

State of Florida



Enhancement of Traffic Control Tool for Reopening of Flooded Roadways

Final Report

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.196	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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16. Abstract Flooding can temporarily reduce the structural capacity of flexible pavement due to increased moisture in the unbound pavement layers including the embankment, which may accelerate fatigue cracking and rutting when traffic is restored before the pavement has sufficiently recovered. The Florida Department of Transportation (FDOT) has previously developed a procedure to support pavement resiliency and post-flood traffic control decisions; however, additional considerations were needed to better evaluate allowable traffic following flooding events. The primary objective of this research project was to enhance FDOT's traffic control (i.e., decision making) tool for reopening of flooded roadways through the development of a Falling Weight Deflectometer (FWD)-based methodology for evaluating flexible pavement structural condition under flooded conditions. The study evaluated relationships between pavement structure, measured FWD deflections, and critical pavement responses including tensile strain at the bottom of the asphalt concrete layer and compressive stress on top of the embankment. These relationships were incorporated into fatigue and rutting analyses to estimate allowable traffic and support post-flood traffic control decisions. The resulting methodology was implemented into an Excel-based tool that allows the user to import FWD data, estimate critical pavement responses, evaluate fatigue and rutting criteria, and obtain traffic control recommendations based on the estimated roadway traffic and current flood condition. The newly developed procedures and the tool provide FDOT with a practical framework for incorporating pavement structural condition into flooding resiliency assessment and post-flood traffic control decisions.			
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EXECUTIVE SUMMARY

Flooding can adversely affect the structural capacity of flexible pavements by increasing the moisture content within the unbound pavement layers and the roadway embankment. The resulting reduction in foundation support may increase critical pavement responses and accelerate the initiation and progression of major distresses such as fatigue cracking and rutting, particularly when normal traffic is restored before the pavement structure has sufficiently recovered its strength. Therefore, assessment of the potential for traffic-induced damage in flooded pavement systems is an important component of pavement resiliency and post-flood traffic management.

The Florida Department of Transportation (FDOT) previously developed a traffic-control decision matrix to provide guidance on roadway restrictions following flooding events based primarily on traffic level, observed (or current) flood condition, and the embankment resilient modulus estimated from Falling Weight Deflectometer (FWD) measurements. The primary objective of the current study was to enhance the flexible pavement traffic control tool by improving its ability to assess the potential for traffic-induced damage.

To support this objective, available literature and existing FDOT practices related to pavement resiliency were reviewed, and a methodology was developed using FWD measurements and pavement structural information. As part of the methodology, a synthetic database of pavement structures, FWD deflection basins, and corresponding critical pavement responses was developed using Layered Elastic Analysis (LEA). Using this database, empirical relationships were developed between FWD deflections, pavement structural characteristics, and critical pavement responses (i.e., tensile strain at the bottom of asphalt concrete and compressive stress on top of the embankment). These empirical relationships were then used to estimate critical pavement responses of the flooded pavement sections from field-measured FWD data. Finally, the estimated critical responses were used as inputs into the fatigue and rutting transfer functions to determine the allowable number of load repetitions for the pavement condition being evaluated.

The newly developed methodology was implemented into a macro-enabled Excel spreadsheet referred to as “FDOT’s Flexible Pavement Traffic Control Tool”. The tool allows the user to import FWD data, define pavement structures, estimate layer moduli and critical responses, evaluate fatigue and rutting criteria, and obtain a traffic control recommendation. The tool also includes a sensitivity analysis option that allows the user to evaluate the effect of multiple variables on the calculated fatigue and rutting criteria.

The methodology and tool developed through this study provide FDOT with an expanded approach for evaluating flexible pavement conditions and establishing traffic restrictions following flooding events, aligning with FDOT’s broader efforts to incorporate resilience into transportation planning, asset management, and operational decision-making.

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1. INTRODUCTION

In recent years, several studies have recognized the impact of climate change on highway pavements (Qiao et al., 2020; Saleh and Hashemian, 2022; Matini et al., 2022; Tseng et al., 2023; Chen and Wang, 2023; Abdollahi et al., 2024; Chen et al., 2026). Climate change may result in increased air temperature, more frequent flooding, and sea level rise, as well as devastating hurricanes. Over the past few decades, flooding and hurricanes have significantly impacted transportation infrastructure including pavements, foundations, and bridges, resulting in closure of roadways, delay in traffic, and economic loss in the U.S. and worldwide. The National Oceanic and Atmospheric Administration (NOAA) reported that tropical cyclones have caused more than \$1.5 trillion in damages in United States since 1980 with an average \$23 billion per event (NOAA, 2025). In addition, the increase in sea level – induced by both climate-related and non-climate-related causes – has the potential to degrade highway pavements through inundation of foundation layers (i.e., unbound materials).

State Highway Agencies (SHAs) are already spending substantial resources constructing and maintaining safe, smooth, and durable pavements. Highway pavement deterioration due to severe weather events including flooding and rising sea level are very costly and may require a significant increase in SHAs' budget to recover the infrastructure damaged due to severe weather, as illustrated in the following examples.

Within the last decade, states in the Midwest including Missouri, Illinois, and Arkansas were impacted by flooding and experienced a period of heavy rainfall up to 15 inches, which caused severe damage to infrastructure. These severe weather conditions incurred an estimated cost of \$1.8 billion (Smith et al., 2020).

Flooding of the Missouri River in 2011 impacted several cities in Missouri and Iowa including paved and unpaved roadways, bridges, culverts, and embankments, and caused traffic closures on several interstate highways. Falling Weight Deflectometer (FWD) testing conducted within 30 days after flooding showed that the average pavement modulus values in flooded zones were about 1.3 to 3.6 times lower than the non-flooded pavements (Vennapusa et al., 2013; Vennapusa et al., 2016). The monetary damage caused by Missouri River flooding on primary and secondary highways was about \$63.5 million (Vennapusa et al., 2013).

Gaspard et al. (2007) evaluated inundated pavements in New Orleans, Louisiana due to Hurricane Katrina and found a significant reduction in modulus of foundation layers for both concrete and asphalt pavements. The study showed that the strength and resilient modulus of inundated asphalt pavement foundations were more significantly impacted than those of rigid pavements. The inundated asphalt pavements lost strength equivalent to approximately 2 inches of new asphalt concrete. The estimated cost for rehabilitating a 200-mile inundated asphalt pavement was \$50 million.

Excessive moisture in pavement foundation layers can significantly reduce the load bearing capacity, stiffness, and the longevity of pavement foundation (Rada and Witczak, 1981; Cary and Zapata, 2011; Ceylan et al., 2013). Historically, SHAs have had difficulties testing inundated pavements during and after a flooding event, and the time to reopen an inundated pavement after flooding has frequently been determined based on past experience along with visual inspection of pavement (Vennapusa et al., 2013; Elshaer, 2017). In addition, SHAs are faced with the challenge of precisely evaluating the structural capacity of the inundated pavement and selecting

remedial measures to extend the pavement service life. Such challenges, combined with the lack of assessment or evaluation of the inundated pavement foundation (i.e., base/subbase and embankment) and continuing climate change, may increase the rate of foundation degradation and cause extensive rehabilitation.

1.1. BACKGROUND

Inundated highways due to storms, hurricanes, and sea level rise have caused dramatic losses in Florida's economy. Historically, Florida has experienced a number of hurricanes and storms due to its geographical location and ongoing climate change. As shown in Figure 1, annual precipitation has varied substantially, while hurricane events have occurred frequently throughout the historical record. Hurricane-force winds have affected Florida an average of three times every five years (Runkle et al., 2022).

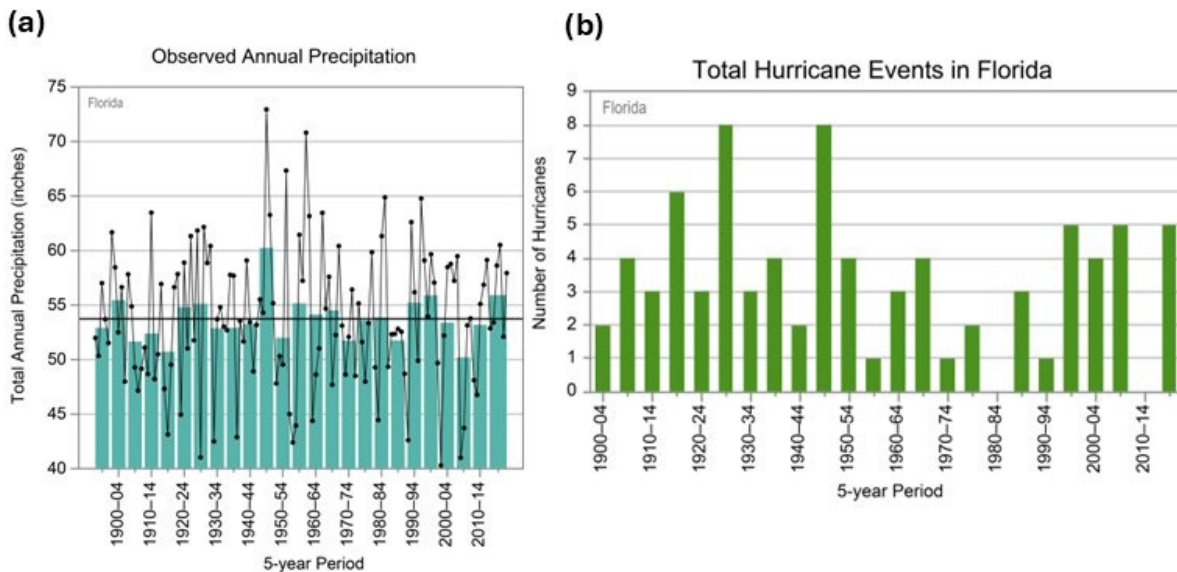


Figure 1. Historical precipitation and hurricane activity in Florida: (a) observed annual precipitation in Florida from 1895 to 2020 and (b) total hurricane events in Florida from 1900 to 2020. Adapted from Runkle et al., (2022).

Hurricane Opal was one of the most devastating natural disasters that impacted Florida (Leadon et al., 1998). This hurricane hit the Panhandle Coast of Florida in 1995. Many structures and roads located in different counties were significantly damaged and inundated. About a mile-long stretch of U.S. Highway 98 was damaged near Eglin Air Force Base and other highways were inundated.

The most unprecedented number of devastating hurricanes in Florida was observed in 2004, which caused significant damage to transportation infrastructure as well as to other properties. The estimated damage was \$41 billion (FDOT, 2005). These hurricanes are Charley, Frances, Ivan, and Jeanne. Pavement sections were damaged resulting in closure of roadways. In 2005, Hurricane Dennis caused severe damage to a section of SR-30 (US-98) in Florida from strong storms (Briaud and Maddah, 2016). This storm damaged a stretch of 14.6-miles highway in Franklin County, Florida.

In 2012, Storm Debby caused significant flooding and heavy rainfall for 36 to 48 hours across north Florida. As an example, Figure 2 shows a photo of a pavement completely submerged under water due to this storm (NOAA, 2020). The estimated rainfall was over 10 inches with a peak rate of 28.8 inches in 24 hours. Significant flooding struck many highways including a section of US-90, leading to closure of this section for a period of two weeks. The estimated cost of flood damage across Florida was over \$40 million and the total storm damage was estimated at \$250 million.



Figure 2. Flooding at Suncoast Parkway in Hernando County, FL (courtesy: *Tampa Bay Times*/Will Vragovic).

Hurricane Michael struck the Panama City area in Florida, which caused catastrophic damage and inundated large areas from Tyndall Air Force base down to Mexico Beach (Cleary et al., 2018). This hurricane caused severe damage to pavements where a number of highways remained closed for an extended period. The pavement was damaged due to raised water levels and high levels of storm surge.

Recently, Hurricane Nicole produced high waves, storm surge, and coastal flooding along Florida's Atlantic coast, damaging sections of SR-A1A in Flagler, St. Johns, and Volusia Counties. The storm washed out adjacent dunes, eroded roadway shoulders, and undermined portions of the roadway. FDOT completed emergency repairs and reopened the affected sections after approximately three days of work (State of Florida, 2022).

In addition to the devastating storms and hurricanes, sea level continues to rise in Florida with a large uncertainty in projections (Berry et al., 2012). The updated regional projection indicates that relative sea level in Southeast Florida could rise by 10 to 17 inches by 2040, 21 to 54 inches by 2070, and 40 to 136 inches by 2120, relative to the 2000 mean sea level at Key West, as shown in Figure 3 (Compact, 2020). Following a review of the projection against NOAA's 2022 scenarios and observed regional trends, the researchers recommended its continued use for resilience planning, design, and construction (Compact, 2024). The major cause of sea level rise in Florida is contributed by the impact of global warming (Bloetscher et al., 2014). Infrastructure closer to the shoreline in Florida are more prone to the impact of sea level rise and has higher

potential for storm surge damage, surface water flooding, and damaged coastal infrastructure (Knott et al., 2017).

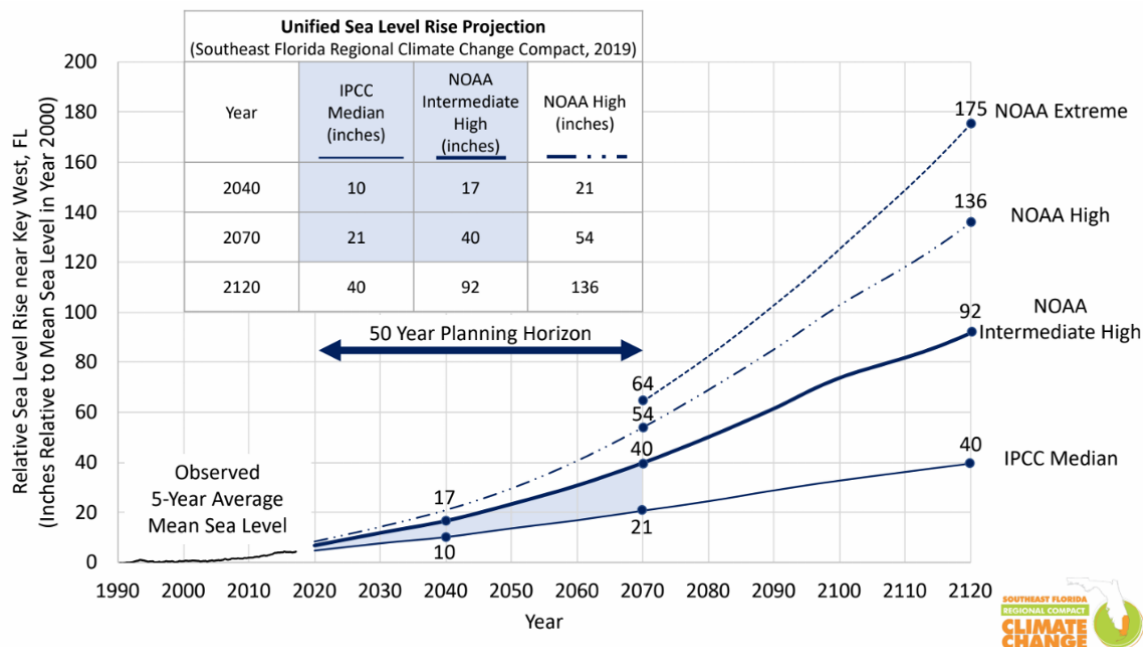


Figure 3. Regionally unified sea level rise projection for Southeast Florida relative to the 2000 mean sea level at Key West (Compact, 2020).

Obviously, the immediate outcome of sea level rise is the rise in Ground Water Table (GWT) along Florida's coast. Higher groundwater levels can reduce the soil bearing capacity, resulting in a weaker foundation and a risk for potential flash flooding (Romah, 2012). Bloetscher et al. (2017) recommended that the impact of sea level rise be considered in FDOT's transportation infrastructure planning, design, construction, and maintenance. Current pavement design procedure is based on historical weather information and assumes that the environmental variables are typically stationary, not changing with time (Knott et al., 2017). In other words, current design procedure does not incorporate the effect of sea level or GWT rise, which could lead to early pavement failures in vulnerable areas.

1.2. RESEARCH OBJECTIVES

Due to the adversely changing climate and the vulnerability of Florida's infrastructure to flooding and sea level rise, it is imperative that advanced and practical tools and models be developed for FDOT's pavement engineers (1) to assess the impact of inundated pavements during and immediately after flooding, (2) to develop proactive measures for climate change, and (3) to enhance the resilience of Florida's pavements to inundation.

