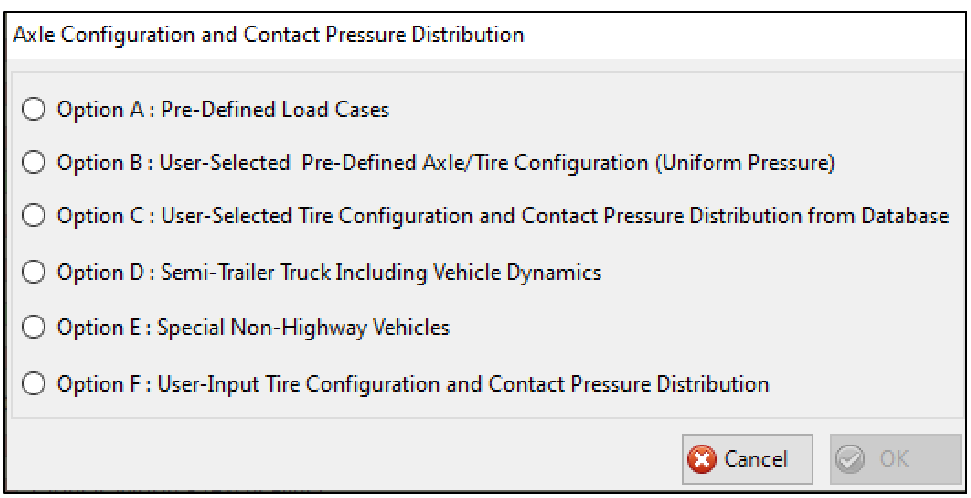


Figure 43. Screenshot of 3D-Move Software's Axle Configuration and Contact Pressure Distribution Window.

The next set of 3D-Move inputs pertains to pavement structure and layer material characteristics. Clicking Pavement Structure opens a tabular form that prompts the user to input the number of pavement layers, layer types, and thicknesses. Once this information is provided, the material properties for each layer may be entered. For the first layer of the pavement structure, the user must select a material model from the following menu:

- Linear elastic materials.
- Laboratory data.
    - Symmetrical sigmoidal function.
    - Nonsymmetrical sigmoidal function.
    - Accelerated mixture performance test.
    - User input (interpolation).
- Model equation.
    - Witczak model.

For simplification, the linear elastic materials option was chosen for this project's load cases. Figure 44 shows the 3D-Move software's pavement layer properties dialogue box.

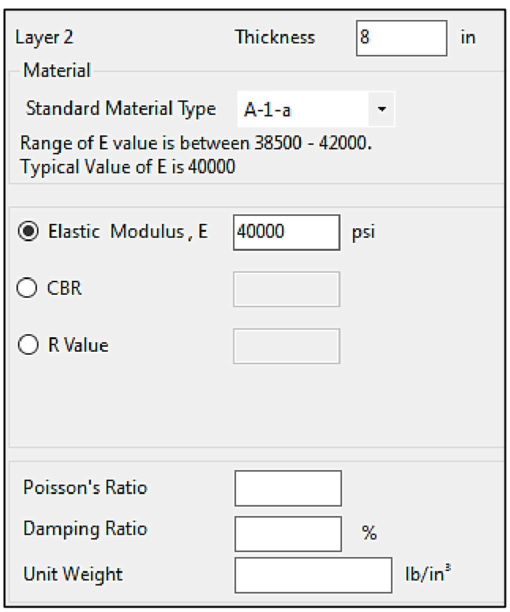


Figure 44. Screenshot of 3D-Move Software's Pavement Layer Properties Dialogue Box.

The final set of inputs defines the coordinate locations or response points at which the simulation will record deflections. Response points are placed on the YZ coordinate plane, while the vehicle (if modeling a dynamic load) travels along the X axis. Figure 45 shows an example 3D-Move software screenshot showing a completed response points dialogue box. After all inputs have been entered, the user can run the analysis.

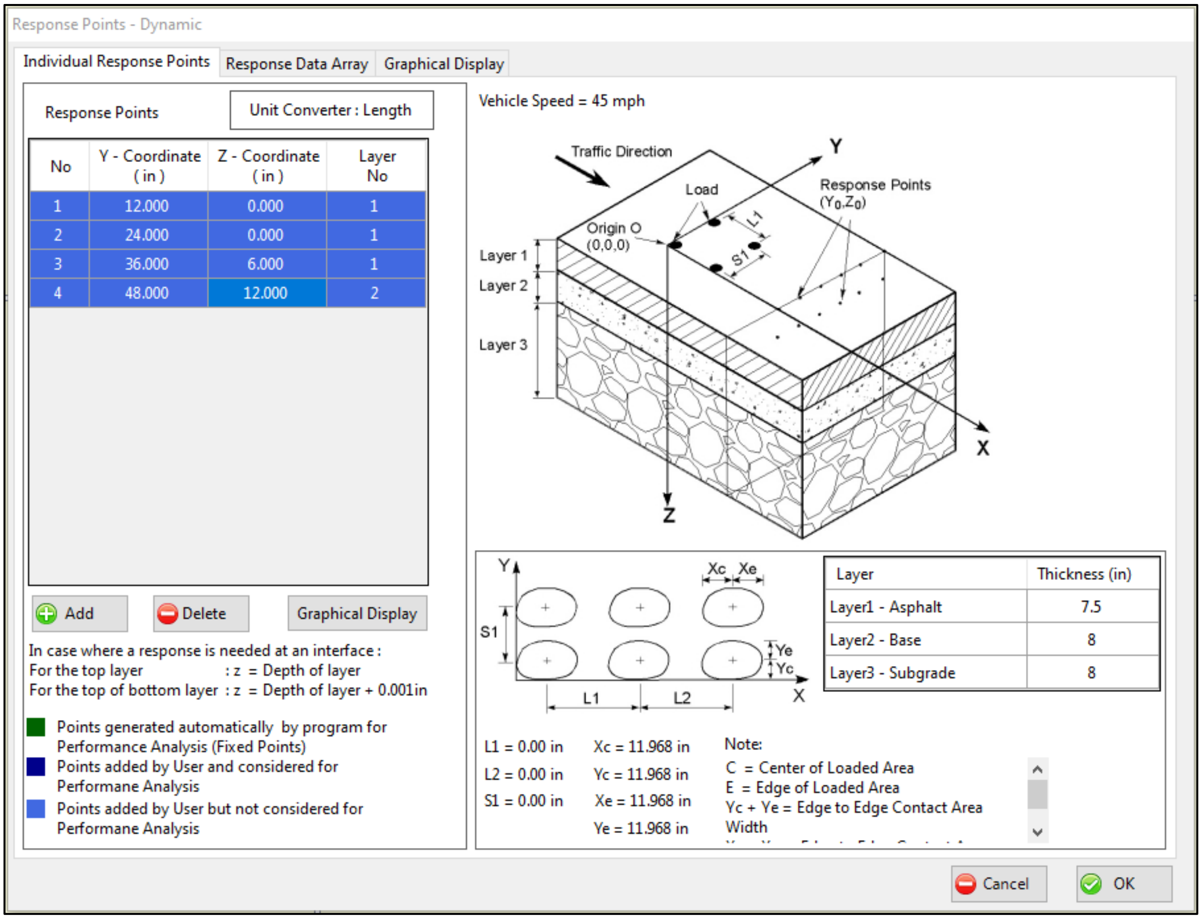


Figure 45. Example 3D-Move Software Screenshot Showing a Completed Response Points Dialogue Box.

TEST LOAD CASES

FWD, semi-truck and trailer, and TSD load cases were defined and simulated using the 3D-Move software, and the results were evaluated and compared to the field tests. The FWD load case was used to evaluate the 3D-Move results for a static response. The simulation parameters were taken from field testing conducted on SH 47 in TxDOT's Bryan District, and the backcalculated moduli values from the field were used in the simulation. The semi-truck and trailer load case was modeled after a water tanker used in previous deflection studies conducted by TTI (Figure 46) [8] [9]. The TSD load case was modeled similarly to the semi-truck and trailer load case but used the known TSD axle loading and pressure distributions. The pavement structures tested in the study were also modeled using the 3D-Move software for comparison.

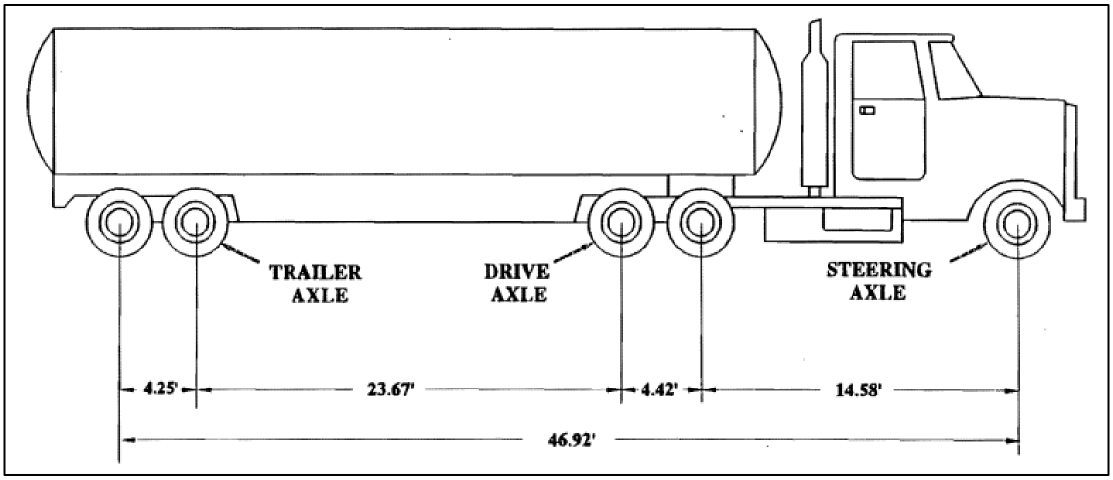


Figure 46. Water Tanker Schematic used to Generate the 3D-Move Case 2 Model [8].

Table 18 details the pavement structures modeled for the FWD and semi-truck and trailer load cases. In the case of the semi-truck and trailer, deflection values were simulated for both thick- and thin-surfaced asphalt pavements.

The TSD field measurements were recorded at nine different test sections of various strengths on SH 47 in TxDOT's Bryan District. Table 19 details the thicknesses and moduli values for each of the nine test sections. These values were used to model each section using the 3D-Move software; the simulation results were directly compared to the field measurements.

Table 18. Pavement Structure Thicknesses and Backcalculated Moduli for the FWD and Semi-truck and Trailer Load Cases.

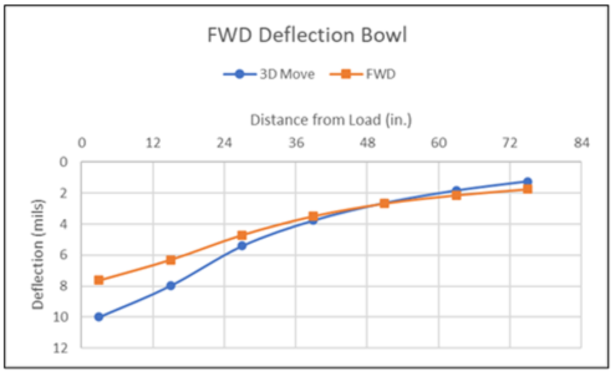
Load Case	Layer	T (inches)	E (ksi)
FWD	Asphalt	7.5	409
	Base	12.5	51
	Subbase	8	35
	Subgrade	120	11
Semi-truck and trailer (thick surface)	Asphalt	7	199
	Base	14	39
	Subgrade	79.1	16
Semi-truck and trailer (thin surface)	Asphalt	1.5	293
	Base	10	35
	Subgrade	288.5	8

Table 19. SH 47 Test Section Pavement Structure Thicknesses and Backcalculated Moduli for the TSD Load Case.

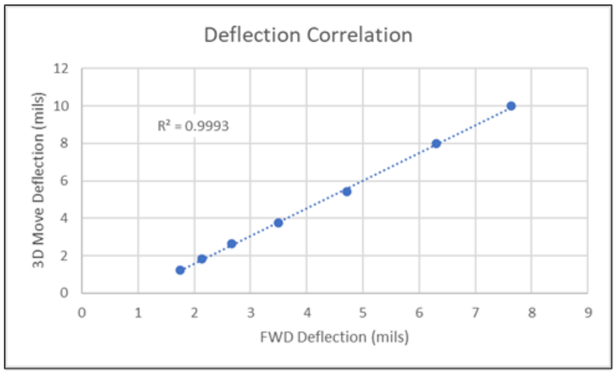
Section	T Surface (inches)	T Base (inches)	T Subbase (inches)	T Subgrade (inches)	E Surface (ksi)	E Base (ksi)	E Subbase (ksi)	E Subgrade (ksi)
SB1	7.5	12.5	8	120	330	72	44	14
SB2	2.8	10	12.5	120	450	621	44	15.6
SB3	2.5	12.5	--	120	450	28	--	15.7
SB4	5.5	10	12.5	120	500	707	37	9.2
SB5	5	6	8	120	400	18	27	7.5
NB1	2.2	8	8	120	450	800	44	11
NB2	5.4	10	--	120	73	40	--	12
NB3	7.6	12.5	8	120	260	37	40	13.9
NB4	5.7	10	12	120	500	800	32	12.7

Results

The results of all three simulated load cases confirm the ability of the 3D-Move software to simulate pavement responses resulting from both static and dynamic loading scenarios with reasonable accuracy. The same distances from the load center were used for both the response points for the FWD load case in the 3D-Move software and the field measurements using the FWD device, resulting in a one-to-one comparison of the deflections. Figure 47 (a) and (b) display the measured and simulated deflection bowls for the FWD load case and their calculated correlation, respectively. The simulated deflections had very good agreement with the field data, reflected in a coefficient of determination of 0.99.



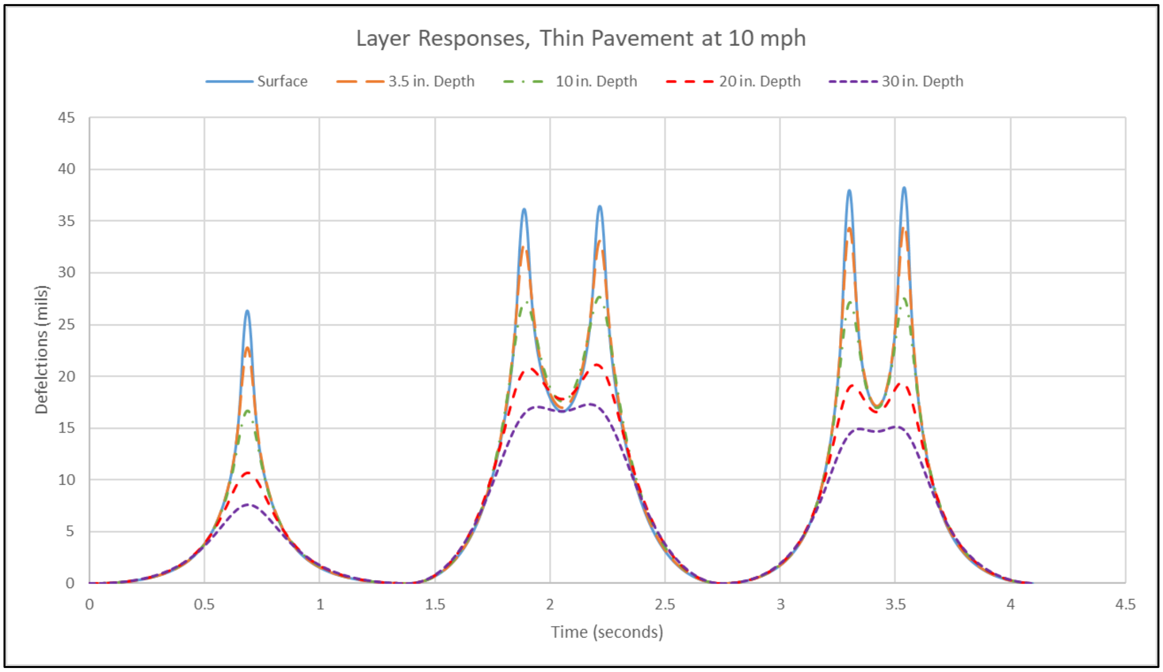
(a)



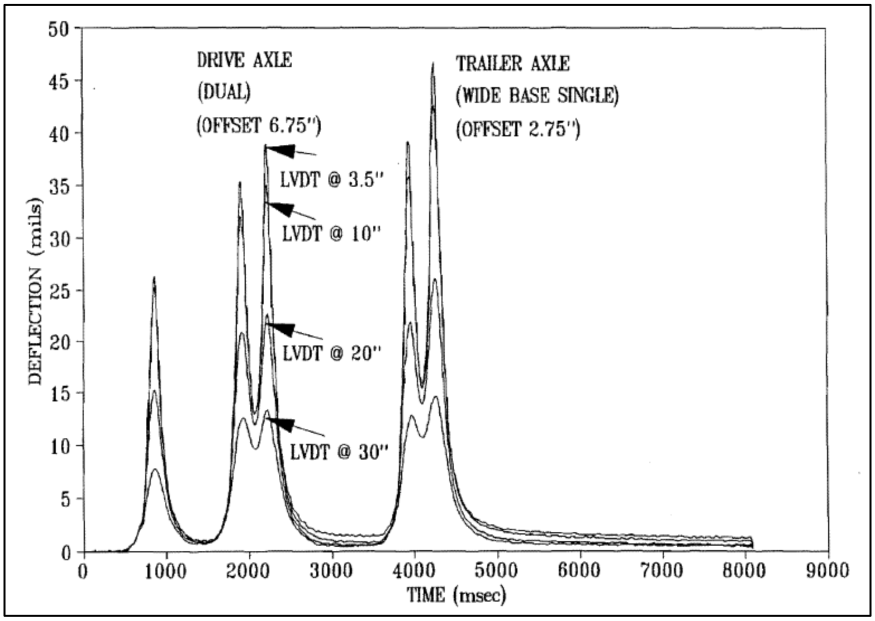
(b)

Figure 47. Measured and Simulated FWD Deflections: (a) FWD vs. 3D-Move Deflection Bowls and (b) Correlation.

The semi-truck and trailer load case included thick and thin pavements and speeds of 10 and 55 mph. The 3D-Move software simulated vehicle characteristics and dynamic loads, with response points that matched the field sensor locations. Figure 48 and Figure 49 show the measured field responses and corresponding simulation results for the thin pavement section at 10- and 55-mph speeds, respectively. On thin pavement, the simulated results were within 5 mils of the field data.

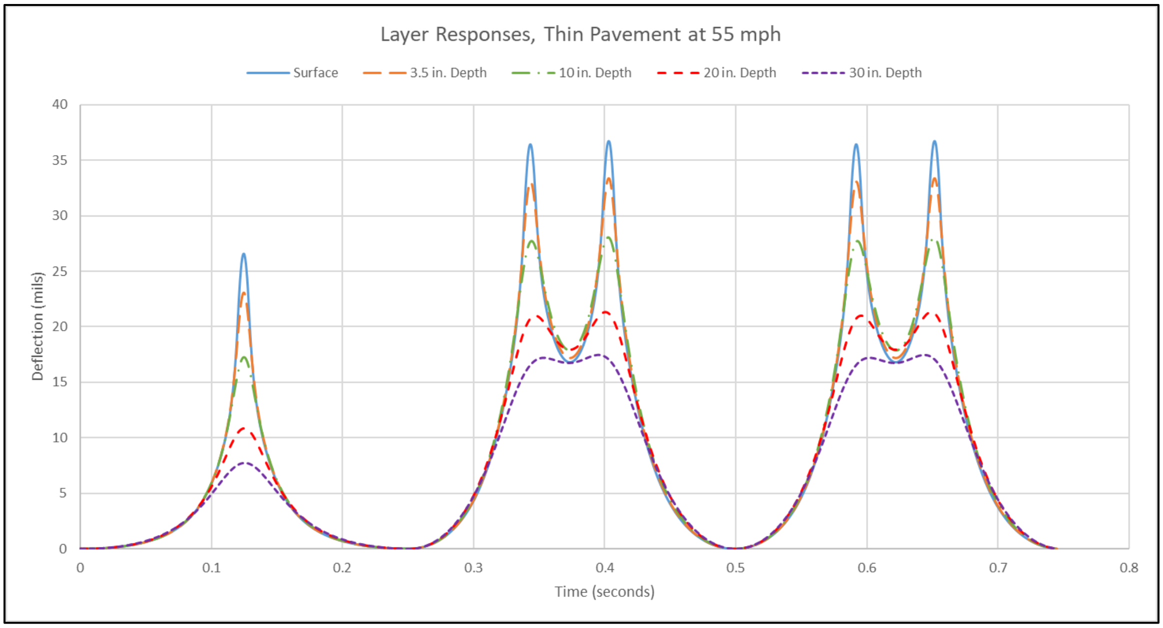


(a)

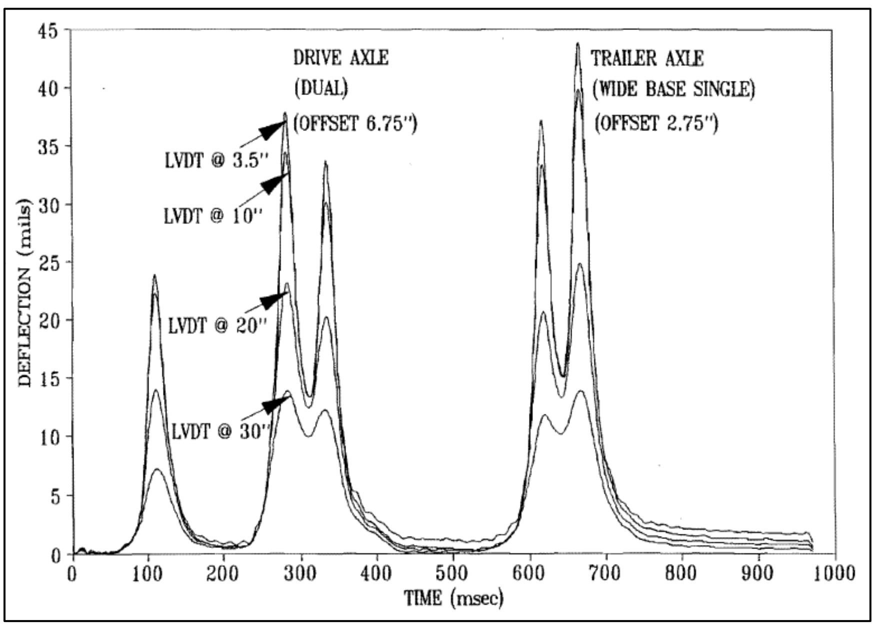


(b)

Figure 48. Measured and Simulated Semi-truck and Trailer Deflections on Thin Pavement at 10 mph: (a) Simulated and (b) Measured [8].



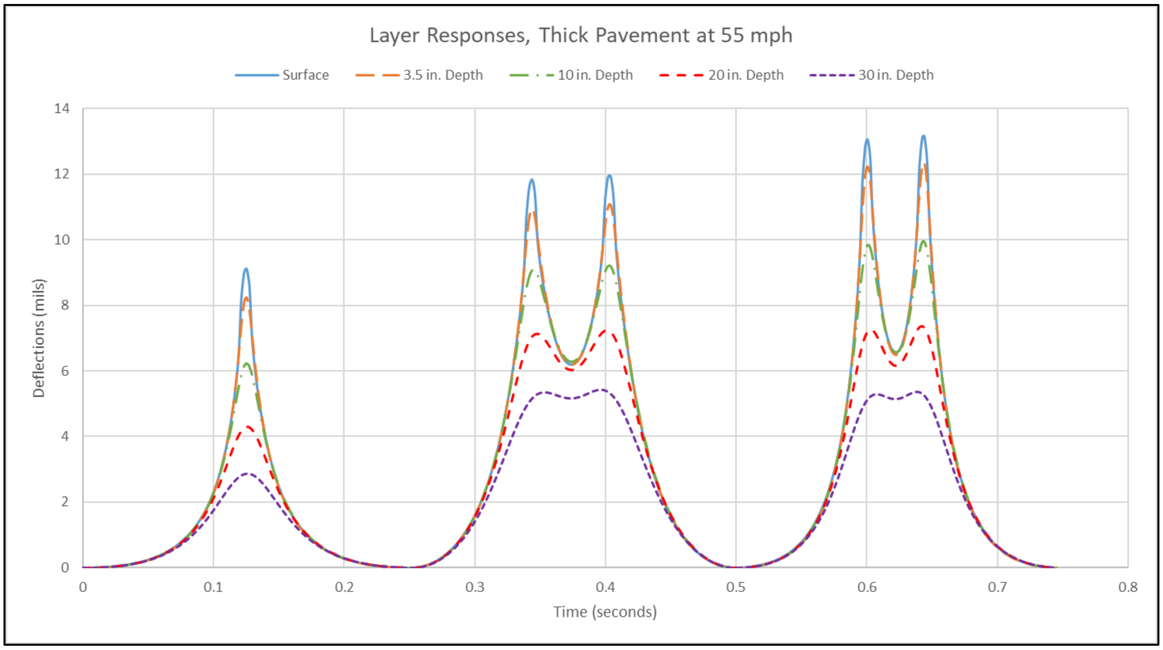
(a)



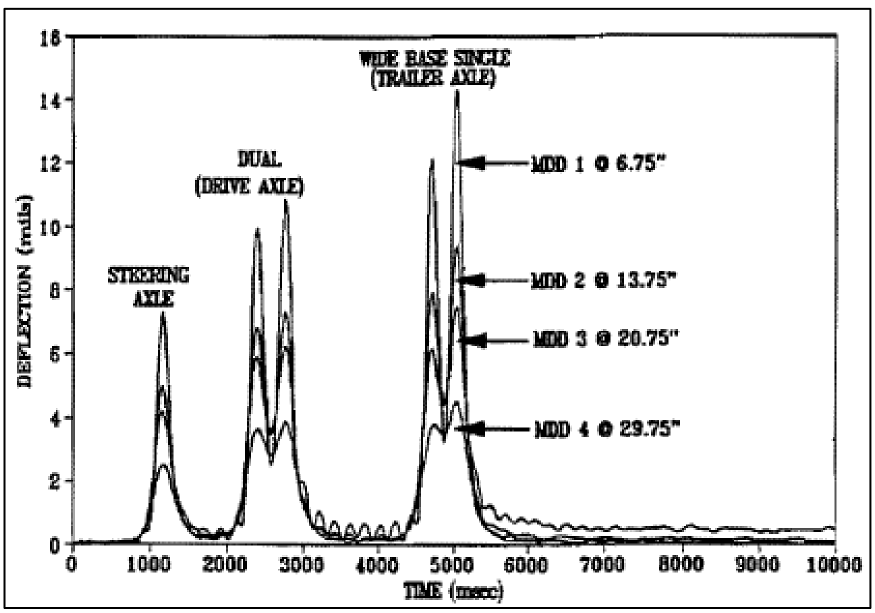
(b)

Figure 49. Measured and Simulated Semi-truck and Trailer Deflections on Thin Pavement at 55 mph: (a) Simulated and (b) Measured [8].