The primary objective of this study is to investigate how FDOT's current decision-making process for flooded pavements can be enhanced. The methodology should account for rutting failure as well as fatigue failure (which is the predominant failure mode for FDOT's roadways) to determine when to reopen a roadway after a flooding event.

2. LITERATURE REVIEW

In this chapter, a summary of the relevant literature review gathered and reviewed for this project is provided. The review includes an overview of pavement resiliency, existing agency practice, recent studies and developments on pavement resiliency, and a summary of the main takeaways.

2.1. OVERVIEW OF PAVEMENT RESILIENCY

Transportation infrastructure resiliency generally refers to the ability of a system to prepare for, withstand, respond to, and recover from disruptive events while maintaining or restoring its essential functions (UN, 2016; FHWA, 2014). For pavement systems, this concept extends beyond post-event repair and includes coordinated actions in planning, design, construction, operation, maintenance, and asset management. Pavement resiliency therefore concerns both the magnitude of performance loss caused by a disruptive event and the ability of the pavement to recover its functional and structural capacity over time (Barami, 2013; Dylla and Hyman, 2018).

Within this broader context, pavement resiliency can be evaluated and addressed through a range of performance criteria, assessment framework, and adaptation strategies. A comprehensive review of these concepts is provided by Lee and Rao (2023) and is therefore not repeated in detail here.

2.2. REVIEW OF FDOT'S EXISTING PRACTICES

2.2.1. FDOT's Resiliency Initiatives

Along with the Federal Highway Administration's (FHWA) nationwide resilience initiatives, FDOT has progressively incorporated resilience into its long-range and modal plans, Work Program, asset-management plans, research activities, and internal guidance governing planning, project development, design, construction, operations, and maintenance (Carver and Spirio, 2019; FDOT, 2020a; FDOT, 2023b; FDOT, 2026). FDOT's principal resilience policies, plans, assessments, and decision-support tools are reviewed below.

2.2.1.1. *FDOT's Definition of Resiliency*

Several SHAs including FDOT have developed their definitions of resiliency. FDOT's definition of resiliency is given as the following (FDOT, 2020a).

“The ability of the transportation system to adapt to changing conditions and prepare for, withstand, and recover from disruption.”

2.2.1.2. *Florida Transportation Plan (FTP)*

The 2045 Florida Transportation Plan (FTP), which was published in 2020, serves as FDOT's statewide long-range transportation plan (FDOT, 2020b). The plan comprises four elements: Vision, Policy, Performance, and Implementation. The Vision Element established seven long-range goals for FDOT one of which is to achieve “Agile, Resilient, and Quality Infrastructure” in Florida by 2045.

The Policy Element defines a total of fifteen objectives in support of the seven long-range goals, four of which are tailored to infrastructure. These objectives are:

1. Maintain Florida's transportation assets in a state of good repair for all modes.
2. Increase the resilience of infrastructure.
3. Meet customer expectations for infrastructure quality and service.
4. Improve transportation system connectivity.

Furthermore, the Policy Element stipulates a total of twelve progress indicators for measuring progress toward the above objectives. Among them, the following four indicators are related to infrastructure (or pavements to be more specific) resiliency.

1. Pavement condition.
2. Vulnerability to flooding or storm surge.
3. Hours or days of transportation facility closure due to smoke, fire, flooding, wind, or extreme temperature.
4. Frequency of repairs due to damage from extreme weather or other events.

The Performance Element reports on how Florida's assets are performing in terms of a few key measures that could be assessed currently. For example, the Performance Element indicated that Florida's pavement and bridge conditions have met or exceeded the targets established for 2019 (measured using the 2017 data as baseline). However, the Element also notes that various climatic threats (such as hurricanes, storm surge, and sea level rise) may have a significant impact on performance (or condition) of Florida's pavements and bridges. While the progress metrics were not provided for all of the above-mentioned indicators, FDOT has assessed the risk or vulnerability of Florida's Strategic Intermodal Systems (SIS) in a separate study. This study is described subsequently.

The Implementation Element, which was developed as a web-based application defines the short-term and mid-term actions to be carried out by FDOT and other local transportation authorities. While the details are still being developed and updated on a continuous basis, the four major action items pertaining to infrastructure are listed as the following.

1. Continue to enhance asset management practices at the State and local levels.
2. Develop policies and standards for next generation transportation corridors.
3. Strengthen research, development, and deployment of new technologies and practices.
4. Retrofit, adapt, or provide more diversity in the location of critical infrastructure to reduce vulnerability to extreme weather and other environmental conditions.

2.2.1.3. Risk Assessment of SIS Facilities

As a first step towards achieving the goal of "Agile, Resilient, and Quality Infrastructure", FDOT conducted a study to assess the vulnerability and risk of various Strategic Intermodal Systems (SIS) within the State (FDOT, 2018).

The vulnerability was assessed using three components mentioned previously; Exposure, Sensitivity, and Adaptive Capacity. Exposure of SIS facilities to climate hazard was determined based on GIS analysis of various datasets (see Figure 4 as an example). Sensitivity was assessed by the condition of the asset (e.g., pavement condition) and Adaptive Capacity was assessed by Daily Vehicle Miles Travelled (DVMT).

The overall vulnerability or risk was assessed for SIS highways, bridges, and military access facilities under different climate-related issues including storm surge (Categories 1, 3, and 5), projected flooding (100-year), and sea level rise (1 ft. and 2 ft.). The centerline miles and DVMT of SIS highways that were determined to be vulnerable to these natural hazards are summarized in Table 1.

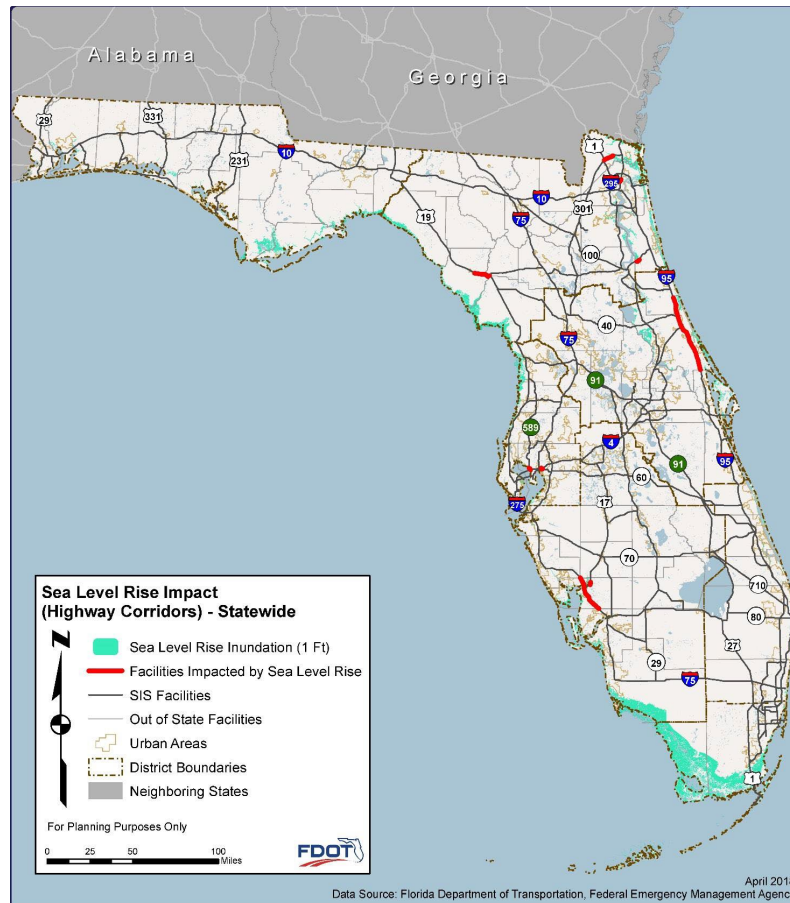


Figure 4. SIS Highway Facilities Impacted by 1 Foot Sea Level Rise Projections (FDOT, 2018).

Table 1. SIS highway corridor impacted by different hazards (FDOT, 2018).

Hazard Type	Hazard Category / Level	Centerline Miles at Risk (% of Statewide)*	Potentially Impacted DVMT, ×1000 (% of Statewide)*
Storm Surge	Category 1	160 (3%)	10,659 (5%)
	Category 2	621 (13%)	28,833 (13%)
	Category 3	983 (21%)	48,751 (23%)
Exposure to Flooding	Low (≤ 3 ft.)	215 (4.5%)	14,092 (6.6%)
	Medium (3 ft. to 10 ft.)	268 (5.6%)	10,999 (5.1%)
	High (> 10 ft.)	62 (1.3%)	2,196 (1.0%)

Hazard Type	Hazard Category / Level	Centerline Miles at Risk (% of Statewide)*	Potentially Impacted DVMT, ×1000 (% of Statewide)*
Sea Level Rise (SLR)	1 ft. SLR	39 (0.8%)	1,939 (0.9%)
	2 ft. SLR	248 (5.2%)	24,018 (11.0%)

Note*: The centerline miles and DVMT are not cumulative (e.g., centerline miles under high flooding risk do not include those of medium risk).

2.2.1.4. State Highway System Resilience Action Plan

As part of its broader resilience efforts, FDOT published the State Highway System Resilience Action Plan in June 2023 in accordance with Section 339.157 of Florida Statutes. The Action Plan assesses potential effects of flooding, storms, and sea-level rise on the State Highway System and identifies strategies for improving the resiliency of transportation facilities. As shown in Figure 5, the vulnerability assessment consists of three principal steps: (1) identifying geographic areas potentially affected by flooding, storm surge, and sea-level rise, (2) establishing priority tiers for State Highway System segments within those areas, and (3) compiling a list of potential improvement projects in high- and medium-priority areas (FDOT, 2023b).

VULNERABILITY ASSESSMENT

The vulnerability assessment of the State Highway System (SHS) included three steps:

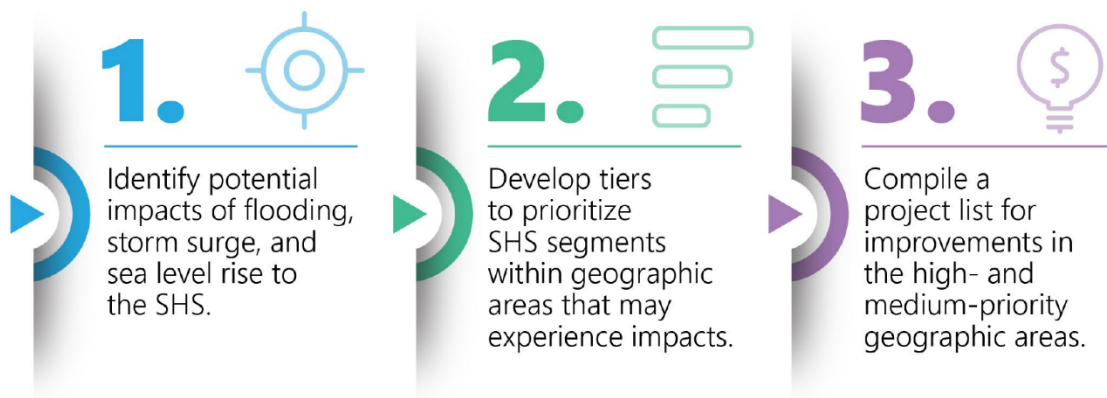


Figure 5. FDOT’s three-step vulnerability-assessment process for the State Highway System (FDOT, 2023b).

The Action Plan recognizes that the location of a roadway within a hazard-exposure area does not necessarily establish that the facility itself will be damaged. Additional facility-specific evaluations are needed to account for pavement elevation, structural characteristics, material sensitivity, drainage, and other site conditions. Relevant adaptation strategies identified in the plan include pavement designs and materials capable of withstanding inundation or overtopping, stabilization of pavement foundations, drainage improvements, roadway elevation, and protection of shoulders and embankments. The plan also recommends continued research, testing, and implementation of asphalt and concrete materials and construction techniques that improve infrastructure performance under flooding, saltwater exposure, and storms (FDOT, 2023b).

Using 2021 State Highway System data, the assessment identified approximately 1,820 centerline miles and 2,156 bridges within the 100-year floodplain; 1,412 centerline miles and 1,334 bridges within the Category 3 storm-surge zone; and 138 centerline miles and 967 bridges in areas potentially affected by two feet of sea-level rise by 2070. The Action Plan also identifies strategies applicable to planning, project development, design, construction, operations, maintenance, and asset management (FDOT, 2023b).

2.2.1.5. 2024 Freight Mobility and Trade Plan (FMTP)

In alignment with FDOT's effort on resiliency, the Freight Mobility and Trade Plan was updated in 2024. One of the plan's principal objectives is to create a more resilient multimodal freight system capable of preparing for, responding to, and recovering from disruptions. The 2024 FMTP provides a direct connection between resilience assessment and investment decisions by incorporating the low-, medium-, and high-vulnerability tiers from the 2023 Resilience Action Plan into the quantitative prioritization of highway improvement projects. Its project-evaluation criteria also consider system reliability and redundancy, infrastructure durability in vulnerable coastal areas, support for evacuation and recovery, and the ability to restore access and mobility rapidly following an emergency (FDOT, 2024).

2.2.1.6. Sea-Level Scenario Sketch Planning Tool

In collaboration with University of Florida (UF) GeoPlan Center, FDOT developed the Sea-Level Scenario (SLS) Sketch Planning Tool (<https://sls.geoplan.ufl.edu/viewer/>) to assist in identifying transportation infrastructure exposed to current and future flood risks.

The tool visualizes current flood hazards, including 100-year and 500-year floodplains and hurricane storm-surge zones, as well as future sea-level-rise scenarios. In 2025, the tool was updated with revised transportation data layers, sea-level-rise projections, and inundation models based on NOAA's 2022 sea-level-rise scenarios (UF GeoPlan Center, 2025; FDOT, 2026). An earlier version of the SLS Sketch Planning Tool was a major data source for the 2018 SIS risk assessment discussed previously. The statewide Digital Elevation Model (DEM) and the sea-level-rise projections available at that time were used to assess the exposure of SIS facilities to flooding and sea-level rise (FDOT, 2018).

2.2.1.7. Closing Remarks on FDOT's Resiliency Efforts

As mentioned previously, FDOT has incorporated resiliency into all phases of transportation planning. Based on FDOT's resiliency efforts reviewed above, the authors are of the opinion that FDOT's efforts align with FHWA's five-step resilience framework (FHWA, 2021). More specifically, FDOT has defined goals and objectives for its resiliency initiative, compiled or identified sources of necessary data, and assessed the vulnerability of critical transportation assets, initially through the SIS assessment and subsequently through the statewide vulnerability assessment included in the 2023 State Highway System Resilience Action Plan (FDOT, 2018; FDOT, 2023b). While the Implementation Element of FDOT's FTP outlined action items for resilient infrastructure within the State, the 2023 State Highway System Resilience Action Plan subsequently identified strategies applicable to planning, design, construction, operations, maintenance, and asset management. The 2026 Florida Strong Status Report further documents FDOT's completed and ongoing implementation activities throughout the transportation project lifecycle (FDOT, 2020b; FDOT, 2023b; FDOT, 2026).

It is also to be noted that the objective of this study is closely related to FDOT's continued efforts on implementing resiliency, but with a scope that is limited to structural resiliency of flexible pavements under inundated conditions.

2.2.2. FDOT's Decision Matrix for Flooded Pavements

In an effort to protect Florida's major roadways that are vulnerable to flooding events, FDOT developed a simple decision matrix for inundated pavements (ARA, 2013). The decision matrix (shown in Figure 6) was used as a general guidance for decision making (i.e., closing, partially-opening, or fully-opening) for an inundated roadway based on visual assessment of the surrounding condition (e.g., standing water at pavement shoulders) as well as the Annual Average Daily Truck Traffic (AADTT) and the allowable number of load repetitions for the particular roadway.

The allowable number of load repetitions was developed as a function of resilient modulus (M_R) of the inundated embankment layer and is presented in Table 2. The thresholds shown in this table were developed using Shell's rutting failure criterion by limiting the permanent deformation within the inundated embankment to 0.5 in.