Figure 50 shows the measured field responses and corresponding simulation results for the thick pavement section at a 55-mph speed. In this case, the simulated layer responses were within 2 mils of the measured field data. For both thin and thick pavement types, vehicle speed did not greatly impact the measured or simulated pavement responses.



(a)



(b)

Figure 50. Measured and Simulated Semi-truck and Trailer Deflections on Thick Pavement at 55 mph: (a) Simulated and (b) Measured [9].

For the TSD load case, a dynamic response analysis was simulated within 3D-Move. The vehicle speed was 60 mph, and the rear axle single tire load was 4500 lb. To simplify the model, the tire contact area was reduced to a circle with a radius of 4.4 in.

The 3D-Move simulation was found to adequately replicate the field testing conducted on nine SH 47 test sections in TxDOT's Bryan District. The TSD vehicle characteristics and the known pavement structures were used in the 3D-Move software to compare the simulated deflection measurements to the measured field data. Figure 51 shows the measured and simulated deflections for each of the nine test sections. TSD deflection data was reported at 50 ft intervals in the field. The simulated deflection values were closer to the average measured TSD values than the maximum measured TSD values for each section.

For most of the test sections, the simulated deflections at locations beyond 18 inches from the load center were 2 standard deviations greater than the field-measured deflections. This pattern was most noticeable when analyzing the calculated deflection indices, SCI 8 and SCI 36–60, which are indicators of base and subgrade strength, respectively. Figure 52 (a) and (b) compare the measured and simulated SCI 8 and SCI 36–60 indices, respectively. Each comparative index was calculated using the average TSD data and the 3D-Move simulated data. The SCI 8 calculated using the 3D-Move simulation results agreed with the SCI 8 calculated using the measured TSD data, especially for pavement sections with a subbase layer. However, the SCI 36–60 calculated using the 3D-Move simulation results was much greater than the SCI 36–60 calculated using the measured TSD data. This finding may indicate that the simulated deflection data from the 3D-Move software underestimate the strength of subgrade materials compared to the field measurements. The exception to these patterns is the NB2 section, where known issues regarding delamination of the HMA layer exist.

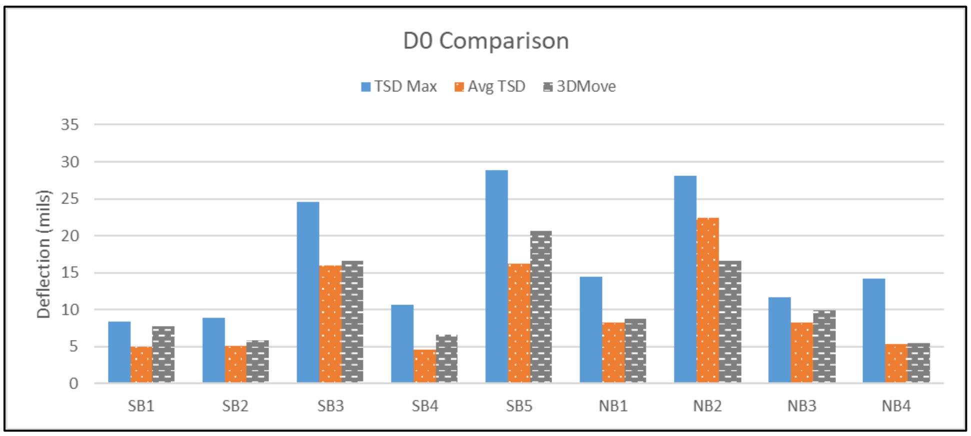
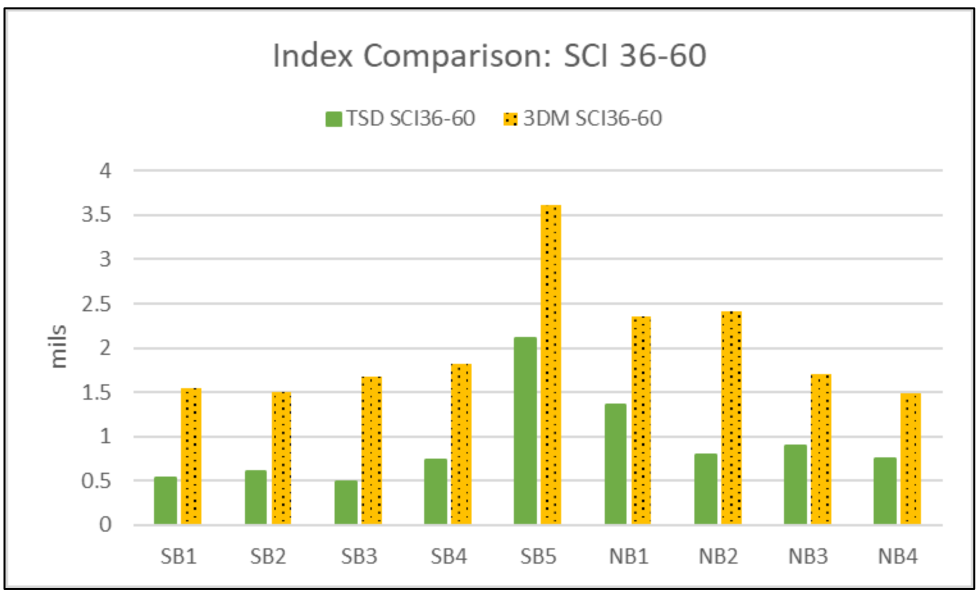


Figure 51. Measured and Simulated TSD Deflections on the SH 47 Test Sections.

(a)



(b)

Figure 52. Measured and Simulated TSD SCI on the SH 47 Test Sections: (a) SCI 8 and (b) SCI 36–60.

EXPERIMENTAL BACKCALCULATION PROCEDURE

The 3D-Move software is of particular interest because of its potential to backcalculate layer moduli values from the TSD deflection data. Table 20 details seven test cases that were developed to assess the effects of variable layer modulus values on simulated deflections. The pavement structures were derived from the SH 47 test sections, and the modulus ranges were selected using the MODULUS backcalculation software for FWD data.

Specifically, a database of simulated deflection bowls was generated by iterating through the modulus range of the variable layer. The error between each simulated deflection bowl and the field-measured deflection bowl from the SH 47 test sections was calculated, and the layer modulus value that resulted in the lowest error was selected as the backcalculated modulus value.

Table 20. Experimental Backcalculation Procedure Test Cases.

Test Case	Pavement Structure	E (ksi)	Comments
1	2.5-inch surface	450	SB3 section, variable subgrade modulus
	12.5-inch base	28	
	subgrade	2–50	
2	2.5-inch surface	450	SB3 section, variable base modulus
	12.5-inch base	5–150	
	subgrade	15.7	
3	5-inch surface	400	SB5 section, variable subgrade modulus
	6-inch base	18	
	8-inch subbase	27	
	subgrade	2–50	
4	5-inch surface	400	SB5 section, variable base modulus
	6-inch base	5–150	
	8-inch subbase	27	
	subgrade	7.5	
5	2.2-inch surface	450	NB1 section, variable CTB modulus
	8-inch base	100–2,000	
	8-inch subbase	44	
	subgrade	11	
6	5-inch surface	400	SB5 section, variable subbase modulus
	6-inch base	18	
	8-inch subbase	5–150	
	subgrade	7.5	
7	5-inch surface	400	NB1 section, CTB, variable subbase modulus
	8-inch base	800	
	8-inch subbase	5–150	
	subgrade	11	

Table 21 compares the simulated backcalculated modulus values using 3D-Move software and the modulus values backcalculated using FWD field measurements. Figure 53 displays this modulus value comparison in graphical form. The variable layer included subgrade, base, CTB, subbase beneath a CTB, and subbase beneath a flexible base (FB).

Table 21. Comparison of Backcalculated Modulus Values Based on Measured FWD Data and Simulated 3D-Move Data.

Test Case	Variable Layer	FWD Backcalculation (ksi)	3D-Move Backcalculation (ksi)	Difference (percent)
1	Subgrade	15.7	22	33
2	Base	28	40	35
3	Subgrade	7.5	12	46
4	Base	18	105	141
5	CTB	800	1850	79
6	Subbase beneath FB	27	150	139
7	Subbase beneath CTB	44	45	2

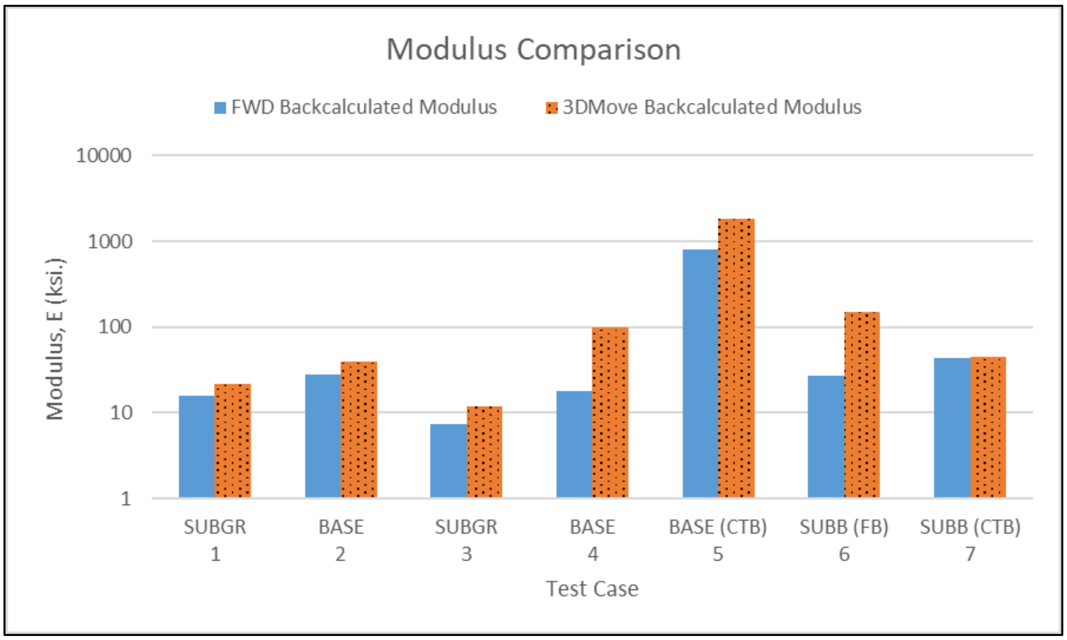


Figure 53. Comparison of Backcalculated Modulus Values Based on Measured FWD Data and Simulated 3D-Move Data.

Both Table 21 and Figure 53 indicate that, on average, the experimental backcalculation procedure utilizing 3D-Move overestimated the modulus of the variable layer by 68 percent. The modulus backcalculations for test cases 1, 2, and 7 were the most accurate, where the difference between the FWD and 3D-Move backcalculated modulus was 33, 35, and 2 percent, respectively.

The measured TSD deflection bowls were compared to the backcalculated deflection bowls created from on the 3D-Move procedure for each corresponding test case. Test cases 1 and 2 simulated the SB3 test section (Figure 54); test cases 3, 4, and 6 simulated the SB5 test section (Figure 55); and test cases 5 and 7 simulated the NB1 test section (Figure 56). As with the TSD load cases, the backcalculated deflection bowls had higher outer sensor deflections than the measured deflection bowls for each case.