Although the decision matrix shown in Figure 6 is easy to use and has served FDOT well for the last decade, it is not without limitations. The following provides a brief summary of the limitations of the existing decision matrix:

- The decision matrix only considers the allowable daily load repetitions that are obtained using Shell's rutting failure criterion and omits the effect of flooding on other flexible pavement distresses such as fatigue cracking.
- The allowable daily repetitions shown in Table 2 were developed assuming a constant vertical stress of 10 psi at the top of the embankment. While the assumption makes the procedure easy to apply, it does not explicitly account for differences in pavement structure (i.e., layer thickness and stiffness) which may affect the level of compressive stress experienced by the embankment.

Flood Waters on Pavement Surface	Closed to all Traffic	Closed to all Traffic	Restricted Traffic (Emergency Vehicles Only)
Flood Waters at Shoulder Edge	Closed to all Traffic	Restricted Traffic (Emergency Vehicles Only)	Open to All Traffic
Normal Ditch Flow	Closed to all Traffic	Passenger vehicles with Restricted Trucks if Pavement is in Good Condition	Open to All Traffic
	Allowable Loads less than AADTT	Allowable Loads near AADTT	Allowable Loads greater than AADTT

Figure 6. FDOT's existing decision matrix (ARA, 2013).

Table 2. Allowable daily load repetitions as a function of resilient modulus (ARA, 2013).

Embankment M_R (psi)	Allowable Daily Load Repetitions	Embankment M_R (psi)	Allowable Daily Load Repetitions
2,000	< 1	8,000	119
2,500	< 2	9,000	182
3,000	3.5	10,000	265
3,500	6	11,000	373
4,000	10	12,000	510
4,500	15	13,000	679
5,000	22	13,500	777
5,500	31	14,000	885
6,000	42	14,500	1004
7,000	74	15,000	1134

2.3. RECENT STUDIES ON PAVEMENT RESILIENCY

Climate changes have increased the risk of flooding, hurricanes, and precipitation, and all States in the U.S have experienced floods or flash floods in the past 5 years (Hemmati et al., 2020). As such, the impact of flooding (or inundation) on pavements has been widely investigated and several strategies were proposed to mitigate the impact of flooding or hurricane events on pavement systems. The following provides a review of recent studies or developments on flexible pavement resiliency, options for evaluating the effect of flooding, and pavement design considerations for flooding and inundation.

2.3.1. Effects of Flooding on Pavement Materials and Structural Response

A fundamental component of pavement resilience assessment is quantifying how flood- and climate-related changes in moisture and groundwater conditions affect pavement material properties and structural response. The following is a brief summary of previous studies that have assessed the effect of flooding (or inundation) on flexible pavements using mechanistic and/or empirical approaches.

- Knott et al. (2019) developed a hybrid framework for integrating the effect of climate change into asphalt pavement management. The framework uses both bottom-up and top-down approaches; the top-down approach (or scenario-based approach) is used for studying the future pavement life reductions under one or more climate-change scenarios, while the bottom-up approach (or asset-based approach) is used for evaluating the effect of various climate parameters and their combinations on pavement life reduction. In both approaches, the performance of flexible pavements was modeled using MnPAVE which is Minnesota DOT's (MnDOT's) mechanistic-empirical pavement analysis and design software. MnPAVE uses the mechanistic layered-elastic theory for simulating the mechanistic response of flexible pavements.
- Mallick et al. (2014) studied the long-term effect of climate change on pavement performance and maintenance cost using a system dynamics approach. The system dynamics model was developed to provide a link between the long-term pavement

performance predicted by AASHTOWare Pavement Mechanistic-Empirical Design (PMED) and the climate parameters. The results were then used to simulate the effect of climate on multiple pavement factors such as life-cycle cost of flexible pavements including maintenance cost. The framework considers various elements including a change in temperature, precipitation, sea level rise, and number of inundations to estimate the rate of pavement deterioration.

- Elshaer (2017) and Elshaer et al. (2017b) divided the pavement structure (or the unbound layers below the asphalt layer to be more specific) into sublayers of 6 in. thickness for simulating different levels of Ground Water Table (GWT). The GWT was initially located on top of the unbound base layer and sequentially lowered to 112 in. below the top of subgrade at an interval of 6 in. The sublayers below the GWT were assumed to be fully saturated, and the Soil-Water Characteristic Curve was used to estimate the degree of saturation for the layers above GWT. For each case (i.e., for each GWT level), a hydrostatic condition was assumed (i.e., effect of transient flow of water, evaporation, and precipitation events were ignored) and the estimated degree of saturation was used to adjust the resilient modulus of the unbound layers. The pavement structure whose modulus was adjusted for GWT in the above manner was used in a layered elastic analysis program (KenLayer to be specific) for the analysis of stress, strain, and deflections of the asphalt pavement.
- Asadi (2020) integrated a hydraulic model for simulating the water flow within the pavement foundation layers, with a finite element pavement model for assessing the post-flood impacts on the performance of flexible pavements. The hydraulic analysis was conducted using an open-source finite difference code VS2DI for simulating unsaturated water flow within the pavement layers of a flexible pavement developed by Hsieh et al. (1999). It is a graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media and is available to download from United States Geological Survey (USGS) website. Pavement responses were calculated using a finite element software known as IntPave developed by Tirado et al. (2007) at the University of Texas, El Paso, which incorporates the moisture-dependent resilient modulus profile. Pavement responses were used to estimate the damage of pavement (i.e., remaining service life of the pavement) due to flood or precipitation through the use of distress models.
- Qiao et al. (2023) used SEEP/W, a commercial finite element software for modeling groundwater flow, to simulate moisture movement in three flexible pavements with sand, silt, and clay subgrades under 0.3-m floods lasting one, two, and six hours. The calculated moisture contents were converted to corresponding resilient modulus and incorporated into KenLayer to estimate fatigue and rutting damage. A scaled physical pavement instrumented with moisture sensors was also tested to evaluate the simulated weakening and recovery behavior. The laboratory and modeling results showed rapid moisture infiltration and stiffness loss followed by a substantially longer recovery period, which was estimated to extend approximately one month.
- Ajorlou et al. (2024) used the Random Forest (RF) method of Machine Learning (ML) along with a system dynamics model for pavements to conduct a data-driven local and global sensitivity analyses of flexible pavement structures under flooded conditions. In

their analyses, the surface deflection and the time associated for the deflection to increase and decrease (due to flooding and subsequent recovery, respectively) was used as metrics for assessing pavement performance. The sensitivity analyses indicated that the surface deflection is sensitive to short, heavy rainfall events, with precipitation rate influencing all performance measures. In addition, the results indicated that the recovery time is influenced primarily by soil particle size. Furthermore, it was emphasized that the Liquid Limit (LL) of soils has a significant impact on recovery of pavement deflection.

- Abdollahi et al. (2024) developed a flood-specific version of the Unified Pavement Distress Analysis and Prediction System (UPDAPS), referred to as UPDAPS-Flood, which incorporated short-duration flooding events into mechanistic-empirical flexible pavement analysis. Conventional UPDAPS analysis procedures use longer climatic increments and may not adequately represent the rapid weakening and gradual recovery of pavement layers during and after a flood. To address this limitation, the researchers modified the original UPDAPS framework to perform daily analyses during flooding and recovery, reduce the resilient modulus of the base and subgrade, account for different drainage rates, and represent increased post-flood truck traffic. Linear elastic analysis was used to calculate pavement responses, which were then converted into accumulated rutting, fatigue cracking, and IRI using the UPDAPS distress models.
- Chen and Wang (2026) developed an integrated hydro-mechanical framework to evaluate subsurface moisture recovery and the resulting structural damage in flooded flexible pavements. Laboratory experiments first demonstrated that moisture beneath an impermeable pavement surface increased later and recovered more slowly than moisture in exposed soil, particularly for fine-grained soils. A laboratory-validated hydrological model was then applied to hurricane-related flooding cases in Florida and North Carolina, accounting for floodwater history, post-flood precipitation and evaporation, and groundwater recession. The predicted moisture distributions were transferred to a three-dimensional moving-load model incorporating moisture-dependent unbound-material properties and temperature-dependent asphalt behavior. Although groundwater returned to its preflood level after approximately 200 days, subsurface moisture required about 500 days to recover.

In summary, the above studies generally indicate that the structural resiliency assessment of flexible pavement involves 3 general steps: (1) assume or simulate different climate conditions (i.e., temperature, moisture, etc.), (2) adjust the pavement structure (mostly the modulus of affected layers) for the different conditions identified in the previous step, and (3) conduct structural analysis (for stress, strain, or other performance indicators).

2.3.2. Flood-Induced Pavement Deterioration and Recovery

Flooding events can produce temporary reductions in pavement strength, accelerated deterioration, or permanent deformation. The following studies have evaluated the short- and long-term effects of flooding on pavement condition, structural capacity, deterioration, and recovery.

- Sultana et al. (2016) developed a deterministic, statistical model for flexible pavement deterioration with and without flooding. A Modified Structural Number (SNC) calculated using the peak deflection (D_0) obtained from FWD testing was used to represent the

structural capacity of the pavement ($SNC = 3.2 \times D_0^{-0.63}$). Based on a series of FWD test results obtained from flooded and non-flooded pavements in Australia, a statistical model was developed that can predict the short-term behavior (up to 42 days) of a flexible pavement immediately after flooding as a function of time. A comparison of before- and after-flood FWD data indicated that inundation may have a significant effect on pavement strength (up to 15 percent loss in 42 days).

- Elseifi et al. (2022) used long-term pavement-management data to quantify the effects of the 2016 Louisiana flood on asphalt pavement service life. The study examined 10 inundated pavement sections, representing 72 log-miles, using pavement condition, alligator-cracking, and rutting indices collected for up to 11 years before and four years after flooding. For each 0.1-mi increment, the researchers fitted a quadratic curve to the preflood PCI measurements to estimate the expected service life without inundation. A second curve incorporating the post flood measurements was used to estimate the post flood service life, with a PCI of 80 serving as the maintenance threshold.
- Matini et al. (2022) distinguished between functional recovery (i.e., when a roadway can be reopened) and structural recovery (i.e., when the pavement layers have regained their strength). The researchers used SEEP/W to simulate floodwater infiltration into flexible pavements with sand and clay subgrades and converted the resulting moisture changes into reductions in resilient modulus. The weakened layer properties were then incorporated into FlexPAVE 2.0, a finite element-based mechanistic empirical pavement analysis software, to predict rutting and fatigue damage under six single and repeated flooding scenarios over a 10-year period. Flooding reduced the resilient modulus of the unbound layers by approximately 50 percent, with the clay subgrade remaining weakened longer than the sand subgrade.
- Vallès-Vallès and Torres-Machi (2023) evaluated the short- and long-term deterioration of flexible pavements affected by the 2013 Colorado flood using CDOT ride-quality data collected before the flood and for five subsequent years. The researchers developed Markov deterioration models for flooded and non-flooded pavements and used 10,000 Monte Carlo simulations to estimate the resulting loss of service life. The results indicated that flooding could cause both an immediate reduction in pavement conditions and accelerated deterioration in subsequent years. The flooding shifted the deterioration curves downward and caused pavements to reach the terminal condition earlier, with the greatest service-life reduction occurring for pavements in very good preflood condition.
- Matini and Underwood (2026) expanded an earlier case-based flood-analysis framework into a generalized method for evaluating pavement structural resilience across different climates, materials, structures, and flooding scenarios. The researchers developed exponential relationships of the form ($y = ae^{-bx}$) to estimate additional subgrade rutting from the amount of rutting present before flooding, with the coefficients accounting for pavement structure, Structural Number, base and subgrade materials, climate, and groundwater depth. The resulting equations provide a practical starting point for network-level flood screening, although additional soil conditions, groundwater depths, pavement cracking effects, and field validation are needed before they can be applied as standardized prediction models.

2.3.3. Pavement Evaluation and Traffic-Restriction Decision Making

In practical applications, characterization of the flood-induced weakening and recovery of unbound pavement layers must be translated into an operational decision regarding whether unrestricted traffic can safely resume or whether temporary traffic restrictions are warranted. Several studies have developed procedures that combine pavement condition information, non-destructive testing, and anticipated traffic loading to support post-flood roadway traffic control decisions. The following studies are particularly relevant to the development of post-flood pavement evaluation and traffic control procedures.

- Ghayoomi et al. (2020) developed a system dynamics model to assess asphalt pavement performance and to identify load restriction decision in Minnesota due to ground water level rise, flood, or precipitation that lead to excessive moisture in pavement foundation layers. The model includes three main elements; hydrological, geotechnical, and pavement response structure (Figure 7). Hydrological structure model inputs include climate information and unsaturated soil hydraulics properties and simulates the moisture movement (i.e., degree of saturation) within the pavement layers. Geotechnical structure model determines the corresponding moisture-dependent resilient moduli of unbound layers (base/subbase and subgrade). Lastly, pavement response structure model simulates the stress, strain, and deflection due to traffic loading and the pavement conditions before, during, or after flooding or precipitation, using Boussinesq theory for layered elastic structures.

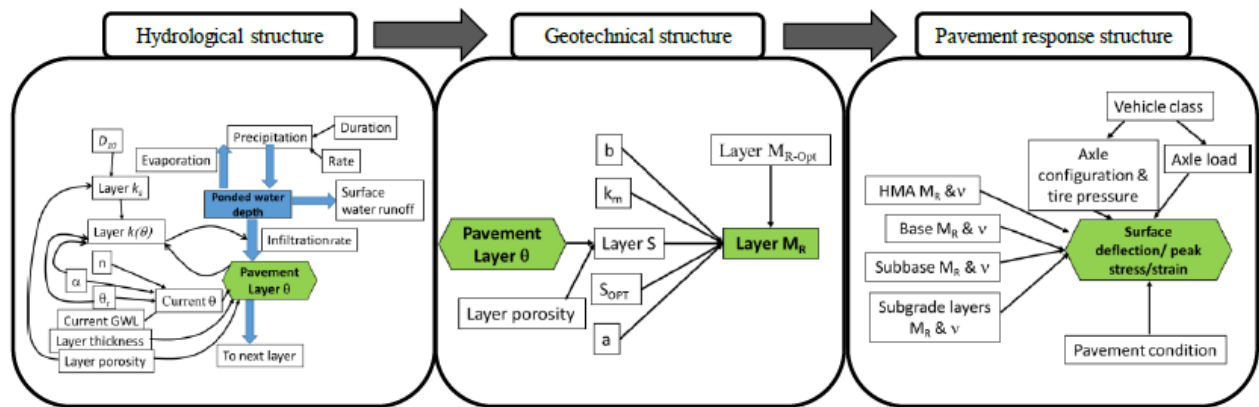


Figure 7. Conceptual framework of the system dynamics model and its variables (Ghayoomi et al., 2020).

- Elshaer et al. (2017a) developed a methodology that can be used for making decisions on traffic restrictions while considering the load carrying capacity of a flooded pavement structure. The methodology uses the Soil-Water Characteristic Curve (SWCC) for predicting the matric suction of unbound soils, which was then used for the analysis of shear failure in soils. The bearing capacity of soil was calculated using modified Terzaghi's formula including the effect of matric suction and shear strength parameters (effective cohesion and friction angle) for three different flexible pavement cross sections. These parameters were used along with KenLayer analysis to backcalculate the vertical stress corresponding to the ultimate bearing capacity of the pavement system.

- Tao and Mallick (2020) developed a holistic approach for assessing the roadway damage due to flooding. In their approach, three factors, namely the hazard factor, vulnerability factor, and the consequence factor, were assessed for the pavements expected to experience flooding. These three factors were then combined into a composite risk factor that can categorize the pavement into one of the following: high, medium, and low risk pavement. For high-risk pavements, it was recommended that the hydraulic analysis as well as visual inspection and nondestructive testing (e.g., FWD) be conducted to assess the damage due to flooding. On the other hand, nondestructive testing and visual inspection were recommended for medium risk pavements, while only the visual inspection was recommended for low-risk pavements.
- Chen and Wang (2024b) developed an FWD-based procedure for evaluating flexible pavement condition and managing traffic during post-flood recovery. Existing procedures commonly use FWD measurements to backcalculate pavement-layer moduli; however, the results may be nonunique and may not adequately represent moisture and modulus variations with depth. To address these limitations, the researchers developed and validated finite-element models that represented the asphalt layer as a viscoelastic material and the unbound-layer modulus as dependent on stress, moisture content, and matric suction. Using 148 combinations of pavement structure, subgrade type, moisture condition, and groundwater depth, relationships were established between FWD center deflection and traffic-induced pavement surface deflection and asphalt tensile strain. These responses were then used with mechanistic-empirical fatigue and rutting models to calculate the pavement damage ratio under anticipated ESALs. As shown in Figure 8, if the calculated damage ratio is below an agency-established threshold, the roadway can be opened to normal traffic. Otherwise, maximum allowable ESALs can be calculated and used to establish temporary truck-weight or traffic-volume restrictions. The case analysis showed that pavement damage increased substantially during the first month after flooding and had not fully returned to its preflood level after three months. However, additional post-flood field testing is needed to validate the predicted deterioration and recovery trends.