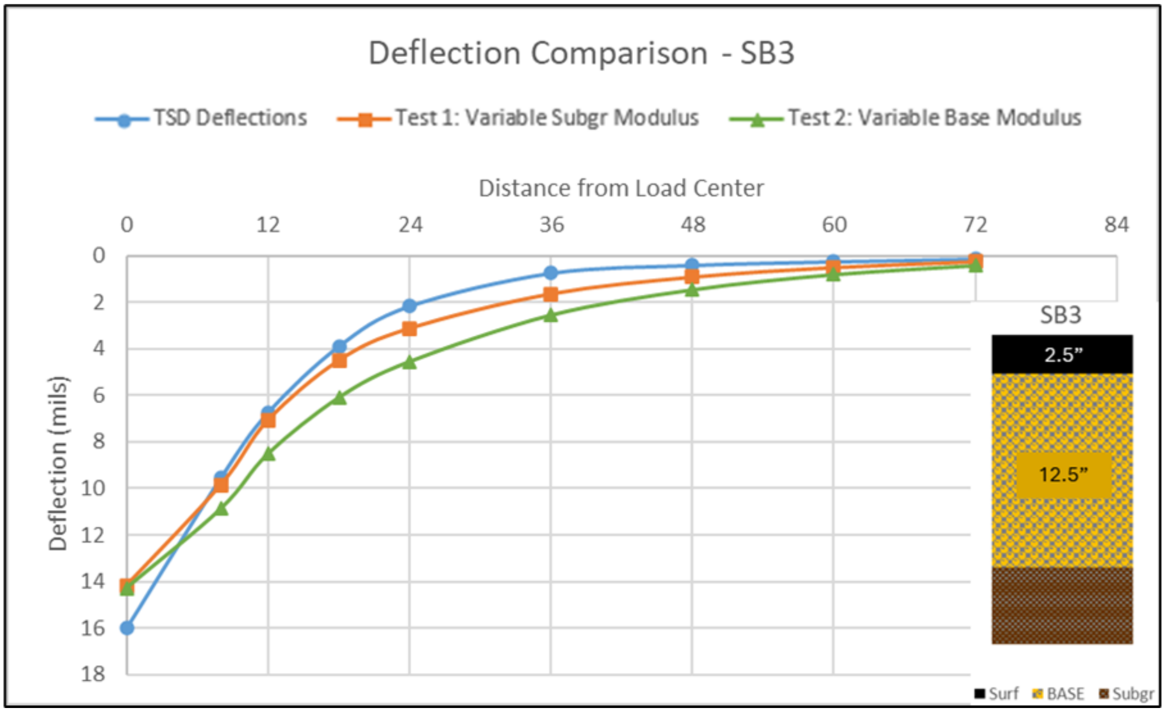


Figure 54. Comparison of the Measured TSD Deflection Bowls and the Backcalculated Deflection Bowls Using the 3D-Move Software for the SB3 Test Section.

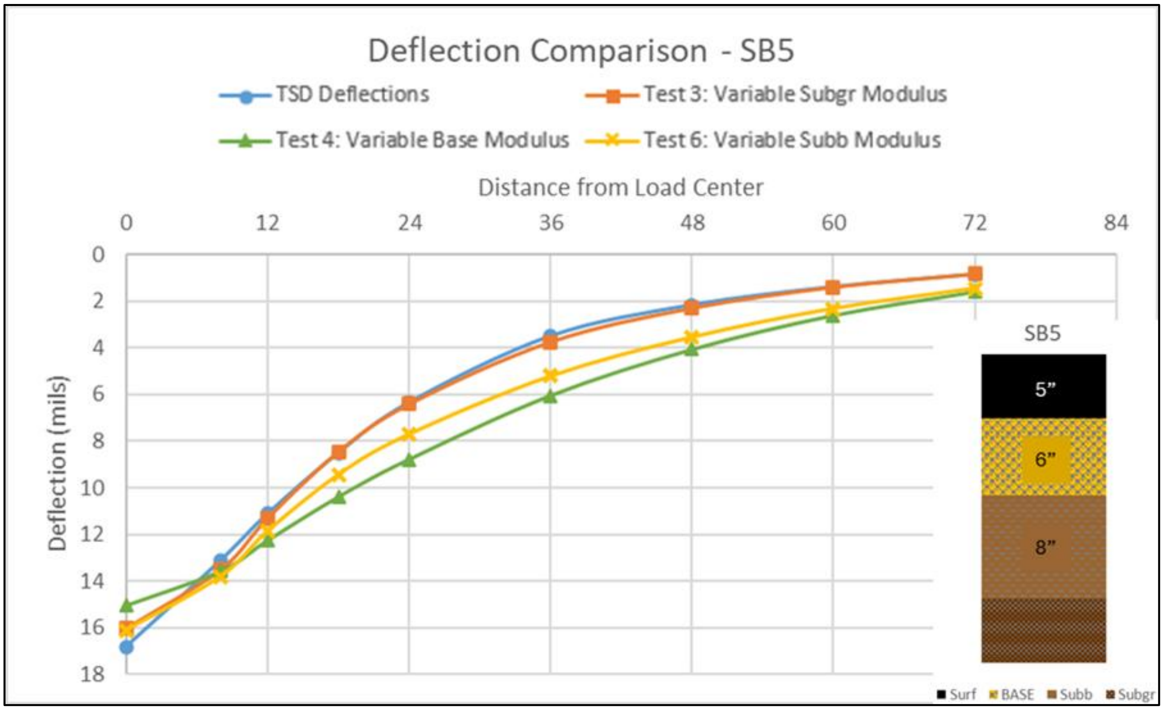


Figure 55. Comparison of the Measured TSD Deflection Bowls and the Backcalculated Deflection Bowls Using the 3D-Move Software for the SB5 Test Section.

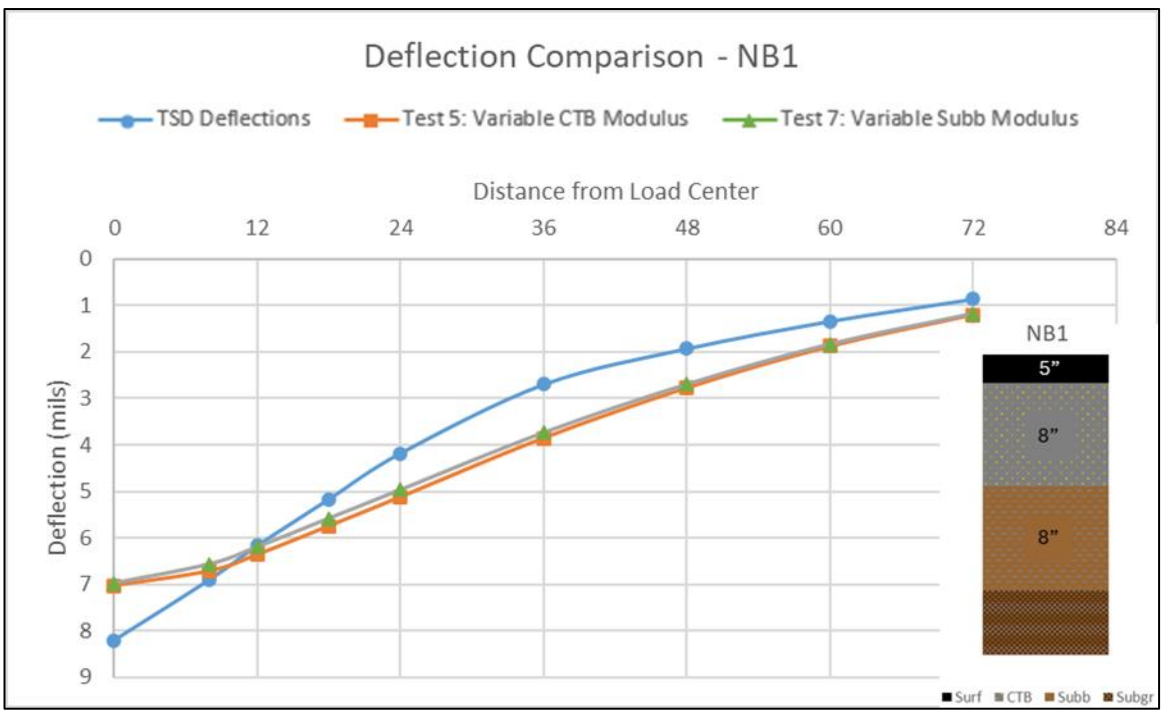


Figure 56. Comparison of the Measured TSD Deflection Bowls and the Backcalculated Deflection Bowls Using the 3D-Move Software for the NB1 Test Section.

LESSONS LEARNED

To validate the results from the 3D-Move software, three load cases were developed based on different field-testing scenarios. The simulated output deflections were compared to the measured field deflections. For the first load case—a static FWD drop, the 3D-Move software accurately simulated deflections with a high coefficient of determination. The second load case included a moving semi-truck and trailer with pavement responses measured at multiple depths beneath the pavement surface for two different speeds over two different pavement types/thicknesses. The results from the 3D-Move software matched the field deflections at all depths and for both pavement types/thicknesses and test speeds. The third load case included a TSD device traveling at 60 mph. Field deflection measurements were taken at nine test sections on SH 47 in TxDOT's Bryan District and simulated in the 3D-Move software. The simulated pavement deflections showed good agreement with the field deflections close to the center of the load. However, the simulated deflections further away from the load center were greater than those measured in the field for most test sections. Based on the results from all three test cases, the 3D-Move software accurately and reliably simulated the maximum pavement deflection measured under the load center for both static and dynamic loads, regardless of vehicle speed and pavement type/thickness. However, deflections simulated further from the dynamic load center were greater than those measured in the field.

The 3D-Move software was also evaluated as part of an experimental procedure to backcalculate pavement layer modulus values from reported TSD deflections. For the seven defined test cases, all of the backcalculated modulus values were greater than those calculated from FWD measurements (i.e., *true* values). The experimental procedure did not adequately backcalculate modulus values for stiff layers with high modulus values. The three test cases in which the backcalculated modulus values were reasonably similar to the *true* values (test cases 1, 3, and 7) each included subgrades and a subbase layer beneath a CTB. To further test the potential of this backcalculation procedure, determinations must be made regarding the effects of three-layer (surface, base, subgrade) versus four-layer (surface, base, subbase, subgrade) pavement structures. Additionally, the effects of various materials must be studied and accounted for in future iterations. For this procedure to be effective in future applications, the modulus values of multiple pavement layers must be variable such that the error between the simulated and measured deflection bowl can be minimized.

CHAPTER 9. APPLICATION OF TSD DATA FOR PROJECT-LEVEL ANALYSES

The application of the TSD data for project-level decision-making and analyses is of particular interest to TxDOT districts. The ARRB System's Hawkeye system can be used to identify roadway sections that are structurally weak/strong or visually in good/poor condition. To define the optimal rehabilitation alternatives, other data items related to the existing pavement structure and layer condition are required. The use of GPR can support both needs. TxDOT districts perform extensive maintenance on the highway network that is typically not captured in the existing databases. Furthermore, frequent seal coats temporarily seal surfaces and hide damaged layers. Also, in many parts of Texas, moisture damage to lower HMA layers is widespread and a frequent cause of recurring cracking. The ideal repair can only be determined once the root cause of the current pavement distress is identified. This determination often requires field coring and possible lab testing in addition to GPR measurements. This chapter presents two case studies—FM 99 in TxDOT's Corpus Christi District and OSR in TxDOT's Bryan District—in which the TSD data were used to assist districts with project-level decision-making.

FM 99 IN TXDOT'S CORPUS CHRISTI DISTRICT

The FM 99 segment of interest to TxDOT's Corpus Christi District is approximately 7.4 miles long and includes three different pavement structures (Table 22). These structures (sections 1, 2, and 3) were constructed in 2014. Sections 2 and 3 have a two-course surface treatment (2-CST) as the wearing surface; section 1 has a thick HMA wearing surface that is not currently of concern for TxDOT. Figure 57 shows the section breakdowns using the Poor Surface + Structurally Weak filter in the Hawkeye system. Approximately 2.5 miles of section 3 were flagged as needing major rehabilitation, while the first 2 miles of this section (section 3) and all of section 2 were determined to be in good condition. The main type of distress occurring in the problematic 2.5-mile segment is excessive roughness. Several major humps have developed, where local measured IRI values exceed 500 inches/mile. Figure 58 shows the major change in condition midway through section 3, where the TSD deflection data relating to subgrade strength (D36–D60) indicates a very weak subgrade throughout the rough segment. District staff have requested a forensics study for sections 2 and 3 and subsequent rehabilitation recommendations.

Table 22. FM 99 Pavement Structures in TxDOT's Corpus Christi District.

Section	From–To (Westbound from IH 37)	Surface	Base	Subbase
1	Mile 0–2.3	7-inch HMA	8-inch FB	--
2	Mile 2.5–3.1	2-CST	11-inch foam treated base	3-inch FB
3	Mile 3.1–7.4	2-CST	8-inch FB	6-inch CTB

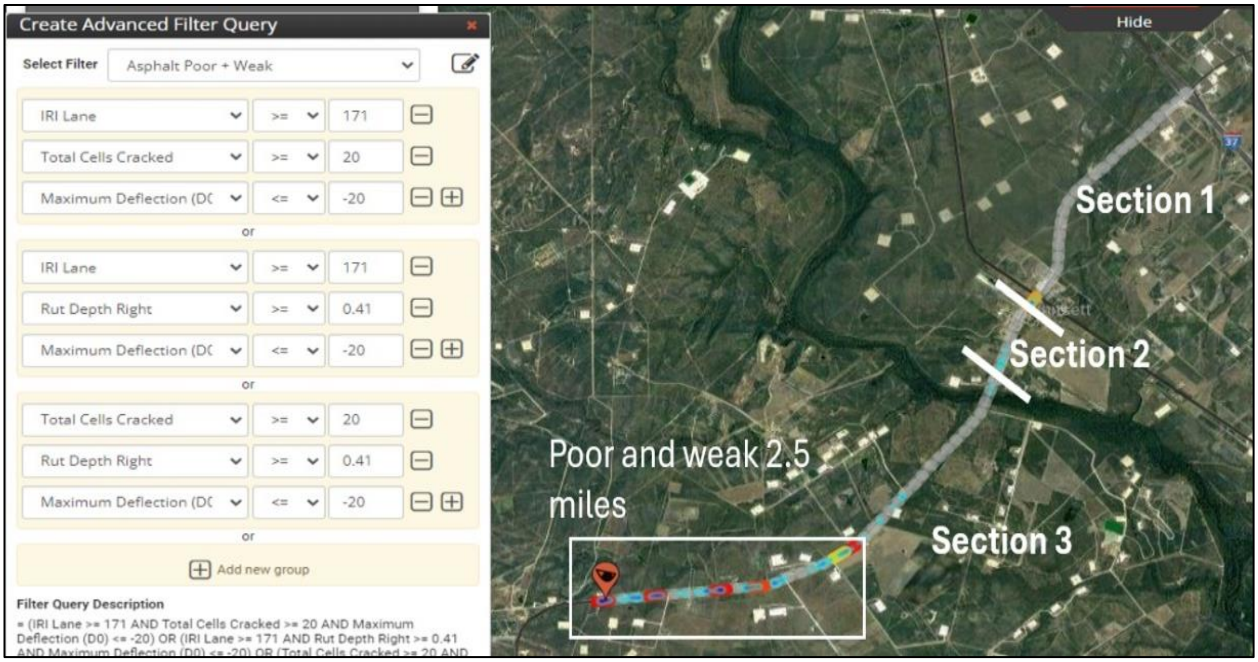


Figure 57. Screenshot of the FM 99 Section Breakdown Using the Hawkeye System's Poor Surface + Structurally Weak Filter.