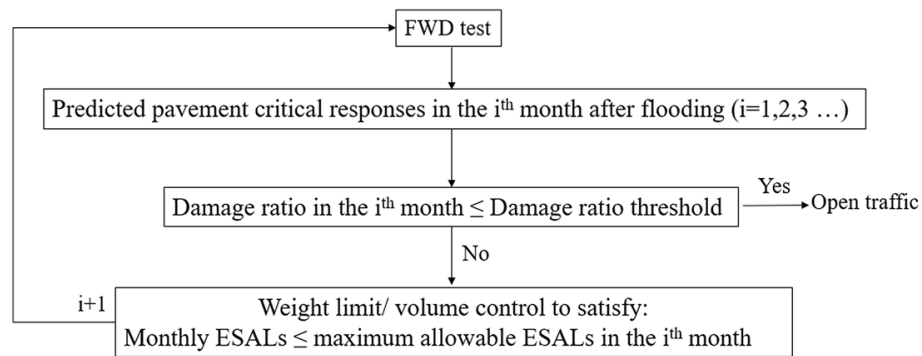


Figure 8. Decision-support framework for post-flood roadway operation based on FWD testing and pavement damage thresholds. (Chen and Wang, 2024b).

- FHWA (2024) summarized laboratory, mechanistic, empirical, and nondestructive-testing procedures for evaluating the load-carrying capacity of flooded pavements and supporting post-flood traffic decisions. Laboratory testing showed that seismic modulus

measurements were sensitive to moisture-induced asphalt deterioration, while layered elastic analyses evaluated changes in surface deflection, asphalt tensile strain, and subgrade compressive strain as the groundwater level and unbound-layer stiffness changed. The analyses indicated that most flooded pavements could support typical individual tire loads without immediate subgrade shear failure; however, repeated traffic on saturated layers could substantially accelerate fatigue and rutting damage. Under full saturation, approximately 20 to 40 percent additional Structural Number was required within the framework of empirical pavement design (i.e., AASHTO 1993) to carry the same traffic, depending on roadway type. The report also found that reducing the subgrade resilient modulus to 80 percent of its optimum-moisture value could reduce the allowable traffic to approximately 60 percent of the original design ESALs. FHWA recommended combining field observations, moisture information, FWD testing, and mechanistic analysis when establishing post-flood traffic restrictions.

- Chen et al. (2026) combined post-flood FWD testing with the AASHTO 1993 method to quantify flooding-induced serviceability loss for a flexible pavement on US 441 in Florida following Hurricane Irma. FWD measurements from flooded and adjacent non-flooded sections were used to backcalculate the asphalt, base, and subgrade moduli. These values were used to update the pavement Structural Number and effective subgrade resilient modulus, while actual FDOT traffic data were used to calculate the change in pavement serviceability, (Δ PSI), during three recovery periods. The results indicated that the base modulus decreased by approximately 15 percent and recovered after about 4 months, while the subgrade modulus decreased by as much as 50 percent and required an estimated 18 months to recover. In contrast, the asphalt modulus remained approximately 40 percent lower in the flooded section, indicating potentially permanent moisture damage. The recovery of the base and subgrade reduced the rate of serviceability loss, but the flooded pavement continued to deteriorate faster after subsurface recovery because of the remaining asphalt damage. The results showed that maintaining the same (Δ PSI) as the non-flooded pavement would require limiting traffic on the flooded section to approximately 38, 48, and 55 percent of normal ESALs during the first, second, and post-recovery periods, respectively. The findings support temporary traffic restrictions during moisture recovery, followed by rehabilitation when permanent asphalt damage remains.

2.3.4. Flood-Resilient Pavement Design and Mitigation Strategies

A more limited body of research has investigated approaches for reducing pavement vulnerability to flooding events. The following studies present pavement design and mitigation approaches investigated to reduce the vulnerability of pavement structures to flooding.

- Barbi et al. (2023) developed a procedure in which the effect of climate change (or more specifically temperature increase and moisture effects) can be incorporated into the design methodology used by Federal Aviation Administration Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD). Essentially, these researchers utilized the temperature dependent dynamic modulus of the asphalt layer and the Mechanistic-Empirical Pavement Design Guide (MEPDG) model for the moisture content within the unbound layers, in lieu of constant material properties used in FAARFIELD. The

cumulative damage of the pavement was calculated using the same ME methodology as in FAARFIELD, but using KenLayer as the mechanistic engine.

- Chen and Wang (2024a) evaluated an inverted pavement structure as a potential design strategy for improving flexible pavement resilience to flooding. The inverted pavement consisted of a relatively thin asphalt layer and granular aggregate base placed over a cement-treated base, whereas the conventional pavement consisted of asphalt and granular base placed directly over the subgrade. In the conventional pavement, water could move from the saturated subgrade into the granular base, reducing its modulus. In the inverted pavement, the cement-treated base limited this moisture movement and maintained greater granular-base stiffness. Consequently, flooding produced smaller increases in asphalt tensile strain and subgrade compressive strain in the inverted pavement. These findings demonstrate its potential as a flood-resilient design alternative, although field validation is needed because the cement-treated base was assumed to remain intact and post-flood recovery was not evaluated.
- In another study, Chen and Wang (2025) systematically reviewed flood-damage mechanisms, pavement-assessment methods, and mitigation strategies for improving roadway resilience. Flood-related deterioration was classified into surface material degradation, hydraulic scouring, subsurface saturation and weakening, subgrade erosion, and washout. As illustrated in Figure 9, the structural response of a flooded pavement may follow four patterns: full recovery, partial recovery with permanent damage, progressive deterioration to failure after reopening, or sudden loss of structural capacity during flooding. Mitigation options included nature-based solutions, roadway elevation or realignment, increased pavement thickness, base stabilization, inverted and permeable pavement structures, geotextiles, improved drainage, and temporary traffic restrictions. The review concluded that current recovery models remain oversimplified and insufficiently validated and that standardized fragility curves and life-cycle-based guidance are needed for selecting appropriate mitigation and post-flood operational strategies.

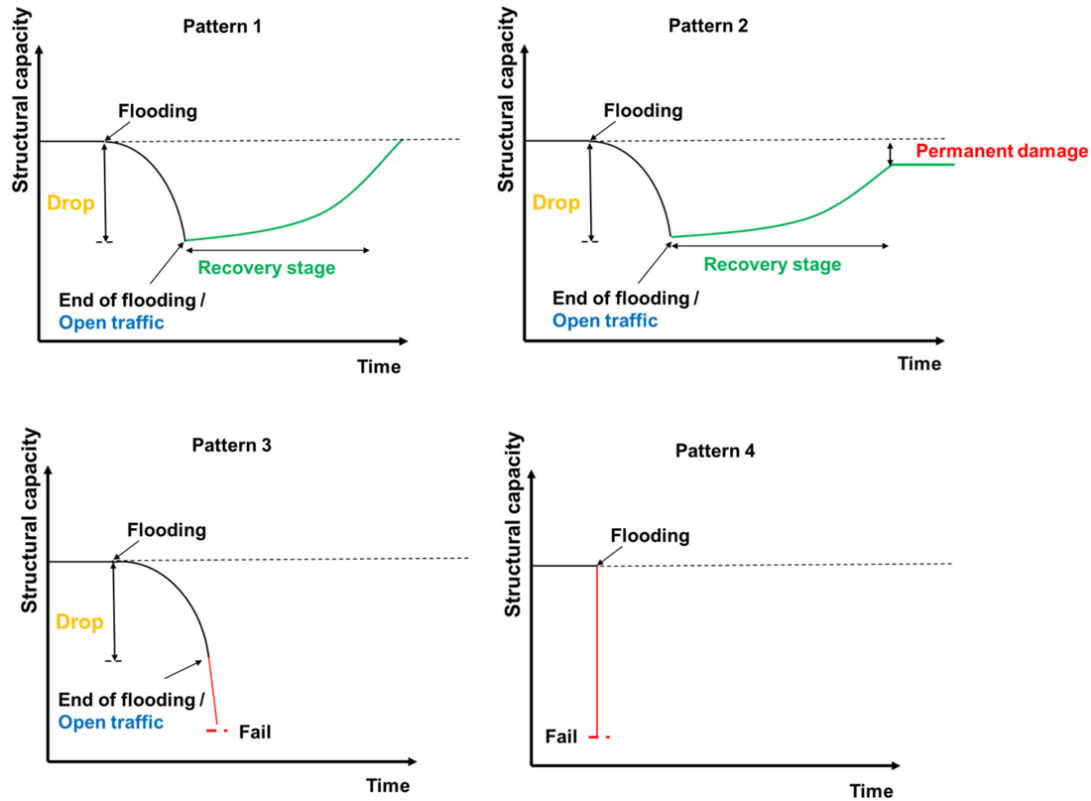


Figure 9. Conceptual structural-capacity responses of flooded pavements: (1) full recovery, (2) partial recovery with permanent damage, (3) progressive failure after reopening, and (4) sudden failure (Chen and Wang, 2025).

2.4. SUMMARY AND MAIN TAKEAWAYS

In this chapter, literature related to the resilience of flexible pavement systems was gathered and reviewed. The review included an overview of pavement resilience, existing agency practices, and recent development on flexible pavement resilience. In general, the review indicates that FDOT has progressively incorporated resilience considerations into its transportation planning, asset management, and operational activities. Within this broader effort, the flooding resilience of flexible pavements is particularly important because inundation can temporarily or permanently reduce pavement structural capacity.

Approaches used to evaluate these effects vary considerably in complexity. Several of the more comprehensive mechanistic approaches explicitly simulate water movement through the pavement system using finite element or finite difference approaches and relate changes in moisture content or degree of saturation to reduction in the resilient modulus of the unbound layers. The resulting moisture-dependent materials are then incorporated into layered elastic or finite element analyses to estimate pavement responses and, ultimately, pavement fatigue cracking and/or rutting damage. In general, these approaches provide a detailed representation of the process governing pavement weakening due to flooding and recovery. However, their application typically requires characterization of the flooding event, and numerous hydraulic and material properties, many of which may not be readily available. They may also require

simulation of transient moisture conditions within the pavement layers and relatively intense numerical analyses, which can limit their practicality for rapid and reliable post-flood decision-making.

Other studies have evaluated flooded pavement using directly measured indicators of structural condition, particularly using FWD measurements. These approaches are especially relevant to post-flood traffic control applications because they characterize the pavement in its actual condition at the time of testing rather than relying primarily on simulated moisture distributions and material properties. This general approach is also consistent with FDOT's existing traffic-control procedure. However, the existing FDOT procedure simplifies the evaluation of the flooded pavement by relying primarily on the flooded embankment modulus and embankment rutting criterion to establish the traffic control recommendation. As a result, other aspects of pavement structural response and distress mechanism are not explicitly considered.

Based on collective information available in the literature, it is believed that an improved post-flood traffic control procedure should retain the practicality of a field-based approach, such as FDOT's existing decision matrix, while incorporating a more representative evaluation of pavement structural response and damage. To provide a reliable assessment of the post-flood condition of the unbound pavement layers, the procedure should rely primarily on measured pavement data rather than on simulated moisture conditions and assumed hydraulic material properties. At the same time, it should consider both embankment rutting and asphalt concrete fatigue cracking, which represent primary damage mechanisms in flexible pavement. Such an approach provides a practical balance between simplicity required for traffic control decisions and the mechanistic basis needed to evaluate the effects of traffic loading. The following chapter describes the development of the enhanced traffic control methodology based on these considerations.

3. DEVELOPMENT OF FDOT'S ENHANCED FLEXIBLE PAVEMENT TRAFFIC CONTROL TOOL

3.1. INTRODUCTION

The primary objective of this study is to investigate how FDOT's current decision-making process for flooded pavements can be enhanced. The methodology should account for rutting as well as cracking (which is the predominant failure mode for FDOT's roadways) to determine when to reopen a roadway after a flooding event.

This chapter documents the development of FDOT's enhanced flexible pavement traffic control tool for reopening of flooded roadways (referred to as the "FDOT's Traffic Control Tool" or "Pavement Flooding Tool"), including the conceptual framework and the models incorporated. A user manual for the Traffic Control Tool is provided in Appendix A.

3.2. CONCEPTUAL FRAMEWORK

The flexible pavement flooding tool was developed as an update to FDOT's existing decision-making methodology for flooded flexible pavement sections. The existing decision matrix was designed to provide an easily understood and practical procedure for determining whether a roadway should be reopened after a flood event. Its decision logic is based on three main inputs: the embankment resilient modulus estimated from FWD deflections, the roadway Annual Average Daily Truck Traffic (AADTT), and the observed flood condition at the pavement section (ARA, 2013).

The existing framework (which will also be referred to as "FDOT's Legacy Method" in this report) provides an important operational foundation because it links field-measured pavement condition, traffic demand, and flooded condition in a practical format suitable for post-flood decision-making. However, its process for decision making is solely based on accelerated rutting within the embankment. More specifically, the allowable number of load repetitions is calculated using the Shell rutting equation (Huang, 2004) and an assumed vertical stress of 10 psi on top of the embankment. This 10-psi assumption was developed based on Boussinesq's stress distribution for a pavement depth of approximately 16 inches and a dual-wheel load with a 100-psi tire pressure (Yoder and Witczak, 1975). While the assumption makes the procedure easy to apply, it does not explicitly account for differences in pavement structure (i.e., layer thickness and stiffness) which may affect the level of compressive stress experienced on top of the embankment.

The updated framework retains the practical structure of FDOT's existing flood decision matrix but refines the way pavement damage is considered. Rather than relying on a fixed representative stress value, the updated procedure estimates the vertical stress on top of the embankment from the measured FWD deflection basin using response prediction models developed from layered elastic analysis, which will be discussed later in Section 3.4. As a result, the rutting analysis remains consistent with the same logic of the current FDOT procedure while better reflecting the measured pavement condition

In addition to the refined rutting analysis, the updated framework incorporates fatigue criterion. This criterion is controlled by the horizontal tensile strain at the bottom of the asphalt concrete

layer, which is also estimated from the measured FWD deflection basin. Including this response allows FDOT to evaluate the potential for accelerated asphalt fatigue cracking when truck traffic is allowed on pavement sections that may still be affected by post-flood moisture conditions.

After the critical responses are estimated, respective transfer functions are used to calculate the allowable number of load repetitions for rutting and fatigue. As was the case for FDOT's Legacy Method, these allowable load repetitions are then compared with the expected number of truck traffic to support the traffic-opening decision evaluation. When FWD data from a control or non-flooded section is available, the estimated post-flood damage can also be compared with the damage expected under a normal or non-flooded condition. This comparison provides a relative measure of the additional damage (or loss of pavement life) associated with opening the roadway under the FWD-tested post-flood condition. In this manner, the tool provides both a traffic-opening (or closing) recommendation and an indication of the relative damage associated with allowing truck traffic under the current moisture condition of the unbound materials.

Figure 10 summarizes the framework for the newly developed flexible pavement traffic control tool while Figure 11 presents the decision logic for the traffic control recommendations. The development of the simulation database and the response prediction models used to support this framework are discussed in the following sections.