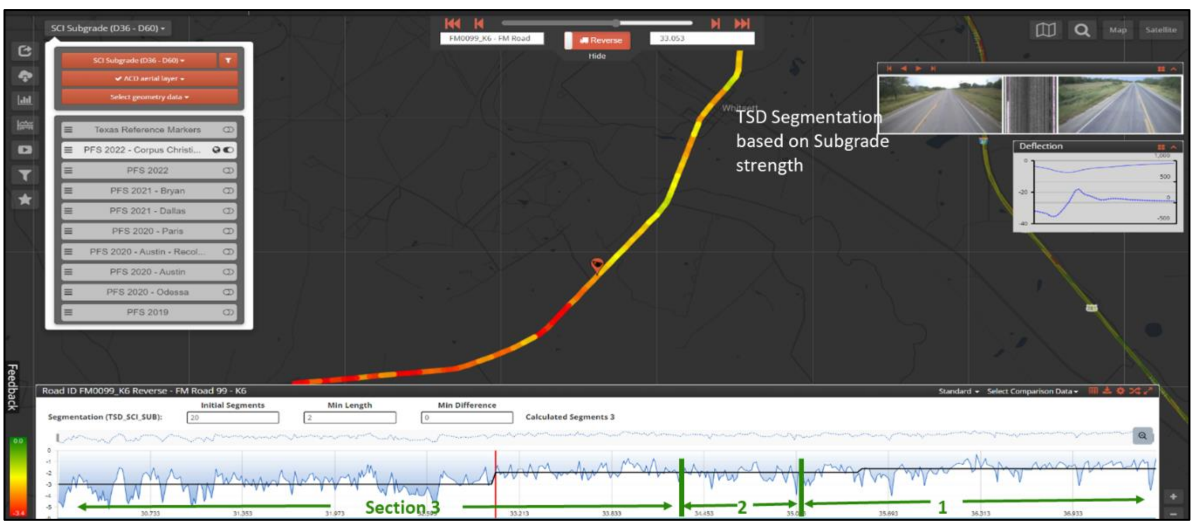


Figure 58. Screenshot of the FM 99 Subgrade Strength Plot and Segmentation Recommendations from the Hawkeye System.

In response to district staff requests, a field investigation was initiated, additional nondestructive testing was completed, and coring and auger samples were taken for the sections of concern. Figure 59 shows a soils map obtained from the United States Department of Agriculture (USDA) that indicates very high plasticity index (PI) clays present throughout the rough segment.

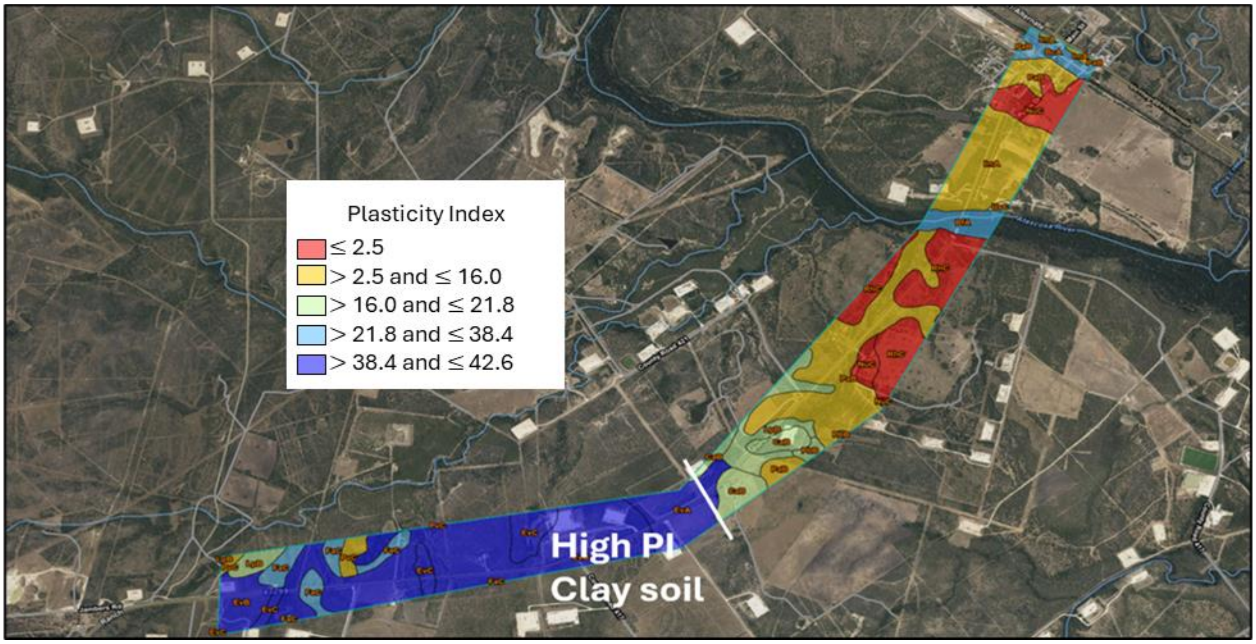


Figure 59. USDA Soils Map for FM 99 in TxDOT's Corpus Christi District.

The presence of clay was validated in the field. Figure 60 shows the soils taken from the bore holes in the excessively rough part of FM 99. The soils 46–60 inches below the surface were found to have a PI of 72; the swelling of these soils was determined to be the cause of the excessive roughness on FM 99. These data were used to determine a potential vertical rise of over 4 inches; the maximum recommended potential vertical rise for low-volume roadways is 2 inches [10]. Based on these findings, the following project-level recommendations were made:

- For section 2 and half of section 3, patching any localized cracked areas (very few areas were identified using the TSD data) is recommended, and then placing a thin overlay to improve the ride.
- For the problematic 2.5-mile-long section, we recommend a full reconstruction that involves removing the top 23 inches of material and then applying a stabilizer (e.g., lime) or completely replacing the top 3 feet of subgrade soil with low PI materials is recommended. If lime stabilization is to be considered, additional tests are needed to check for sulfates.

Texas A&M Transportation Institute

Coring Log

District	Corpus Christi	**Core Date**	6/18/2024
Roadway	FM 99	**Site Number**	3
TRM	269+0.1	**Core Number**	1
Location	Next to CL	**Cored by**	Tony Barbosa

Depth			**Description**	**Comment**	
0	-	2	Asphalt		
2	-	7.5	Top Base		
7.5	-	13	Middle Base		
13	-	23	Bottom Base		
23	-	45	Dark Brown Clay	LL = 68	PI = 64
46	-	60	Light Brown Clay	LL = 99	PI = 72
60	-	72	Tan Sandy Clay	LL = 72	PI = 49
72	-	84	Tan Sandy Clay	LL = 71	PI = 49

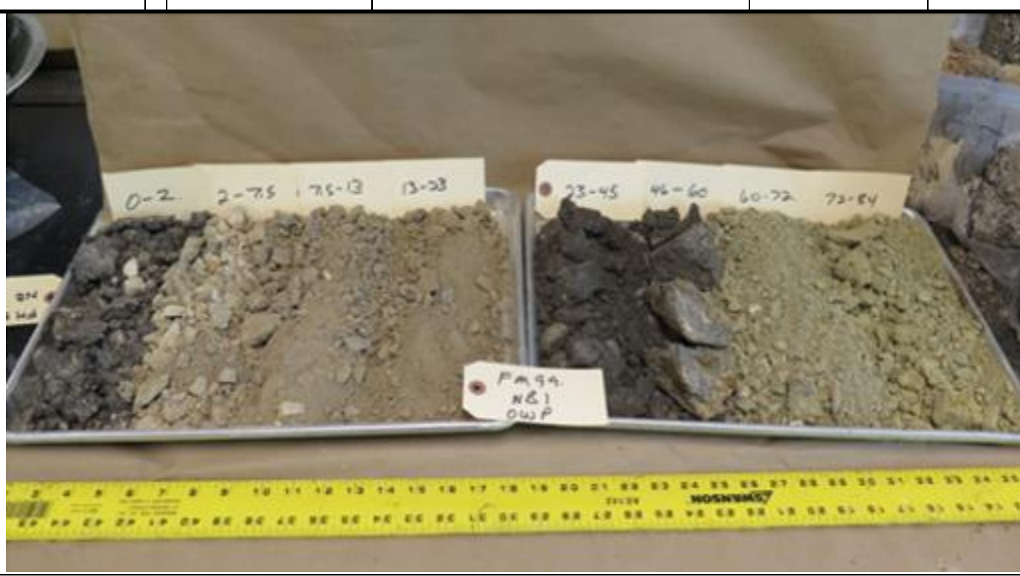


Figure 60. Auger Hole Soils for FM 99 in TxDOT's Corpus Christi District.

The TSD and FWD deflection data collected on FM 99 allowed researchers to correlate the backcalculated subgrade modulus values determined from the MODULUS (Version 7.0) software using FWD data and TxDOT's standard pavement design methods with the raw TSD SCI 36–60 data. Figure 61 shows these correlation results. The correlation appeared reasonable, with R^2 values ranging from 0.5 to 0.6 across multiple iterations. Slightly higher R^2 values were obtained with an exponential equation, but such formulations can be unrealistic at low TSD values. Combining data from several runs, the following equation was developed:

$$\text{Subgrade modulus (ksi)} = 22.3 - 3.7 \times (\text{SCI } 36\text{–}60) \qquad \text{(Eq. 9-1)}$$

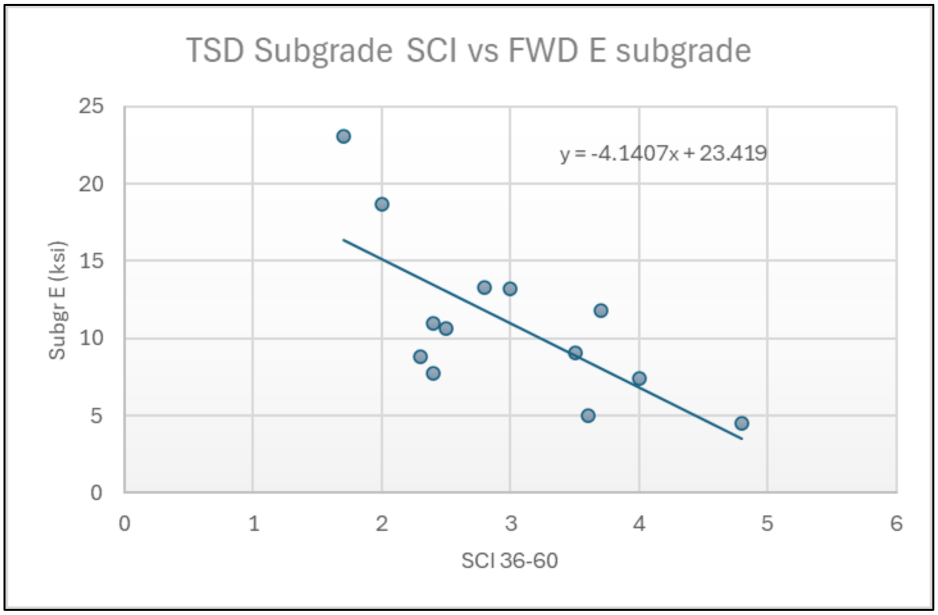


Figure 61. Correlation Between FWD and TSD SCI 36–60 Based Subgrade Modulus Values on FM 99.

OSR IN TXDOT'S BRYAN DISTRICT

As part of a larger TSD loop in 2022, data were collected on the OSR in the EB direction from SH 21 to IH 45 in Normangee in TxDOT's Bryan District. Figure 62 shows the reported maximum deflection values; the green color indicates low deflections and the red color indicates high deflections. In addition to the TSD data, TTI researchers collected GPR data along the same route to evaluate the pavement structure. Researchers first determined the roadway section's construction history and traffic and pavement structure characteristics. Next, they compared the collected TSD data to measured FWD data collected in 2024. The data were used to assist district staff in assessing overall pavement conditions and premature failures following a hard freeze and heavy rainfall in early 2024. The TSD data successfully identified at-risk pavement sections in need of maintenance and/or structural repair.