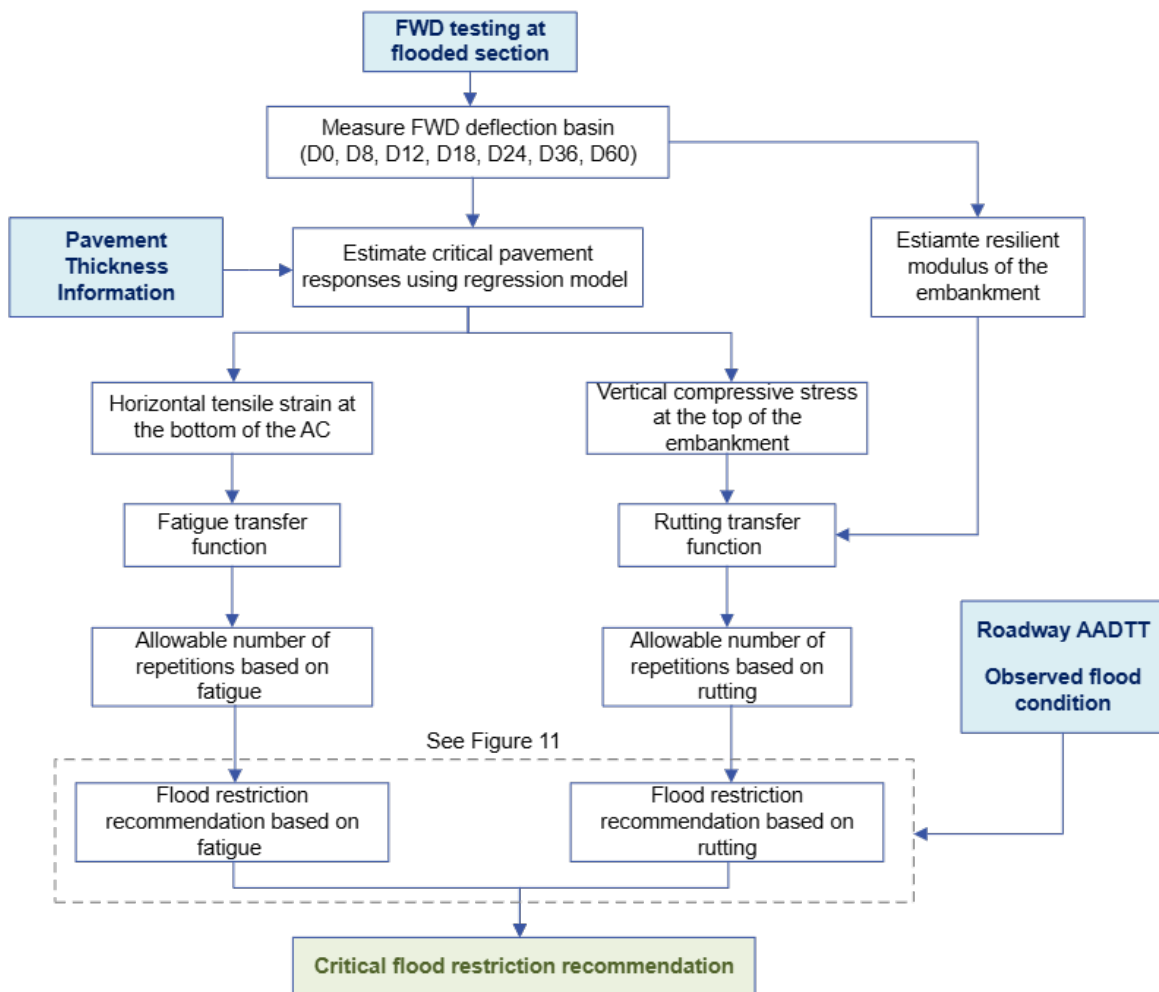


Figure 10. Framework for the updated Flexible Pavement Traffic Control Tool.

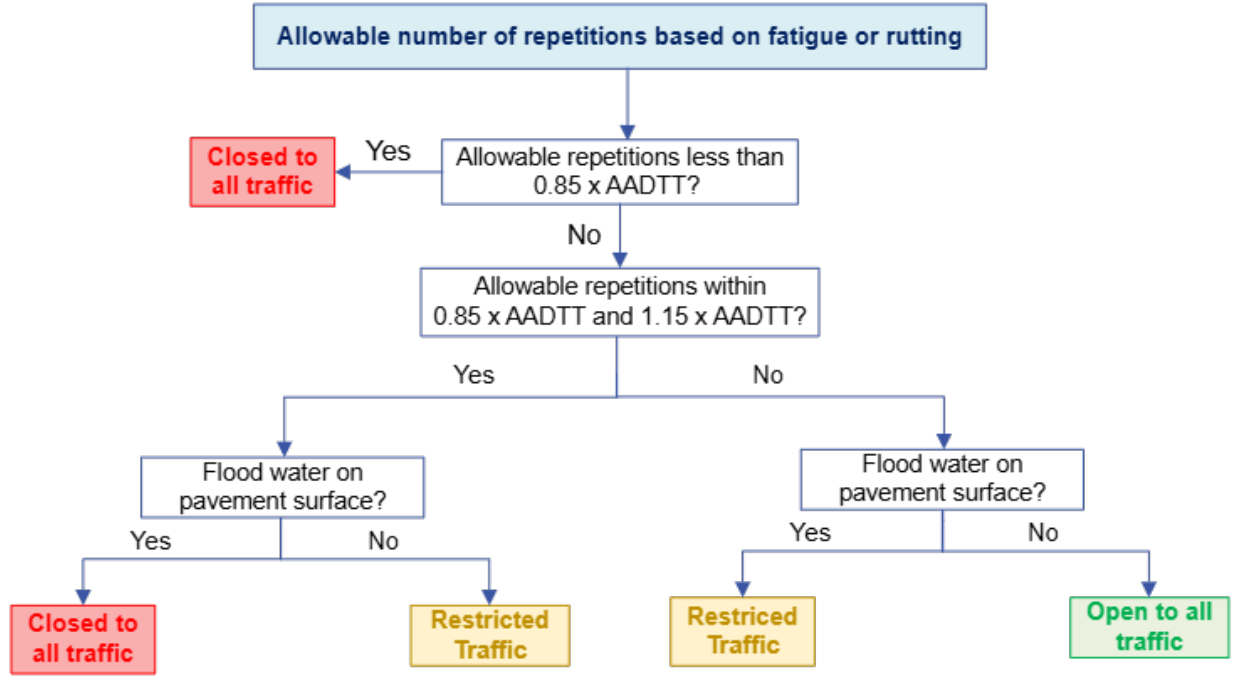


Figure 11. Decision logic for traffic control recommendation.

3.3. BASIS FOR DEFLECTION-BASED REGRESSION MODELS

One of the main improvements of the updated tool over FDOT’s Legacy Method is the use of estimated pavement responses instead of assumed values. One option to obtain these responses would be to use FWD deflections to backcalculate the pavement layer moduli and then analyze the backcalculated pavement structure using layered elastic analysis for critical stresses and strains. However, multilayer backcalculation is subject to several challenges. The backcalculated results can be sensitive to the initial seed moduli, and the solution may not be unique. In addition, backcalculated results are often subject to the “Compensating Layer Effect” where errors in the backcalculated modulus of one layer are offset by those of adjacent pavement layer(s) while still producing a reasonable match to the deflection basin (Nakhaei and Timm, 2023).

An alternative and practical approach to eliminate the need for backcalculation (and the challenges associated with it) is to estimate the critical pavement responses directly from the measured FWD deflection basin and available pavement structural information. This concept was investigated under NCHRP Project 10-48 (Kim et al., 2000). As part of that study, mechanistic analyses using finite element modeling were used to generate surface deflections and the corresponding critical stresses and strains. The resulting database was used to establish empirical relationships between selected deflection-basin parameters, pavement layer thickness, and critical pavement responses. Of relevance to this study, the NCHRP study developed the following equations for estimating the tensile strain at the bottom of the Asphalt Concrete (AC) layer and the vertical strain on top of the subgrade (or embankment).

$$\log(\varepsilon_{ac}) = 1.3426 + 0.5492 \cdot \log(SCI) + 0.385 \cdot \log(BDI) + 0.7812 \cdot \log(H_{ac}) - 0.0424 \cdot H_{ac} \quad (1)$$

$$\log(\varepsilon_{sg}) = 2.3622 + 0.5321 \cdot \log(BDI) + 0.3496 \cdot \log(BCI) - 0.1395 \cdot \log(H_{ac}) - 0.0144 \cdot H_{abc} \quad (2)$$

where,

- ε_{ac} = Strain at the bottom of the AC layer
- σ_{emb} = Stress at the top of the embankment
- SCI = Surface Curvature Index ($SCI = D_0 - D_{12}$)
- BDI = Base Damage Index ($BDI = D_{12} - D_{24}$)
- H_{ac} = Thickness of the AC layer
- H_{abc} = Thickness of the aggregate base layer

A couple of observations from the above equations are relevant to the development of the models in this study and are discussed in the following.

- Equation (1) for the horizontal strain includes AC thickness variable (H_{ac}) in both logarithmic and arithmetic forms. The logarithmic term has a positive coefficient of 0.7812, while the arithmetic term has a negative coefficient of 0.0424. As a result, the positive contribution associated with the logarithmic term becomes progressively smaller as AC thickness increases, while the negative contribution of the arithmetic term continues at a constant rate. For these coefficients, the combined thickness effect changes direction at approximately 8.0 in, allowing the model to represent different trends for thinner and thicker pavement structures rather than imposing a single monotonic relationship over the entire thickness range typical for flexible pavement structures.
- The base thickness (H_{abc}), is not included as a predictor in the fatigue strain equation (i.e., Equation (1)). The results from this observation suggest that after accounting for SCI , BDI , and H_{ac} , base thickness did not provide sufficient additional predictive information for inclusion in the final model.

In general, Equations (1) and (2) provide a technical basis for using the measured deflection basin and the pavement structural information as a surrogate to backcalculating the layer moduli and obtaining the critical pavement responses from subsequent simulations. Although NCHRP Project 10-48 equations were not developed for flooded pavement evaluation, the underlying concept is applicable to the framework developed in this study.

3.4. MECHANISTIC SIMULATION DATABASE

To avoid multilayer backcalculation while still preserving a mechanistic interpretation of the FWD deflection basin, a synthetic database of mechanistic pavement responses was developed to establish the relationship between the FWD deflections and the critical pavement responses, similar to NCHRP Project 10-48. The database was generated using a layered elastic analysis program called KenLayer which was implemented based on the mathematical formulation provided by Huang (2004). The purpose of the simulation database was to produce a broad set of pavement structures (i.e., thicknesses and modulus), surface deflection basins, and corresponding critical responses that could be used to develop deflection-based response prediction models.

The pavement structures were represented as multilayer flexible pavement systems consisting of an asphalt concrete layer, a base layer, and a semi-infinite embankment layer. Each layer was assumed to be homogeneous, isotropic, and linear elastic. The layer interfaces were assumed to

be fully bonded, and the pavement was subjected to a 9-kip circular load, representing one-half of an 18-kip Equivalent Single Axle Load (ESAL).

The simulation matrix for KenLayer was developed by varying the main structural and material inputs expected to influence the FWD deflection basin and the corresponding critical responses. These inputs included the thickness of AC and base layers as well as the modulus of all layers (AC, base, and embankment). The ranges and intervals used for each input were selected to represent typical flexible pavements in Florida and are summarized in Table 3.

Based on the combination of input ranges and intervals shown in Table 3, a total of 466,200 pavement cases were simulated. For each case, the output database included the simulated surface deflections and the critical pavement responses required for fatigue and rutting analysis. The simulated FWD deflections included D_0 , D_8 , D_{12} , D_{24} , D_{36} , and D_{60} , corresponding to the sensor offsets available in FDOT's FWD equipment. The fatigue-related response was defined as the maximum horizontal strain at the bottom of the asphalt concrete layer, while the rutting-related response was defined as the vertical stress on top of the embankment.

Table 3. Summary of input ranges used in the mechanistic simulation database.

Input Parameter	Units	Range	Interval	Notes
Asphalt concrete thickness	in	4 – 15	1	None
Base thickness	in	6 – 18	2	None
Asphalt concrete modulus	ksi	80 – 800	20	None
Base modulus	ksi	20 – 500	20	None
Embankment modulus	ksi	10 – 100	20	None
Load magnitude	kip	9.0	Fixed	One-half of 18-kip ESAL
Contact area	in ²	109.7	Fixed	Corresponds to a circular contact radius of 5.91 in

After the simulations were completed, the database was screened to remove pavement cases with unrealistic combinations of layer stiffness or atypical response patterns. First, only the cases where the upper layers were stiffer than the lower layers were retained (i.e., asphalt concrete modulus > unbound layer modulus > embankment modulus). This criterion was intended to remove cases with stiffness profiles that are not typically expected for conventional flexible pavement structures. Second, simulations that produced compressive strain at the bottom of the asphalt concrete layer directly beneath the load were removed. These cases were considered atypical for flexible pavement fatigue analysis because the critical fatigue response is generally expected to be tensile strain at the bottom of the asphalt concrete layer. Such response patterns were likely associated with unrealistic combinations of layer moduli and pavement thicknesses. After applying the screening criteria, 265,684 of the original 466,200 simulated pavement cases were retained for subsequent model development.

3.5. DEFLECTION-BASED RESPONSE PREDICTION MODELS

The mechanistic simulation database described in Section 3.4 was first used to develop deflection-based response prediction models. These models provide a link between the FWD deflection basin and the critical pavement responses used in the damage analysis. In this framework, deflection-basin parameters and pavement thickness information were used as predictor (i.e., independent) variables, while the pavement responses computed from layered

elastic analysis were used as the target (i.e., response or dependent) variables. As mentioned earlier, this approach allows the critical responses required for fatigue and rutting analysis to be estimated directly from FWD deflections without the need for multilayer backcalculation.

The regression models were developed using logarithmic transformations of both the predictor and target variables, consistent with the approach used in NCHRP Project 10-48. This transformation was used because the relationship between deflections and critical pavement responses is nonlinear, and because both types of variables can vary over a wide range of magnitudes.

The predictor variables evaluated in this study were based on those used in NCHRP Project 10-48, with the addition of the Foundation Curvature Index ($FCI = D_{36} - D_{60}$). FCI was included to explicitly incorporate the outer portion of the deflection basin into the regression models and provide additional information related to the embankment condition that may not be fully represented by deflection parameters calculated using sensors close to the load center.

The tensile strain at the bottom of the AC layer was estimated using the following regression form:

$$\log(\varepsilon_{ac}) = \beta_0 + \beta_1 \cdot \log(SCI) + \beta_2 \cdot \log(BDI) + \beta_3 \cdot \log(FCI) + \beta_4 \cdot \log(H_{ac}) + \beta_5 \cdot H_{ac} \quad (3)$$

where β_0 through β_5 are the fitted regression coefficients. Similarly, the vertical compressive stress on top of the embankment was estimated as:

$$\log(\sigma_{emb}) = \beta_0 + \beta_1 \cdot \log(SCI) + \beta_2 \cdot \log(BDI) + \beta_3 \cdot \log(FCI) + \beta_4 \cdot \log(H_{ac}) + \beta_5 \cdot H_{ac} + \beta_6 \cdot H_{abc} \quad (4)$$

where β_0 through β_6 are the fitted regression coefficients. Model fitting was performed in *R* using the *lm()* function from the *stats* package which estimates regression coefficients by ordinary least squares. The fitted regression coefficients for both response prediction models are presented in Table 4.

Table 4. Regression coefficients for the deflection-based response prediction models.

Response Type	Intercept	$\log(SCI)$	$\log(BDI)$	$\log(FCI)$	$\log(H_{ac})$	H_{ac}	H_{abc}
	β_0	β_1	β_2	β_3	β_4	β_5	β_6
Fatigue Strain	1.41	0.254	1.11	-0.397	0.563	-0.036	-
Rutting Stress	4.59	1.62	-8.67	10.77	-4.75	1.27	-0.89

Note 1: Strains are in units of microstrain and stresses are in units of psi.

After the final models were fitted, their goodness of fit was evaluated by comparing the predicted responses with the responses computed from the layered elastic analysis. This evaluation was conducted using the same simulation database employed for model development and was intended to verify that the regression models could reproduce the mechanistic responses generated in the simulation database with sufficient accuracy for use in the pavement damage analysis. Accordingly, the results should be interpreted as measures of model fit.

Since the models were fitted in logarithmic space, the predicted logarithmic responses were transformed back to their arithmetic scale before comparison. The following metrics were used for evaluation.

$$\text{Coefficient of determination} \quad R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (5)$$

$$\text{Root mean squared error} \quad RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2} \quad (6)$$

$$\text{Mean absolute error} \quad MAE = \frac{1}{n} \sum_{i=1}^n |Y_i - \hat{Y}_i| \quad (7)$$

$$\text{Mean error} \quad Bias = \frac{1}{n} \sum_{i=1}^n (\hat{Y}_i - Y_i) \quad (8)$$

$$\text{Mean absolute percentage error} \quad MAPE = \frac{100}{n} \sum_{i=1}^n \left| \frac{Y_i - \hat{Y}_i}{Y_i} \right| \quad (9)$$

where $Y_{j,k}$ is the response computed from the layered elastic analysis, $\hat{Y}_{j,k}$ is the response predicted by the regression model after anti-log transformation, $\bar{Y}$ is the average simulated response, and n is the number of observations used for model evaluation. The results of the model-fit evaluation are summarized in Table 5 and a graphical comparison of simulated versus predicted responses is presented in Figure 12.

Table 5. Validation metrics for prediction models.

Response Type	R^2	$RMSE^I$	MAE^I	$Bias^I$	MAPE(%)
Fatigue Strain	0.921	12.19	7.44	0.0911	14.67
Rutting Stress	0.966	0.683	0.36	0.047	7.94

Note 1: Strains are in units of microstrain and stresses are in units of psi.

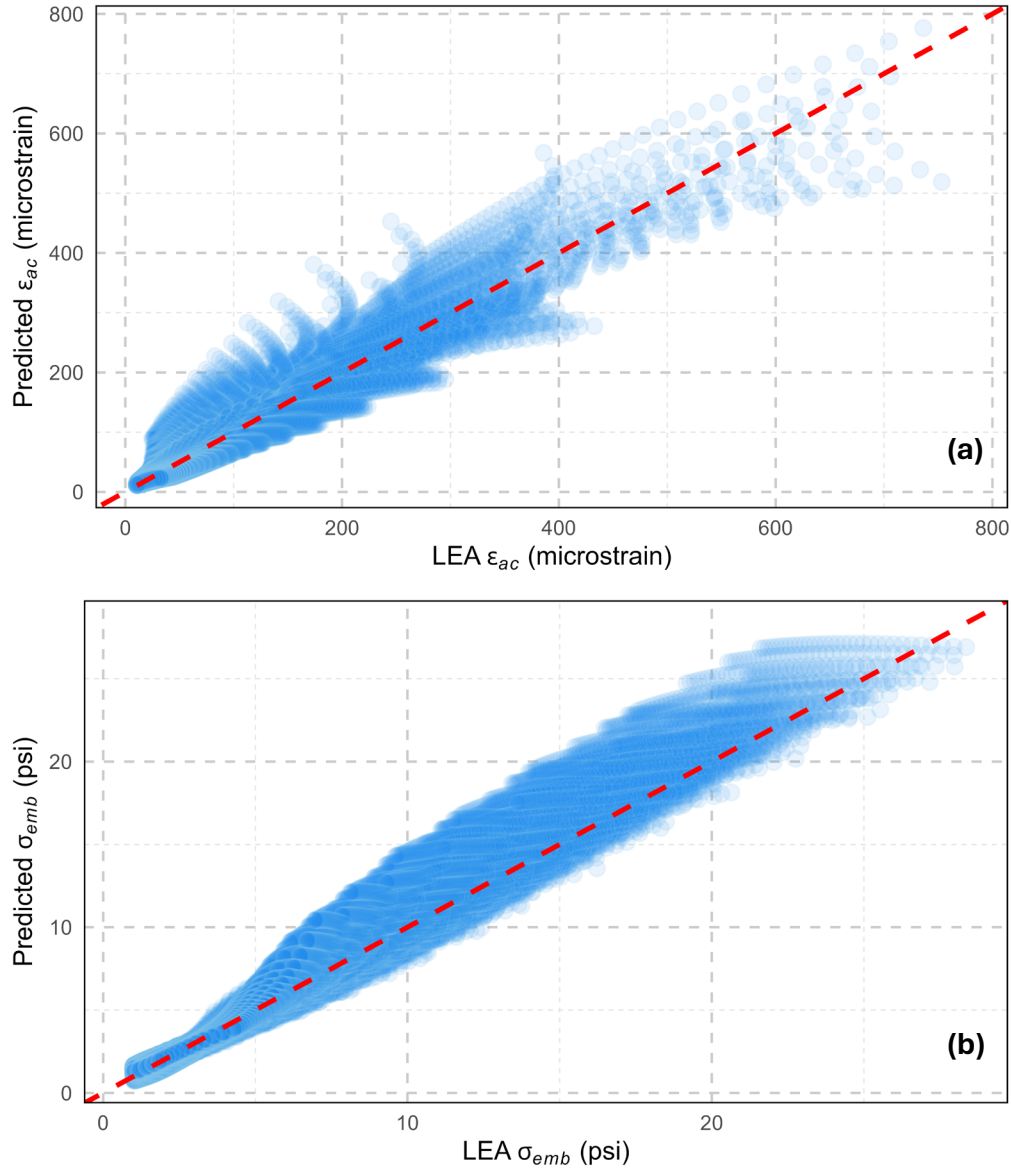


Figure 12. Predicted versus simulated pavement responses: (a) fatigue strain and (b) rutting stress. Note: The red dashed line indicates the line of equality.

3.6. DEFLECTION-BASED MODULUS PREDICTION MODELS

In addition to the pavement response prediction models described in the previous section, the mechanistic database was also used to develop deflection-based regression models for estimating the modulus of asphalt concrete, base, and embankment layers. However, in this application, the database was separated into three pavement categories based on asphalt concrete thickness: thin (less than 6 inches), intermediate (between 6 and 10 inches), and thick (greater than 10 inches) pavements. This separation was introduced during model development as it was necessary to improve the model-fit.

Similar to the previous section, the regression models were developed using logarithmic transformations of both the predictor and response variables. The general form for the regression model is shown in Equations (10) and (11).

$$Y_{k,j} = e^{\log(Y_{k,j})} \quad (10)$$

$$\log(Y_{k,j}) = \beta_{0,k,j} + \sum_{m=1}^{p_{k,j}} \beta_{m,k,j} \cdot \log(X_{m,j,k}) \quad (11)$$

where,

$Y_{k,j}$	=	Pavement response for category (k) and modulus type (j)
k	=	Thickness category: thin, intermediate, or thick
j	=	Modulus type: AC, base, or embankment
$B_{m,k,j}$	=	Regression coefficients

The candidate predictors considered during model development included the asphalt concrete and base thickness, the simulated FWD deflections, D_0 , D_8 , D_{12} , D_{24} , D_{36} , and D_{60} , and three basin shape factors, F_1 , F_2 , and F_3 . These factors were defined as the following.

$$F_1 = \frac{D_0 - D_{24}}{D_{12}} \quad (12)$$

$$F_2 = \frac{D_{12} - D_{36}}{D_{24}} \quad (13)$$

$$F_3 = \frac{D_{24} - D_{60}}{D_{36}} \quad (14)$$

The candidate predictor variables were selected to include the structural characteristics (i.e., thickness) of the pavement section and to represent both the magnitude and shape of the FWD deflection basin. Since several variables were available as potential predictor variables, a statistical variable-selection procedure, referred to as *forward selection*, was employed to identify the subset of predictor variables included in each final model. Forward selection is a stepwise model-building procedure that starts with a simple baseline model and adds additional variables one at a time based on their contribution to model performance (James *et al.*, 2021). The analysis was performed using the programming language *R* and the *leaps* package.

For each pavement category (i.e., thin, intermediate, and thick AC), the final models were selected using the Bayesian Information Criterion (BIC). BIC was selected because it balances model-fit and complexity by penalizing the inclusion of additional predictor variables. This was appropriate for the response prediction model because the objective was not only to maximize the goodness of fit, but also to avoid unnecessarily complex equations that would provide limited additional predictive value.

The final regression coefficients are presented in Table 6. The table includes the intercept, β_0 , and the coefficients β_1 through β_{12} , corresponding to the full set of candidate predictor variables considered during model development.

Table 6. Regression coefficients for the deflection-based response prediction models.

Pavement Category	Predicted Variable	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}
Thin	AC Modulus	18.31	-2.20	16.05	-34.34	12.85	9.85	-1.92	-1.10	-4.07	9.76	-6.95	-0.72	0.05
	Base Modulus	14.24	0.05	0.46	6.62	-8.23	-2.89	4.30	-1.41	-0.38	-5.62	4.95	-0.50	-0.75
	Embankment Modulus	11.58	-0.05	0.13	0.31	0.08	-2.25	0.99	-0.21	0.01	-0.36	1.08	0.01	0.01
Int	AC Modulus	17.03	0.17	7.94	-21.44	7.80	7.86	-4.06	0.83	-3.56	5.76	-3.12	-0.45	0.08
	Base Modulus	16.96	-1.44	2.36	-0.45	18.97	-32.43	13.66	-1.80	1.76	-7.75	4.96	-1.69	-0.89
	Embankment Modulus	11.53	-0.10	0.21	0.48	0.27	-2.85	1.24	-0.26	0.04	-0.52	1.20	-0.01	0.00
Thick	AC Modulus	15.03	1.23	1.12	-6.40	-1.83	5.74	-0.62	-0.23	-2.62	2.34	-0.76	-0.19	0.11
	Base Modulus	25.53	-3.11	3.80	-8.71	19.84	-8.80	-8.00	3.93	4.33	-8.36	2.87	-4.60	-1.31
	Embankment Modulus	11.56	0.02	-0.04	0.54	0.52	-2.87	1.06	-0.23	0.06	-0.65	1.30	-0.04	-0.01

Note 1:

Coefficient Associated predictor variable

β_0 Intercept

β_1 $\log(D_0)$

β_2 $\log(D_8)$

β_3 $\log(D_{12})$

β_4 $\log(D_{18})$

β_5 $\log(D_{24})$

β_6 $\log(D_{36})$

β_7 $\log(D_{60})$

β_8 $\log(F_1)$

β_9 $\log(F_2)$

B_{10} $\log(F_3)$

β_{11} $\log(H_{ac})$

β_{12} $\log(H_{abc})$

The evaluation results are summarized Table 7 and illustrated in Figure 13. Overall, the modulus predictions exhibited greater scatter than the fatigue strain and rutting stress predictions from the previous section. This greater variability is somewhat expected because individual layer properties are difficult to infer from the surface deflection basin, as different combinations of layer thickness and moduli can produce similar deflection responses (similar to the non-uniqueness of backcalculated modulus values).

The results in Table 7 show that the level of agreement between simulated versus predicted moduli varied by layer type and pavement category. The AC modulus models generally performed well, with R^2 values ranging from 0.83 for thin pavements to 0.99 for thick pavements and $MAPE$ from 13.1% to 3.5%. The embankment modulus models showed the strongest agreement across all pavement categories, with R^2 of approximately 0.99 and $MAPE$ values of 0.2% to 0.3%. On the other hand, the base modulus showed substantially greater scatter, especially for intermediate and thick pavements. The R^2 decreased from 0.85 for thin pavements to 0.57 and 0.33 for intermediate and thick pavements, respectively. The corresponding $MAPE$ increased from 17.2% to 29.3% and 41.1%. These results indicate that the deflection-based predictors provide less information for isolating the base layer modulus as pavement thickness increases. Based on these results, the regression-based modulus values should only be regarded as rough estimates of layer stiffness and should not be treated as an equivalent to those obtained from conventional backcalculation.

Table 7. Validation statistics for the deflection-based response prediction models.

Pavement Category	Response Type	R^2	$RMSE$ (psi)	$MAPE$ (psi)	$Bias$ (psi)	$MAPE(\%)$
Thin	AC Modulus	0.83	78,488	57,435	-6,083	13.1
	Base Modulus	0.85	31,072	20,143	-1,372	17.2
	Embankment Modulus	0.99	149	90	2	0.2
Intermediate	AC Modulus	0.93	49,181	32,805	-2,750	7.9
	Base Modulus	0.57	50,332	31,171	-2,838	29.3
	Embankment Modulus	0.99	222	129	1	0.3
Thick	AC Modulus	0.99	21,345	13,318	-944	3.5
	Base Modulus	0.33	45,805	26,867	-3,287	41.1
	Embankment Modulus	0.99	215	94	-0.32	0.3

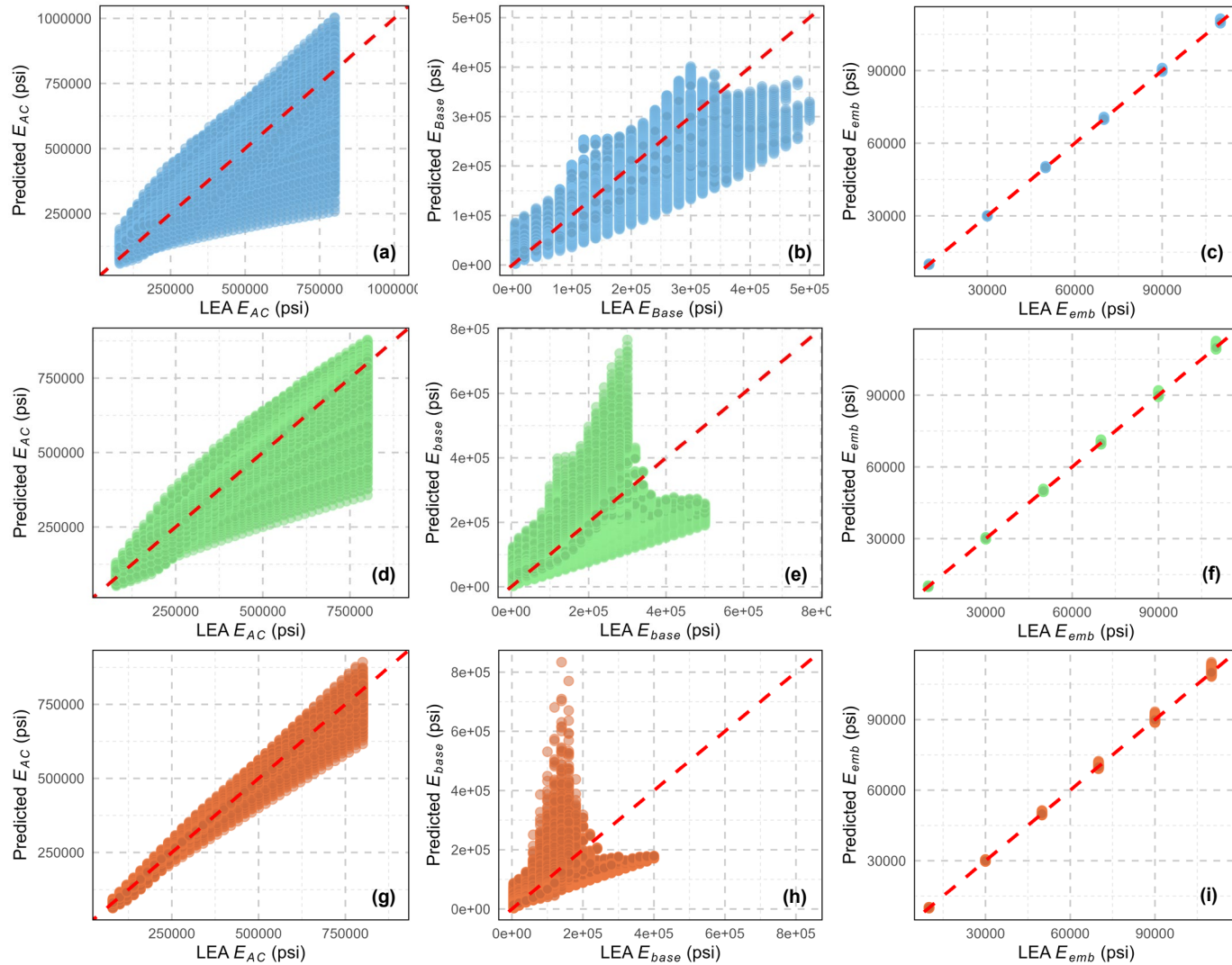


Figure 13. Predicted versus simulated moduli: (a) thin pavement - E_{AC} , (b) thin pavement- E_{base} , (c) thin pavement - E_{emb} , (d) intermediate pavement - E_{AC} , (e) intermediate pavement - E_{base} (f) intermediate pavement - E_{emb} , (g) thick pavement - E_{AC} , (h) thick pavement - E_{base} , (i) thick pavement - E_{emb} .