This portion of the OSR was separated into five sections based on the differing traffic characteristics: (1) from SH 21 to FM 1687, (2) from FM 1687 to US 190, (3) from US 190 to the Madison county line, (4) from the Brazos county line to Normangee, and (5) from Normangee to IH 45. Table 23 details the ADT, truck percentages, and ESALs for each of these five sections. In general, traffic decreases in the eastbound direction, with the highest traffic totals near US 190. Traffic volumes in Madison County were much lower than in Brazos County.

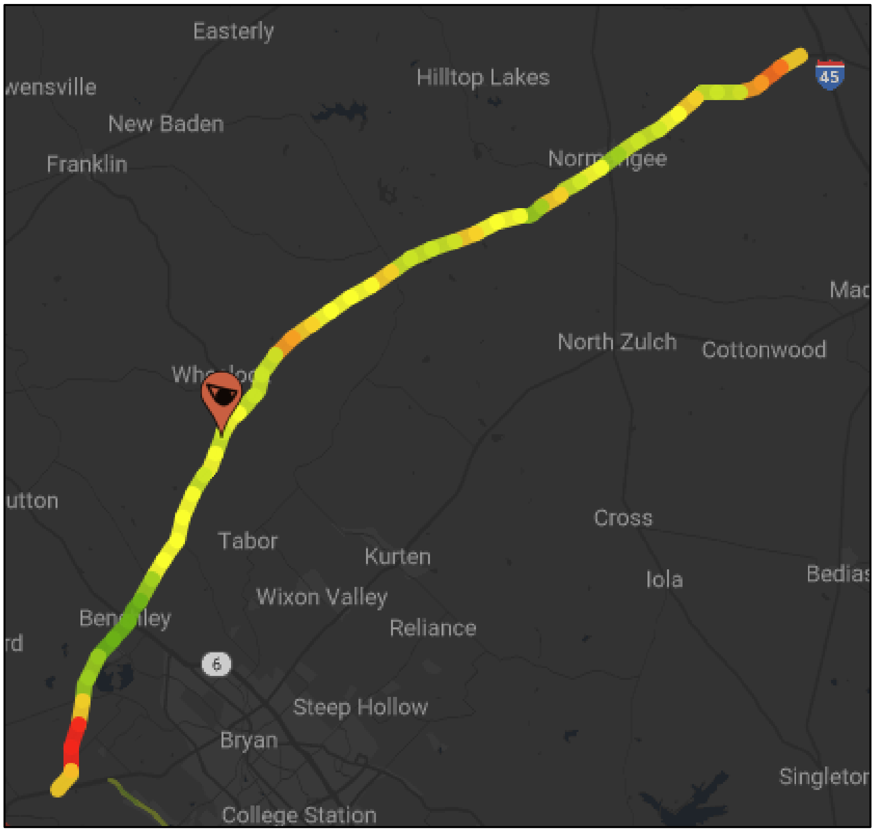


Figure 62. Screenshot of the OSR Measured Maximum Deflection Values from the Hawkeye System.

Table 23. Traffic Characteristics on Five OSR Sections in TxDOT's Bryan District.

Limits	SH 21–FM 1687	FM 1687–US 190	US 190–Madison County Line	Brazos County Line–Normangee	Normangee–IH 45
2022 ADT	1723	3883	3384	1282	2285
2042 ADT	2964	5902	4738	1795	3199
Percent trucks	37	28	13	20	15
ESALs (million)	3.86	6.06	2.35	1.40	1.85

This portion of the OSR was considered for the TSD loop because it had been reconstructed in 2018 and 2019. Table 24 describes the reconstructed sections, which included various combinations of one-course surface treatments (OCSTs), HMA layers, seal coats, FBs, cement stabilized subgrades, and foam stabilized bases/subbases. Following a hard freeze and heavy rainfall in early 2024, the sections with surface treatments instead of HMA were failing. District staff requested that TTI researchers use the measured TSD data to evaluate these failed sections and determine if they were structurally inadequate prior to the severe weather.

Table 24. OSR Reconstruction History.

2018		2019	
Brazos county line to 6.5 miles east of SH 39		**FM 1687 to Madison county line**	
Surface Treatment	**HMA**	**Surface Treatment**	**HMA**
Three OCSTs	3.05-inch HMA layer over an OCST	Seal coat and two OCSTs	Two 3-inch HMA layers
12-inch FB	8-inch FB	8-inch FB	12-inch foam stabilized base
11-inch stabilized subgrade	12-inch cement stabilized subgrade	10-inch foam stabilized subbase	

District staff collected FWD data along the failed section of the OSR in February and March following the freeze. Figure 63 compares this data to the maximum deflection data collected using the TSD device in 2022. The TSD and FWD data matched very well from SH 6 to the Madison county line (Navasota River). Although the measured FWD deflections were greater than the measured TSD deflections, these differences were consistent with expected aging over two years. This section of the OSR was not necessarily structurally adequate for the traffic, but the distresses brought on by the severe weather did not greatly affect its pavement strength. Comparatively, the differences between the measured FWD and TSD deflections from the Brazos county line (Navasota River) to SH 39 were substantially greater, suggesting other factors at play in addition to aging. For this section of the OSR, this trend indicated that the severe weather experienced in 2024 had a significant impact on the structural strength of the pavement.

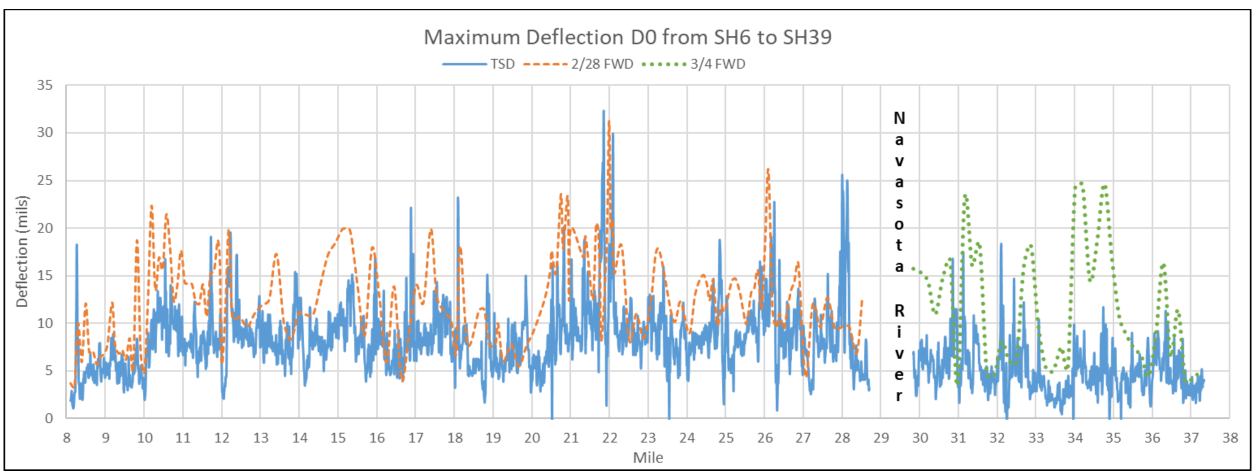


Figure 63. Comparison of FWD and TSD Maximum Deflection Data on the OSR.

Figure 64 shows an annotated plot of the maximum deflection (in blue) on the lower half, the TSD rut depth (in black), and the TSD cracking totals (in red and green) on the top half generated from the Hawkeye system's data viewer feature. These data were used to identify two potential sections of interest. The Structural Issue? section had high deflections and rutting. The Surface Issue? section had lower deflections but high rutting and cracking.

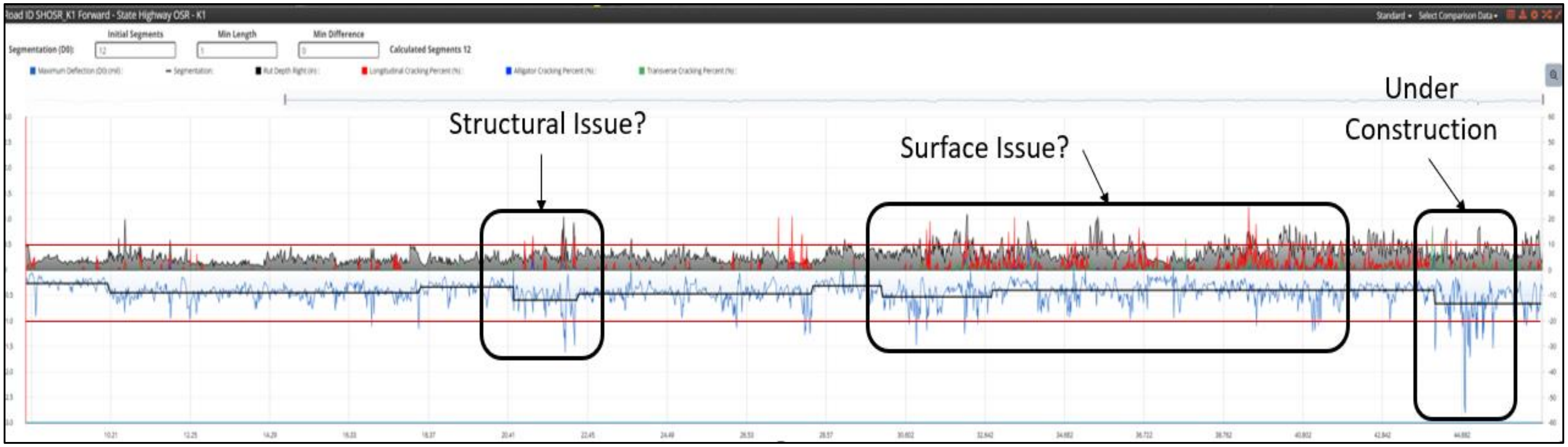


Figure 64. Annotated Plot of Maximum Deflection, TSD Rut Depth, and TSD Cracking Generated by the Hawkeye System to Identify Potential Surface and Structural Issues.

Consistent with the potential structural issues identified using the Hawkeye system, imagery data from the TSD and GPR devices revealed faulting in the outside wheel path (OWP) of this section. The surface was repaired in 2024 following the freeze, but the observed faulting after the repairs indicated that the structural issue persists. Figure 65 (a) and (b) show TSD images from 2022 and GPR images from 2024, respectively.

(a)

(b)

Figure 65. Images Depicting Potential Structural Issues on the OSR: (a) 2022 TSD Image and (b) 2024 GPR Image.

The second section of interest identified using the Hawkeye system had potential surface issues (i.e., high rutting and cracking). The TSD imagery data showed patch repairs in the OWP that contributed to the high reported cracking levels. Figure 66 compares the imagery and deflection data collected by the TSD device in 2022 and the FWD/GPR devices in 2024. The images indicated that this section also failed and was repaired in 2024, but the FWD data indicated that the pavement structure may now also be compromised.

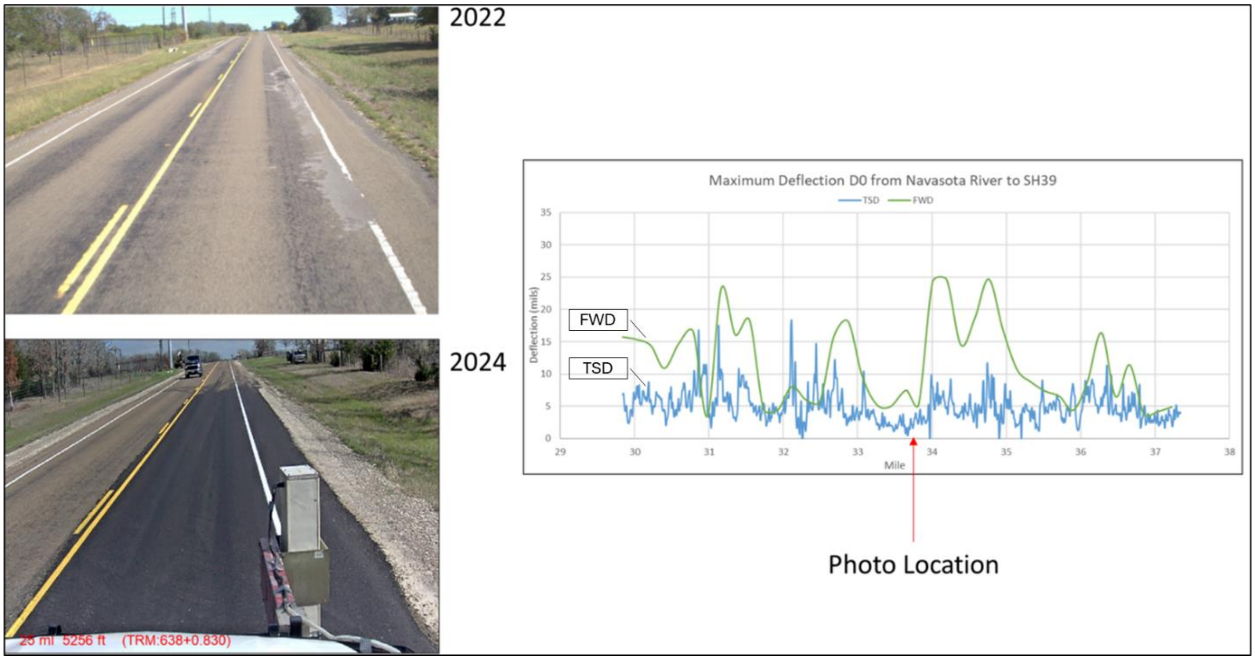


Figure 66. Images Depicting Potential Surface Issues and a Maximum Deflection Plot Suggesting Potential Structural Issues on the OSR.