3.7. TRANSFER FUNCTIONS FOR ALLOWABLE LOAD REPETITIONS

In the new flexible pavement traffic control tool, the critical pavement responses are converted into an allowable number of load repetitions using transfer functions. Transfer functions are commonly used in mechanistic-empirical pavement analysis to relate calculated pavement responses to the number of load repetitions associated with a selected performance criterion. Although FDOT's Legacy Method already considers the Shell rutting equation, several fatigue transfer functions could be incorporated into the updated framework. Because the allowable repetitions are used directly in the traffic-opening evaluation, the selected fatigue transfer function can influence the resulting recommendation for reopening a flooded roadway. The general forms of the fatigue and rutting models implemented in the tool are presented in Equations (15) and (16), respectively.

$$N_{f,fatigue} = C_1 \times 10^{C_2} \times \epsilon_{ac}^{C_3} \quad (15)$$

$$N_{f,rutting} = C_1 \times 10^{C_2} \times \sigma_{emb}^{C_3} \times M_R^{C_4} \quad (16)$$

where,

- $N_{f,fatigue}$ = Allowable number of load repetitions to prevent fatigue cracking from reaching a certain limit (e.g., 10-20% of the pavement surface area).
- $N_{f,rutting}$ = Allowable number of load repetitions to prevent rutting from reaching certain limit (0.4 – 0.5 in).
- ϵ_{ac} = Horizontal strain at the bottom of the AC layer
- σ_{emb} = Vertical compressive stress on top of the embankment
- $C_1 - C_4$ = Regression coefficients

The regression coefficients for different transfer functions are presented in Table 8.

Table 8. Empirical fatigue and rutting transfer functions (Adapted from Behiry, 2012).

Model Type	Organization	C_1	C_2	C_3	C_4
Fatigue Model	Asphalt Institute (AI)	7.96	-2.0	-3.29	N.A
	Illinois Department of Transportation (IDOT)	5.00	-6.0	-3.00	N.A
	Belgian Road Research Center (BRRC)	4.92	-14.0	-4.76	N.A
	Transportation and Road Research Laboratory (TRRL)	1.66	-10.0	-4.32	N.A
Rutting	Shell Research	-4.87	-5.00	-3.73	3.58

In this section, the fatigue transfer functions presented above are compared graphically. The purpose of this comparison is to evaluate how the predicted allowable number of load repetitions to fatigue failure changes as a function of the critical tensile strain at the bottom of the asphalt concrete layer. This comparison provides a basis for assessing the relative conservatism of the available fatigue equations, since each equation predicts a different N_f for the same strain level.

Figure 14 presents the comparison of the fatigue transfer functions. As shown, the AI equation predicts the highest allowable number of repetitions, followed by the IDOT and TRRL equations, while the BRRC equation predicts the lowest allowable number of repetitions.

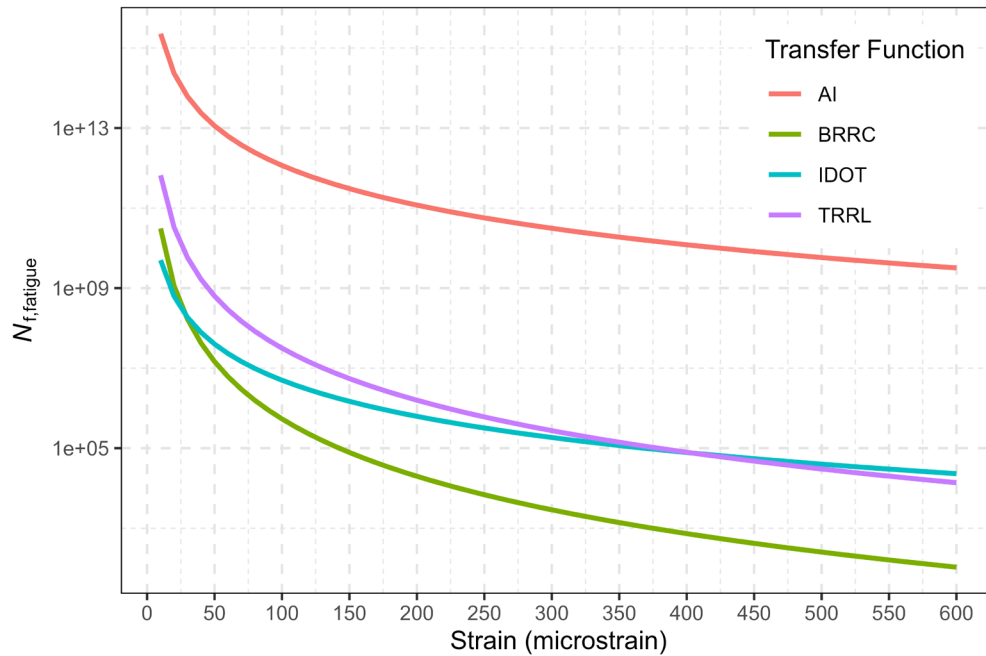


Figure 14. Comparison of fatigue cracking transfer functions.

Figure 15 presents the allowable number of load repetitions for rutting as a function of the vertical compressive stress at different embankment resilient modulus levels. As noted earlier, FDOT's Legacy Method used a constant vertical compressive stress of 10 psi, whereas the updated tool allows the rutting analysis to be performed using the vertical stress estimated from the measured FWD deflection basin. As shown in Figure 15, N_f changes rapidly with compressive stress, especially at low stress levels and low M_R values, the latter being a condition typically associated with flooded pavement foundations. In general, this indicates that assuming a stress level can have significant effect on the estimated rutting capacity and consequently, on the decision to open, restrict, or close the roadway after a flooding event. The comparison presented here reinforces the need to account for actual embankment stress condition using a more mechanistically consistent pavement response analysis from measured FWD data.

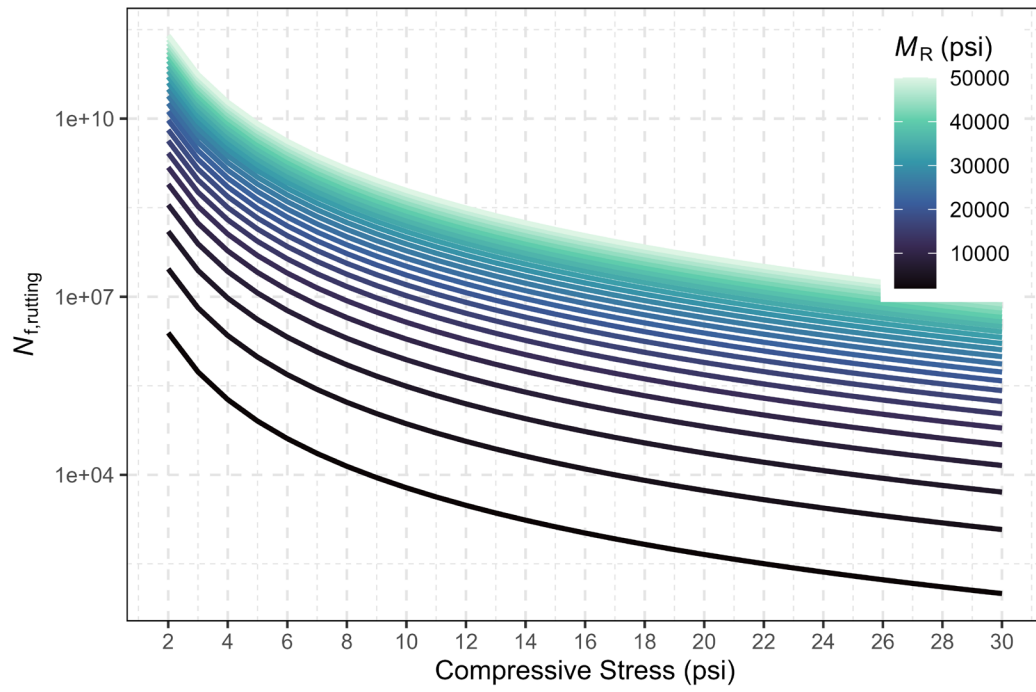


Figure 15. Rutting transfer function.

4. GUIDANCE FOR FLOODING TRAFFIC CONTROL TOOL

In the previous chapter, the development process for FDOT's Flexible Pavement Traffic Control Tool was presented along with its necessary components including its analytical models and principal interface features. This chapter focuses on the practical application of the tool. It describes the information required from the user, the available analysis options, and the interpretation of the results. Three examples are also presented to demonstrate the traffic-control recommendation, relative damage, and sensitivity-analysis features. Detailed step-by-step instructions are provided in Appendix A.

4.1. OVERVIEW OF TRAFFIC CONTROL TOOL

The new Traffic Control Tool is implemented in a macro-enabled Excel spreadsheet environment. The tool also includes macros or code written in Visual Basic for Applications (VBA) language, primarily for the user to navigate through the spreadsheet, import FWD data from .FWD files, run the analysis (e.g., traffic control recommendation analysis), and generate plots.

Figure 16 and Figure 17 shows the main interface of the Traffic Control tool. As shown in these figures, the main program is composed of seven major parts. These are:

1. General Inputs
2. Deflection Data
3. Pavement Information
4. Critical Pavement Responses
5. Layer Moduli
6. Transfer Function Coefficients
7. Analysis

In addition to the above, the Traffic Control includes an additional worksheet called "Sensitivity", which the user can use to perform sensitivity analysis of the allowable daily load repetitions. The user interface for this sheet is shown in Figure 18. The main components of this sensitivity worksheet are:

1. General Inputs
2. Sensitivity Analysis Inputs
3. Sensitivity Analysis Results

Additional description of the above major parts and the flow of the program is the subsequent sections of this report.



Flexible Pavement Traffic Control Tool

GENERAL INPUTS

v1.2

FPID

Roadway Section Number

to

District No.

Milepost

County

Direction

EB

DEFLECTIONS

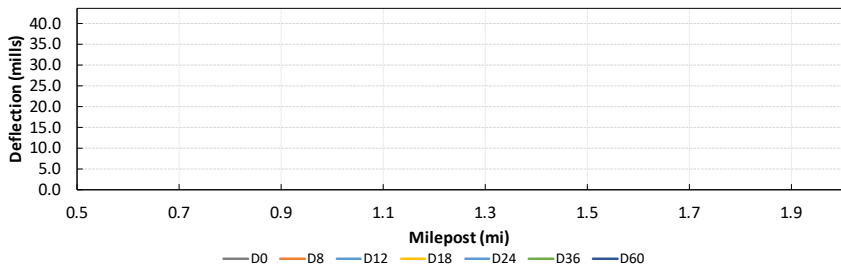
Load Data (Flooded Condition)

FWD Filepath

Load Deflections

Clear All

Deflection Plot



Control Section?

No

PAVEMENT INFORMATION

Pavement Thickness

No. of Sections

1

Section	Begin MP ²	End MP	AC Thickness (in)	Base Thickness (in)	Warning
					Missing inputs

Note 1: The database used to develop the regression models included pavement structures with AC thicknesses ranging from 4 to 15 in. and base thicknesses ranging from 6 to 18 in. Values outside these ranges represent extrapolation beyond the data used for model development and should therefore be interpreted with caution.

Note 2: Non-inclusive

CRITICAL PAVEMENT RESPONSES

Method

Regression Model

Contact Area

109.7

in²

Load Magnitude

9

kips

Warnings

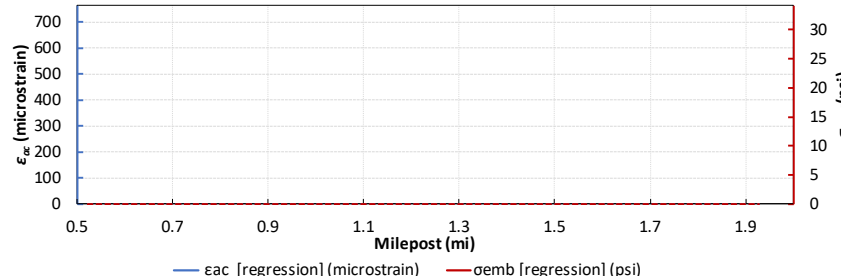
Off

Flooded Condition

Obtain

Clear

Critical Pavement Responses



Average tensile horizontal strain at the bottom of the AC layer, ϵ_{ac}

microstrain

Average compressive vertical stress at the top of the embankment, σ_{emb}

psi

General Inputs

Deflection Data

Pavement Inputs

Pavement Responses

Figure 16. Main interface of traffic control tool – Part 1.

37

LAYER MODULI

Flooded Condition

Obtain Moduli

Clear

Layer

Embankment

Modulus Plot - Embankment

Average embankment modulus [Regression]

_____ psi

Average AASHTO embankment modulus

_____ psi

FDOT embankment modulus

_____ psi

Note 3: [Regression] indicates that the modulus at each station was estimated from the measured deflections using a regression model developed for this purpose. These estimates are subject to considerable uncertainty and should be considered informational only.

TRANSFER FUNCTION COEFFICIENTS

Rutting Transfer Function

$$N_f = C_1 \times 10^{C_2} \times \sigma_v^{C_3} \times M_R^{C_4}$$

$C_1 =$

4.837

$C_2 =$

-5.000

$C_3 =$

-3.734

$C_4 =$

3.583

Fatigue Transfer Function

$$N_f = C_1 \times 10^{C_2} \times \epsilon_h^{C_3}$$

$C_1 =$

1.66

$C_2 =$

-10.00

$C_3 =$

-4.32

ANALYSIS

Calculation Methods

Variable	Method	Condition	
		Flooded	Control
Critical Stress, σ_{amb} (psi)			
Critical Strain ϵ_{oc} (microstrain)			
Resilient Modulus M_R (psi)			

Note 4: Use the dropdown list to define the calculation method for the critical inputs used in the analysis.

Flood Restriction Recommendation

Roadway AADTT

Current flood condition

Open Restriction

Check Flood Restriction

Rutting Criterion

Fatigue Criterion

Allowable daily repetitions

Flood restriction recommendation

Note 5: Annual average daily truck traffic can be consulted in the Florida Traffic Online site (<https://tdaappsprod.dot.state.fl.us/fto/>)

Figure 17. Main interface of traffic control tool – Part 2.



Flexible Pavement Traffic Control Tool

Sensitivity Analysis

GENERAL INPUTS

FPID

District No.

County

Roadway Section Number

Milepost

Direction

to

SENSITIVITY ANALYSIS INPUTS

Sensitivity Variables

Variables	Minimum	Maximum	Increment
AC Thickness (in)	3	7	1
Base Thickness (in)	8	14	2
Resilient Modulus (psi)	2,000	32,000	2,000

Roadway AADTT

AADTT Tolerance

%

Clear

Run Analysis

Note: Use the table to define the ranges of the variables to be included in the sensitivity analysis. The default values represent the recommended values.

SENSITIVITY ANALYSIS RESULTS

Rutting Criterion

X Axis Selection

Varied Parameter

Fixed Parameter

Resilient Modulus

AC Thickness

Base Thickness

=

Load Plot

Clear

General Inputs

Sensitivity Analysis Inputs

Sensitivity Analysis Results

Figure 18. Sensitivity analysis interface.

4.2. GENERAL INPUTS

These inputs provide general project information that defines the project location, as well as other project details (i.e., similar information included in FDOT’s nondestructive testing reports).

These inputs include FDOT's Financial Project Number (FPN), District, County, roadway section number, direction, and limiting mileposts.

4.3. DEFLECTIONS

This section is used to import the .FWD files for pavement deflection. Once the file is imported, the deflection plot is automatically generated, and the file path is populated based on the file location. The plot allows the user to review the measured deflection data before performing any subsequent analyses.

The user may also indicate if a control (non-flooded) section is available. The control section data is not required to generate the traffic recommendation, and it is only needed to perform the optional damage ratio analysis, which is described in a subsequent section. If the user selects "Yes", the tool expands to allow the user to load the deflection data for the control section. Although the control section data is not required, users are encouraged to provide it when available because it is a useful reference for comparison with the flooded section.

 **Deflection data** is the primary input to the Traffic Control Tool because it directly measures the pavement's structural condition after flooding. **Note:** The tool reads deflection data in .FWD file format produced by Dynatest FWDs.