The analysis of both the 2022 TSD and 2024 FWD/GPR data discussed in this case study has been shared with district staff. The sections identified using the TSD data are being considered for structural repair. Additionally, district staff have received training regarding the use of the Hawkeye System’s data viewing feature and intend to utilize the collected data to identify additional projects within their district.

CHAPTER 10. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE DEVELOPMENT

TxDOT has been actively collecting TSD data since 2019 and aims to continue collecting network-level data using TSD equipment. Staff in each district have reviewed their respective data and are looking for ways to implement it in project identification and planning tasks. To this end, TSD data processing methods are successfully being employed in current TxDOT pavement management methods, representing a vital step in delivering TSD data into the hands of district engineers and designers. The primary strength index used in TxDOT's PA system is the SCI, which relies heavily upon current in-situ pavement structure, functional distress, and traffic values. However, the understanding and use of this methodology at the district level is lacking, and the necessary pavement information is insufficient at the network level. Therefore, enhancements to current TSD processing methods and pavement structural indicators are essential to maximize the returns of TSD data collection.

TSD DATA COLLECTION AND ANALYSIS

In 2021 and 2022, TxDOT collected over 400 miles of TSD data in the Bryan District. TTI researchers used this opportunity to evaluate the accuracy and repeatability of TSD data compared to current TxDOT practice. The TSD data collected on SH 47 in both years was evaluated and compared in this report. For both years, the TSD deflection data matched the FWD data trends for the same pavement sections. Based on the sensor correlation matrix, the first seven TSD sensors correlated best with the corresponding FWD sensors. The computed SCI and BCI indices from the TSD data correlated well with those computed from the FWD data, but the computed M_r from the TSD did not match the M_r computed from FWD for either dataset. Based on the results presented in this report, the M_r calculated from the TSD data was not recommended for determining subgrade strength.

Although the TSD data collected in both years trended well with the FWD data, some discrepancies were found in the computed deflection data. The 2021 TSD data had many more invalid deflection bowls for the same pavement sections than the 2022 TSD data. The 2022 TSD deflection data matched the FWD deflection data to a higher degree, especially for pavement sections for which both devices reported low deflections. It was suggested that these disparities may be due to environmental factors, such as seasonal temperature and rainfall. Table 25 shows the average temperature and reported rainfall for the data collection dates according to regional climate surveys conducted by the National Oceanic and Atmospheric Administration [11] [12]. Because the average temperature during the 2022 collection period was greater than the average temperature during the 2021 collection period and the average rainfall during the 2022 collection period was less than the average rainfall during the 2021 collection period, it was concluded that seasonal environmental changes were not the cause of the suspect 2021 data.

Table 25. Temperature and Rainfall During Bryan TSD Data Collection.

Collection Loop	2021 Collection	2022 Collection
Date	March 2022	October 2022
Average temperature (°F)	61.5	71.4
Total rainfall (inches)	3.56	1.85

Because the TSD data collected on the SH 47 test sections in 2021 was determined to be unreliable, it was omitted from the final sensor correlation matrix for the FWD and TSD data. Based on the results generated from the TSD collection in TxDOT's Bryan District, the following recommendations were made:

- Future TSD data collection efforts should focus primarily on flexible pavement types because rigid pavement types have low rates of return.
- Future TSD data collection efforts should include a validation method for TSD devices, such that inaccuracies are discovered before the data are delivered.

TSD DATA APPLICATIONS

The standard TSD data delivery method is via the ARRB System's Hawkeye System data viewer. Use of the Hawkeye system has yielded positive results at the project level but must continue to be verified. The included SCI 36–60 deflection index had good correlation with the subgrade modulus and successfully identified locations with poor subgrade materials. Additionally, the TSD deflection and imagery data within the Hawkeye system has been used in tandem with GPR, condition, and accurate traffic data to effectively identify at-risk pavements. We recommended that the pavement classification code within TxDOT's PA system be used to identify pavement type and thickness. The Hawkeye system also has the ability to filter TSD data based on user prompts. Four filters are preloaded in the system to identify pavements that have good/poor surface condition and good/poor structural condition. The pavements identified by these filters were in good agreements with the observations and four-year plans made by district staff. As such, we recommended that all collected TSD data be categorized according to these filters.

For the purpose of leveraging TSD data within existing TxDOT pavement management practices, the accuracy of TSD crack detection is unverified. Crack detection was generally good on pavements with HMA surfaces, but the TSD device produced poor cracking values on pavements with chip seals. Temperature correction is also recommended for deflection data collected on thick asphalt pavements (surface > 3 inches), as is the current practice.

The TSD deflection data were configured to run through the MODULUS software's remaining life routine. The layer strength classifications produced from the TSD data adequately classified the upper and subgrade layer strengths compared to the FWD data; however, the lower layer strength classifications generated from the TSD data typically overestimated the material strength. The TSD rut remaining life estimates (which include lower layer strength as a variable) were much greater than estimates based on the FWD data, but the crack remaining life estimates were in good agreement with estimates based on the FWD data. More testing is required to validate the TSD layer strength classifications and remaining life estimates before their use at the network level is endorsed.

3D-MOVE SOFTWARE APPLICATIONS

The 3D-Move software was evaluated as a potential TSD data processing and backcalculation tool. The program was able to simulate pavement responses under static and dynamic loading conditions with reasonable accuracy regardless of pavement thickness and vehicle speed. However, the accuracy of the simulated responses decreased as the distance from the load center increased.

The proposed experimental backcalculation procedure overestimated the modulus values compared to the FWD backcalculations from the MODULUS software. Backcalculated subgrade values were in good agreement with the FWD estimates, but the experimental procedure was unable to suitably backcalculate layers with high modulus values. Future testing of this backcalculation procedure will proceed as follows:

- Evaluate the effects of additional subbase pavement layers.
- Investigate the effects of different base, subbase, and subgrade materials.
- Incorporate multiple variable pavement layers to more accurately backcalculate pavement structures with a variety of material qualities.

CHAPTER 11. VALUE OF RESEARCH (VOR)

This study clearly demonstrated that the TSD data correlates well with the TxDOT current FWD device. The savings that are determined for the VOR assume that the TSD will increasingly replace the FWD for structural testing. The savings originate from the fact that the TSD can collect data at highway speeds with no additional traffic control cost. The FWD by nature is a stop-and-go operation which needs a moving traffic control operation. The TSD can collect 400 miles of deflection data in one day. To do the same data collection with the FWD will require 10 days for a two-man crew.

For this estimated VOR, it was assumed that TxDOT will collect 400 miles of TSD data in year 1, and this will increase on an annual basis by 200 additional miles each year. Labor cost for 2 technicians for 10 days was estimated to be $6,400, the traffic control cost for a private contractor was estimated to be $25,000, and the FWD operation service cost was estimated to be $2,000 for the 10 days. The current total cost for 400 miles of FWD data collection was estimated to be $33,400. The expected savings will be increased each year as the amount of data collected by the TSD increases. The expected value duration is based on the expected average pavement life (20 years). The Discount rate is based on OMB Circular No. A-94 for the 7-year Nominal Interest Rated on Treasury Notes and Bonds, which is %4.4. The expected value per year is based on a savings of labor and contracting costs. Table 26 contains the basic project values and the savings per year. Figure 67 is a graph of the change in value over time. Table 26 contains the VOR benefit areas.

Table 26. TxDOT VOR Form Basic Data.

Description	Value	Years	Expected Value
Project #	0-7107	0	$33,400
Project Name:	Determine the Feasibility of using the Structural Data from the TSDD for Network- and Project-Level Decision-Making	1	$50,100
Agency:	TTI	2	$75,150
Project Duration (Yrs)	3.0	3	$112,725
Expected Value Duration (Yrs)	20	4	$169,088
Project Budget	$400,007	5	$253,631
Exp. Value (per Yr)	$166,345.5	6	$380,447
Discount Rate	4.4%	7	$570,670
Economic Value Total Savings:	$332,690.52	8	$856,005
Payback Period (Yrs):	0.0129	9	$1,284,008
Net Present Value (NPV):	$1	10	$1,926,012
Cost Benefit Ratio (CBR, $1:$_):	244	11	$2,889,018

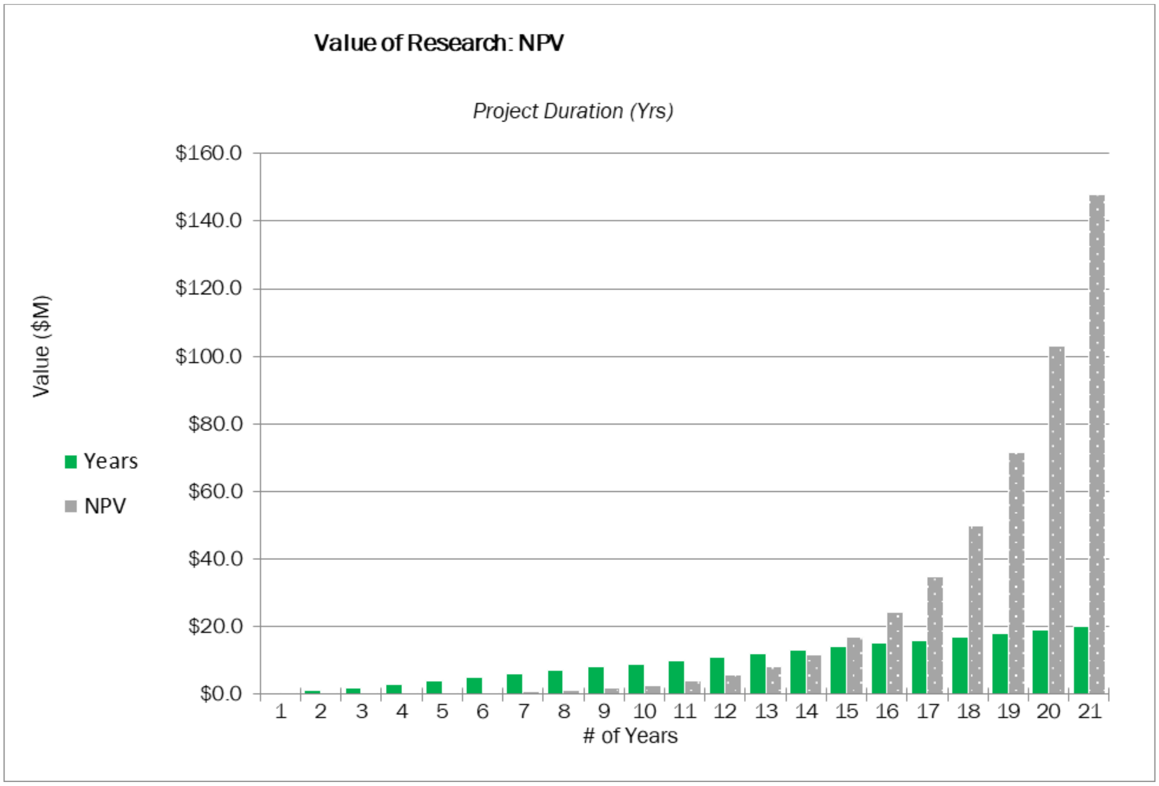


Figure 67. VOR, Net Present Value.

Table 27. VOR Benefit Areas.

Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both	Definition in context to the Project Statement
Level of Knowledge	X			X			This project will greatly enhance the Receiving Agency's utilization and understanding of TSD data within network- and project-level pavement management applications through the verification and validation of TSD data.
Management and Policy	X			X			This project will promote better prioritization of roadways within the existing pavement management framework by developing methodologies to assist the Receiving Agency in implementing standardized TSD data reporting practices.
Environmental Stability	X				X		TSD data delivers high-frequency structural data that will allow the Receiving Agency to enhance the existing pavement management database and assist in prioritizing pavement treatment and rehabilitation projects, potentially reducing the number of large-scale reconstruction projects.
System Reliability		X		X			This project has shown the TSD system has good repeatability, but data validation practices must be followed.
Increased Service Life		X		X			By incorporating TSD data into the existing pavement management system, the Receiving Agency will have a better understanding of pavement structural conditions in the field, allowing for more specialized maintenance practices that will increase service life.
Traffic and Congestion Reduction		X			X		By eliminating the stop and go data collection associated with FWD testing, the TSD will reduce congestion.
Materials and Pavements		X			X		Collecting continuous deflection data will better permit TxDOT designers to select the optimum rehab strategy.
Infrastructure Condition		X				X	This project has shown the TSD can be utilized for network- and project-level operations to deliver pavement structural condition metrics at a high frequency along the roadway.
Safety			X			X	The TSD collects structural data at traffic speed, eliminating the need to stop in traffic for data collection.

REFERENCES

[1] Federal Highway Administration, "TPF-5(385) PAvement Structural Evaluation with Traffic Speed Deflection Devices (TSDDs)," 2024.

[2] ARRB Systems, "intelligent Pavement Assessment Vehicle iPAVe," ARRB Systems, Melbourne, Australia.

[3] M. A. Elsefi and Z. U. A. Zihan, "Assessment of the Traffic Speed Deflectometer in Louisiana for Pavement Structural Evaluation," 2018.

[4] I. Březina, J. Stryk and J. Grošek, "Using Traffic Speed Deflectometer to Measure Deflections and Evaluate Bearing Capacity of Asphalt Road Pavements at Nework level," 2017.

[5] S. Thyagarajan, "Implementation of Structural Strength Data for Network-Level Pavement Management," 2021.

[6] M. Nasimifar, S. Thyagarajan, S. Chaudhari and N. Sivaneswaran, "Pavement Structural Capacity from Traffic Speed Deflectometer for Network Level Pavement Management System Application," Transportation Research Record, 2019.

[7] E. Hajj, *3D-Move Analysis Help Topics.*

[8] T. Akram and T. Scullion, "Estimating Damage Effects of Dual vs. Wide Base Tires with Multidepth Deflectometers," Texas Departmant of Transportation, Austin, TX, 1992.

[9] T. Akram and T. Scullion, "Comparing Pavement Responses Under FWD and Truck Loads," Texas Department of Transportation, Austin, TX, 1992.

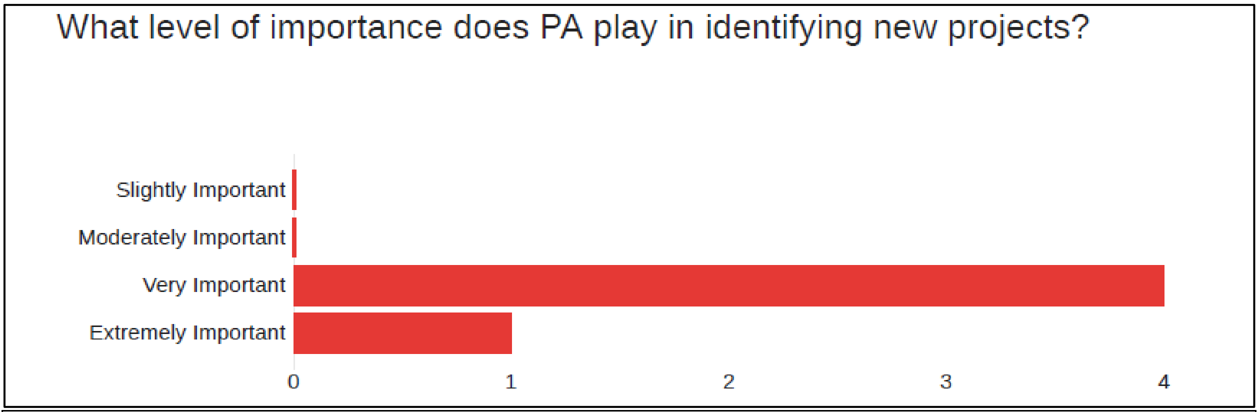
[10] Texas Department of Transportation, *Memorandum: Guidance on Potential Vertical Rise (PVR) for Design,* 2009.

[11] J. Fowler, *NWS Houston, Texas March 2022 Regional Climate Summary,* National Oceanic and Atmospheric Administration, 2022.

[12] J. Fowler, *NWS Houston, Texas October 2022 Regional Climate Summary,* National Oceanic and Atmospheric Administration, 2022.

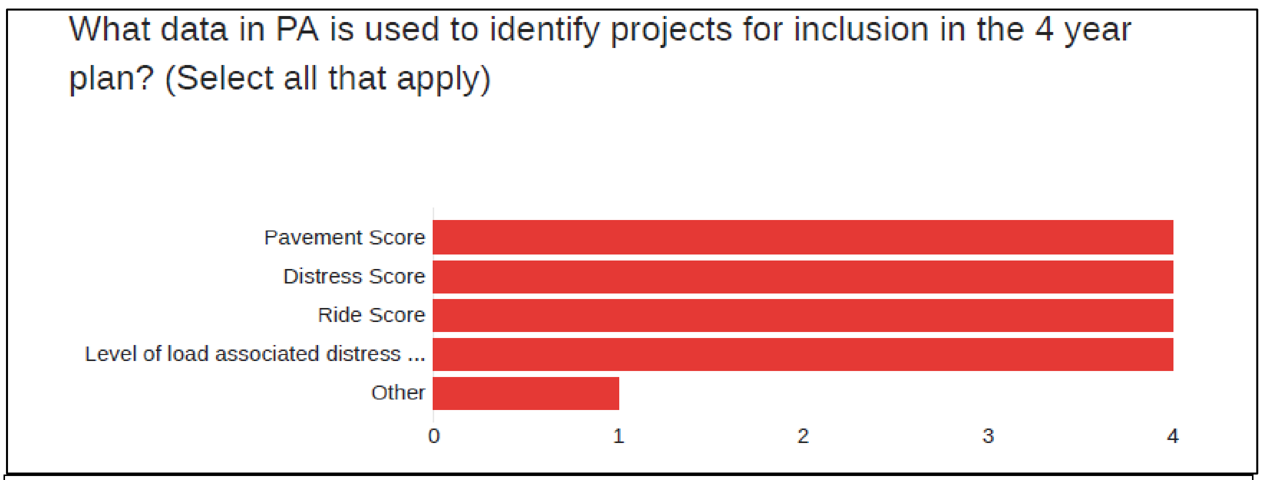
[13] K. Maser, P. Schmalzer, A. Gerber and J. Poorbaugh, "Implementation of the Traffic Speed Deflectometer for Network Level Pavement Management," 2019.

APPENDIX A: TXDOT DISTRICT SURVEYS

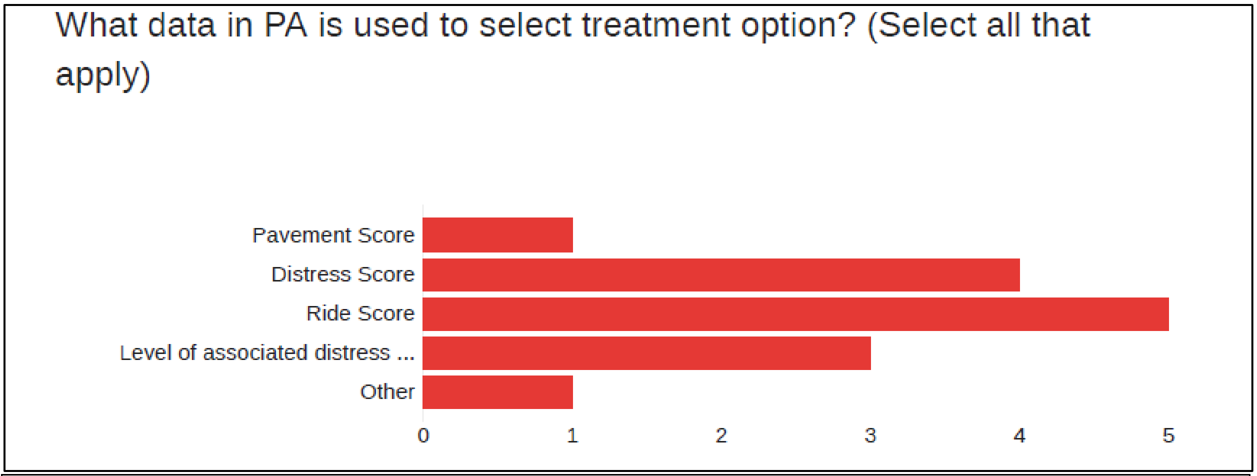


Field	Min	Max	Mean	Standard Deviation	Variance	Responses
Level of Importance	3	4	3	0	0	6

Field	Choice Count
Slightly Important	0
Moderately Important	0
Very Important	4
Extremely Important	1
Total	5

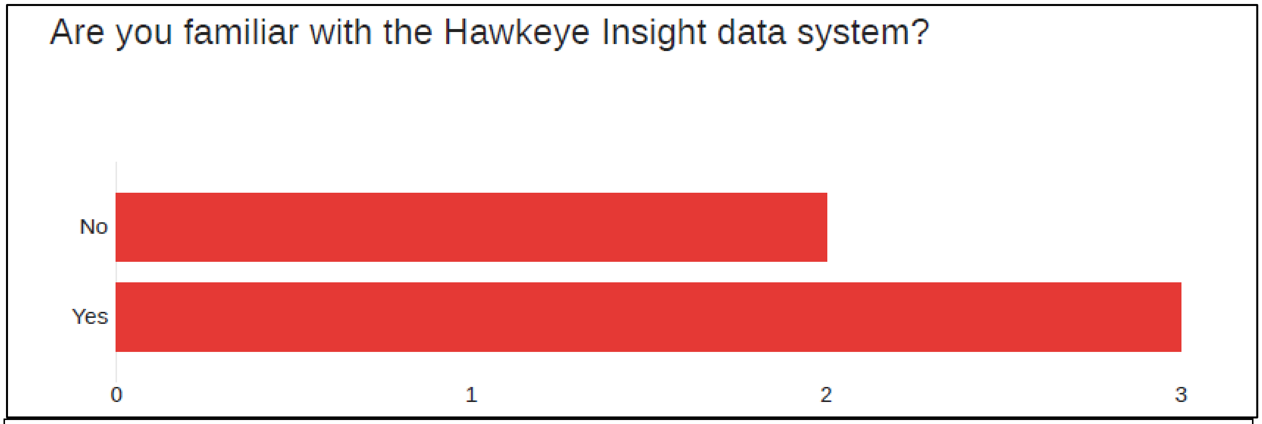


Field	Choice Count
Pavement Score	4
Distress Score	4
Ride Score	4
Level of load associated distress (rutting, alligator, failures)	4
Other	1
Total	17



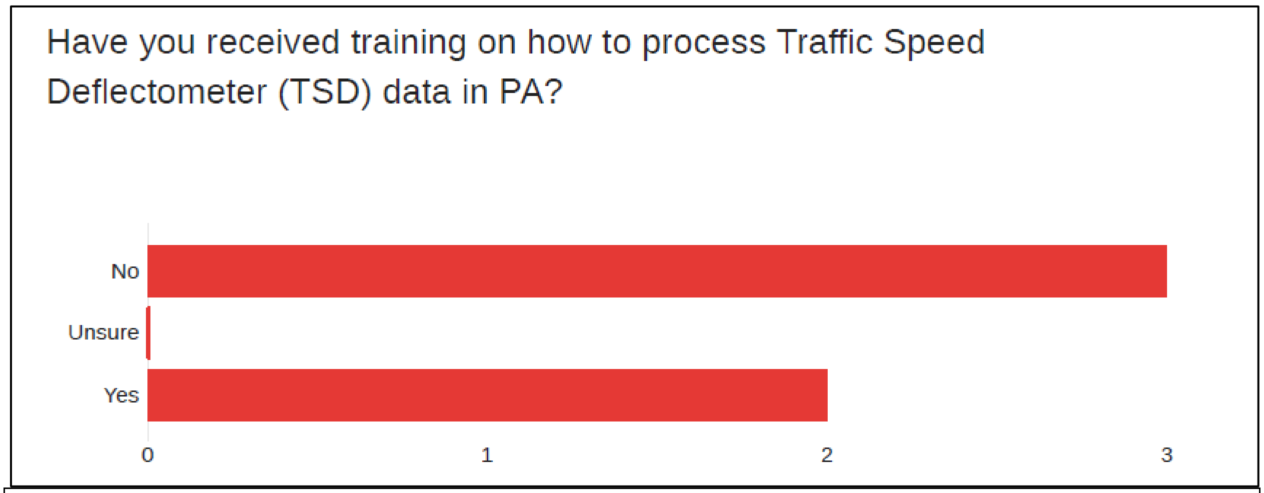
Field	Choice Count
Pavement Score	1
Distress Score	4
Ride Score	5
Level of load associated distress (rutting, alligator, failures)	3
Other	1
Total	14

How can the PA system be improved to better fit your needs?
A report that merges the "section needs" report/data with the planned projects in TxDOTConnect and MMS where the district can compare the recommended treatment and the planned treatment. Having the data merged would make it easier to compare what needs are already being met and allow the district to then analyze the suggested unmet needs. Consider allowing PA to pull projects with other funding sources that have pavement work planned. That could have an impact on the predicted PMIS score analysis that is performed each year. The data would be more useful if it had a more graphical user interface to interact with it, i.e. a map that you can select roadways and define limits with and with overlays that can be turned on and off depending on the type of data you're looking for.



Field	Min	Max	Mean	Standard Deviation	Variance	Responses
Are you familiar with the Hawkeye Insight data system?	1	2	2	0	0	5

Field	Choice Count
No	2
Yes	3
Total	5



Field	Min	Max	Mean	Standard Deviation	Variance	Responses
Have you received training on how to process Traffic Speed Deflectometer (TSD) data in PA?	1	3	2	1	1	5

Field	Choice Count
No	3
Unsure	0
Yes	2
Total	5