4.4. PAVEMENT INFORMATION

In the Traffic Control Tool, the user must provide pavement thickness information across the length of the project. This information should be obtained from available construction plans, core data, Ground Penetrating Radar (GPR) measurements, or other available project records. When such information is not available, the user may enter the best available estimate of the layer thicknesses based on FDOT's typical pavement structures or design practices for the type of roadway being evaluated. The critical pavement responses are estimated based on measured deflection data and the thickness of the pavement provided in this section.

4.5. CRITICAL PAVEMENT RESPONSES

The traffic control recommendation is based on the pavement damage caused by a 9-kip load. The analysis considers two damage mechanisms: fatigue damage at the bottom of the Asphalt Concrete (AC) layer and the rutting damage on top of the embankment. To assess these pavement damages, the tool requires the corresponding critical pavement responses. Consistent with mechanistic-empirical methods, the critical responses considered in the tool are:

1. Tensile strain at the bottom of the AC layer, used to evaluate bottom-up fatigue cracking, and
2. Compressive vertical stress at the top of the embankment, used to evaluate embankment rutting.

An illustration showing the location of the critical pavement responses is shown in Figure 19.

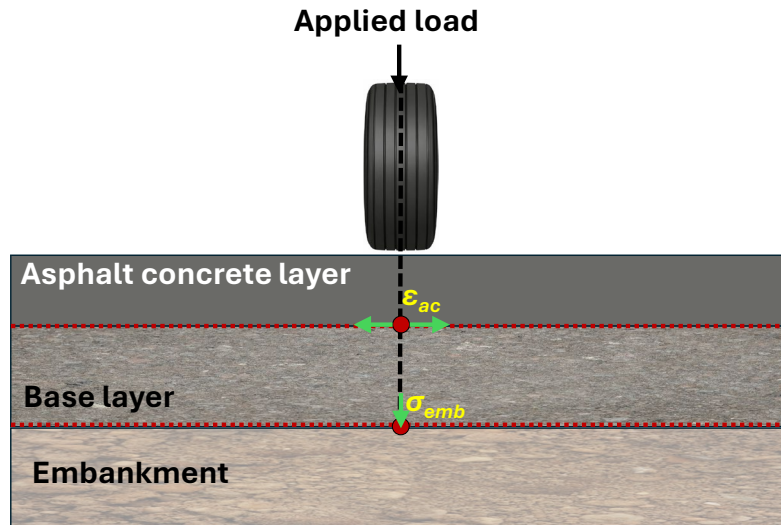


Figure 19. Critical pavement responses in flexible pavement.

Typically, pavement responses are calculated using a forward analysis based on layered elastic theory or finite element modeling. However, these analyses require the pavement layer moduli to be known in advance, and these properties are not directly available when evaluating a flooded roadway.

The Traffic Control Tool estimates the critical pavement responses using statistical models developed from the mechanistic data discussed in the previous chapter. Measured deflection data and pavement structural information are used as inputs to prediction models developed from a database of simulated FWD deflection basins and pavement responses using layered elastic analysis.

This section of the Traffic Control Tool allows the user to obtain these responses along the project length and calculates the average horizontal strain and vertical stress values for the section.

📖 Pavement responses characterize how the pavement structure reacts to traffic loading and are used to estimate fatigue and rutting damage. In the new Traffic Control Tool, these responses are estimated from measured deflections and pavement structural information using statistical regression models.

4.6. LAYER MODULI

The Traffic Control Tool includes a section that presents estimated pavement layer moduli for both the flood and control conditions, when control data are available. Similar to how the pavement responses are estimated within the tool, the layer moduli are also estimated from the measured deflection data directly from regression models. It is emphasized again that the modulus values generated from the regression models are intended for informational purposes only, as considerable uncertainty and scatter were observed during development of the prediction models.

The new Traffic Control Tool provides the following modulus values.

- Estimated AC modulus from regression-based prediction model.
- Estimated base modulus from regression-based prediction model.
- Estimated embankment modulus from regression-based prediction model, FDOT's embankment modulus calculation, and AASHTO's embankment modulus calculation.

4.7. TRANSFER FUNCTION

After calculating the critical pavement responses for fatigue and rutting, the Traffic Control Tool uses transfer functions to estimate the number of load applications the pavement can withstand before reaching a defined level of failure.

Transfer functions are generally developed from experimental relationships between strain or stress levels and the number of cycles to failure, with adjustments made to represent field conditions. Several transfer functions are available in the literature, and they may differ in how failure is defined and how laboratory results are translated into field performance.

The Traffic Control tool allows users to modify the transfer function coefficients when a different transfer function is preferred or when agency-specific calibrated values are available.

4.8. ANALYSIS

Two types of analysis are presented in the main interface of the Traffic Control Tool are:

1. **Flood Restriction Recommendation:** This is the primary outcome of the Traffic Control Tool and provides a traffic control recommendation based on the allowable daily load repetitions, roadway Annual Average Daily Truck Traffic (AADTT), pavement condition as well as the rutting and fatigue criteria.
2. **Relative Damage Analysis:** This optional analysis compares the estimated damage for the flooded section with that of a control, non-flooded section to provide additional context on the effect of flooding on pavement structural capacity.

4.8.2. Calculation Methods

The Traffic Control Tool includes a section in which the user can select the calculation method for each critical variable used in the analysis. These variables consist of the critical stress and resilient modulus used in the rutting analysis, as well as the critical strain used in the fatigue cracking analysis.

For the critical stress on top of the embankment, the user may select "Calculated stress" to use the average value estimated from the regression analysis, "Legacy method" to use 10 psi which was used in FDOT's Legacy Method, or "User input" to use a user-defined value.

For the critical strain at the bottom of the AC layer, the user may select "Calculated strain" to use the average value estimated from the regression model, or "User input".

Finally, the user may select "Regression modulus" to use the average resilient modulus of embankment estimated from the regression equation, "FDOT's resilient modulus", AASHTO's resilient modulus", or "User input" to use a user-defined resilient modulus (e.g., 32,000 psi).

The selected calculation method should be based on the reasonableness of the estimated pavement responses and modulus values, as well as any additional project-specific information available to the user.

 The **Calculation Methods** section allows the user to select the preferred method for determining the critical inputs in the traffic control recommendation analysis.

4.8.3. Flood Restriction Recommendation

The Flood Restriction Recommendation section is the main analysis section of the Traffic Control Tool. In this section, the inputs selected under Calculation Methods are used to calculate the allowable daily load repetitions for both the fatigue and rutting criteria using their respective transfer functions.

The allowable daily repetitions are then compared with the roadway AADTT, which the user can consult the Florida Traffic Online site (<https://tdaappsprod.dot.state.fl.us/fto/>). Based on whether the allowable repetitions are less than, near, or greater than the AADTT, together with the observed pavement condition (i.e., flood water on the pavement surface, flood water at the shoulder edge, or normal ditch flow), the tool provides a traffic control recommendation for both the fatigue and rutting criteria.

The final recommendation is determined using the Flood Restriction Recommendation Matrix shown in Figure 20. For this comparison, the allowable daily repetitions are considered near the roadway AADTT when they fall within ± 15.0 percent of AADTT.

Flood Waters on Pavement Surface	Closed to all Traffic	Closed to all Traffic	Restricted Traffic (Emergency Vehicles Only)
Flood Waters at Shoulder Edge	Closed to all Traffic	Restricted Traffic (Emergency Vehicles Only)	Open to All Traffic
Normal Ditch Flow	Closed to all Traffic	Passenger vehicles with Restricted Trucks if Pavement is in Good Condition	Open to All Traffic
	Allowable Loads less than AADTT	Allowable Loads near AADTT	Allowable Loads greater than AADTT

Figure 20. Flood restriction recommendation matrix.

 The Traffic Control Tool uses FDOT's existing **traffic control decision matrix** while adding a fatigue criterion and allowing daily load repetitions to be evaluated using pavement responses estimated from measured deflection data. **Note:** Control section data is not required to provide a traffic control recommendation.

4.8.4. Pavement Life Reduction Analysis

The Relative Damage Analysis provides a relative measure of the increase in pavement damage associated with the flooded condition. For both fatigue and rutting, the damage factor calculated for the flooded section is divided by the corresponding factor for the control, non-flooded section.

This option is enabled only when a control section is available. It is noted again that the user may override the calculated values by specifying user-defined inputs in the Calculation Methods section.

4.9. SENSITIVITY ANALYSIS

A Sensitivity Analysis worksheet is included in the Traffic Control Tool to evaluate the effect of key input variables on the calculated allowable daily load repetitions. This analysis is particularly useful when pavement properties, such as layer thicknesses or embankment resilient modulus, are not known with certainty.

For each sensitivity variable, the user must provide the minimum, maximum, and increment values. The user also provides the roadway AADTT and an AADTT tolerance used to define the range of allowable daily repetitions considered “near” the roadway AADTT.

The tool then generates all possible combinations of the selected input values based on the specified ranges and increments. For each combination, the Flood Restriction Recommendation analysis is repeated to calculate the allowable daily load repetitions for both fatigue cracking and embankment rutting.

The results are presented graphically to allow the user to evaluate how changes in the selected input variables affect the allowable traffic.

 **Sensitivity Analysis is equivalent to running the Flood Restriction Recommendation Analysis multiple times.** The user can vary one or more input variables at desired intervals and obtain the allowable daily load repetitions.

4.10. USING FDOT'S NEW TRAFFIC CONTROL TOOL

4.10.1. General

In previous sections of this chapter, the features of the Traffic Control Tool were described. The objective of this section is to further explain and demonstrate this new tool by providing practical examples. Note that a Detailed User Manual for the Tool is presented in Appendix A, and the first-time users are recommended to visit the Appendix for more information on setting up the tool and for step-by-step produces for running the tool using different options.

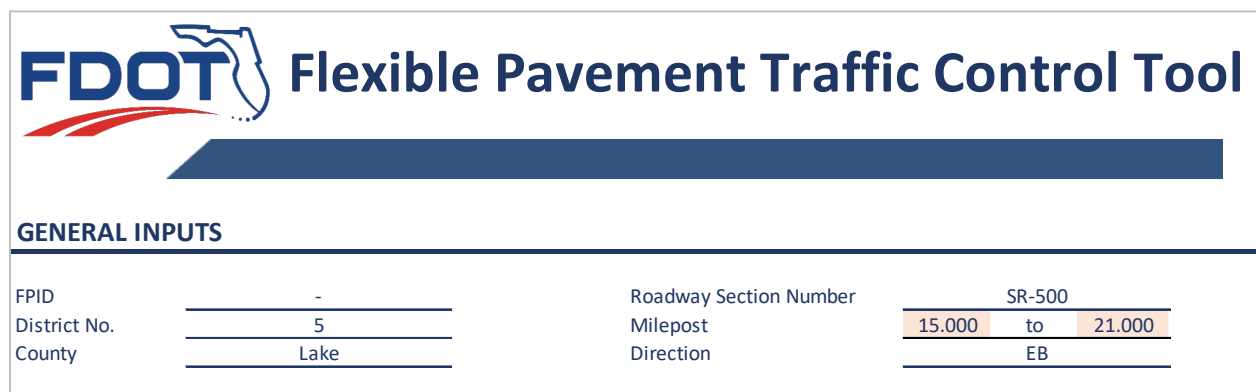
Three examples are presented with increasing level of complexity:

- Example 1: This is the simplest example and considers only flooded data. The objective of this exercise is to demonstrate how to obtain a traffic control recommendation.
- Example 2: This example considers both flooded and control-section data. In addition to obtaining a traffic control recommendation, the user evaluates the relative damage per truck pass in the flooded section compared with the control condition.
- Example 3: This example uses the same data as Example 2 but demonstrates the sensitivity analysis implemented in the Traffic Control Tool. In this example, the user evaluates how results change when different embankment resilient modulus, AC thickness, and base thickness values are considered.

4.10.2. Example 1

4.10.2.1. *Description*

This example considers only flooded data, and the objective is to obtain a traffic control recommendation after a flooding event. The general inputs for this example are shown in Figure 21.



The screenshot shows the title 'FDOT Flexible Pavement Traffic Control Tool' with the FDOT logo. Below the title is a section titled 'GENERAL INPUTS'. The form contains the following fields and values:

FPID	-	Roadway Section Number	SR-500
District No.	5	Milepost	15.000 to 21.000
County	Lake	Direction	EB

Figure 21. General inputs for Example 1.

4.10.2.2. *Deflection Data*

The first example uses deflection data from SR-500 (which runs continuously with US 441) in Lake County. The flooded section extends from milepost 15.2 to 20.2 mi. The measured deflections are shown in Figure 22.

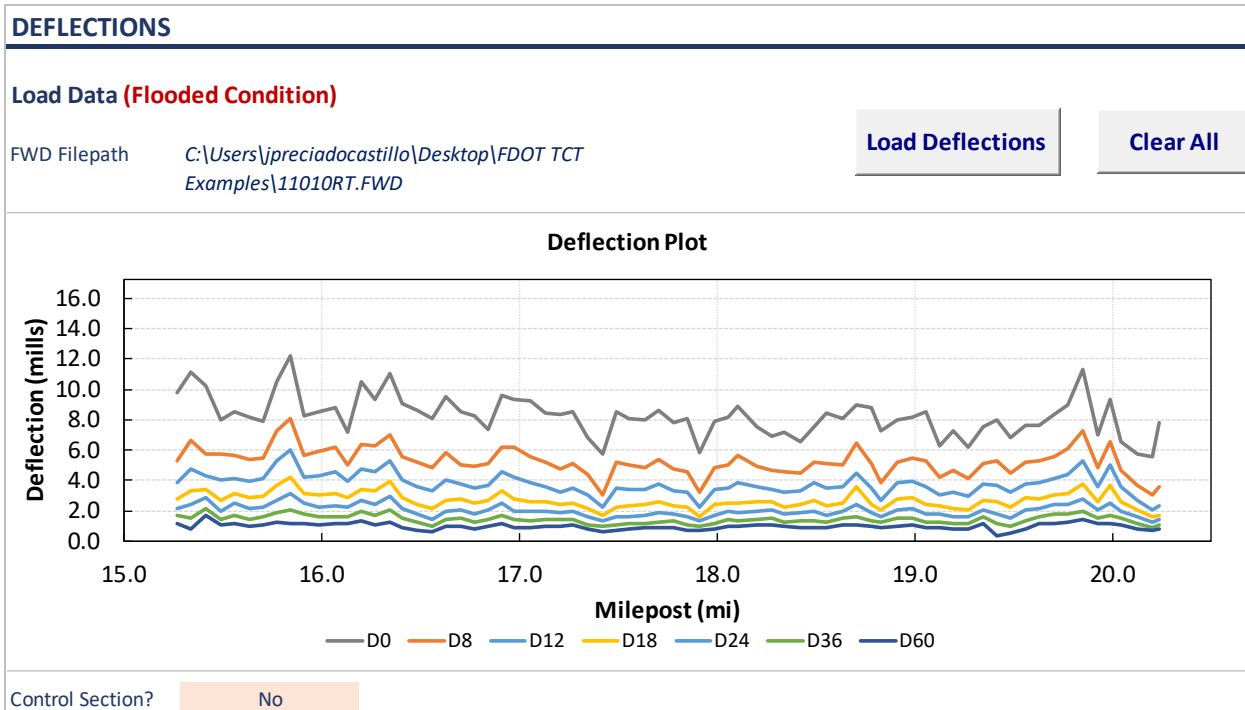


Figure 22. Measured deflections for the flooded section in Example 1.

4.10.2.3. Pavement Thickness

For the purpose of this example, it is assumed that coring data previously collected by FDOT's Pavement Evaluation Unit indicates that the section extending from milepost 15.0 to 25.0 mi. has an average AC thickness of 8.0 in, and an average base thickness of 12.0 in. The pavement thickness inputs entered into the Traffic Control Tool are shown in Figure 23.

PAVEMENT INFORMATION

Pavement Thickness

No. of Sections:

Section	Begin MP ²	End MP	AC Thickness (in)	Base Thickness (in)	Warning
1	15.00	25.00	8.0	12.0	-

Note 1: The database used to develop the regression models included pavement structures with AC thicknesses ranging from 4 to 15 in. and base thicknesses ranging from 6 to 18 in. Values outside these ranges represent extrapolation beyond the data used for model development and should therefore be interpreted with caution.
Note 2: Non-inclusive

Figure 23. Pavement thickness inputs in Example 1.

The critical pavement responses are estimated for the flooded section. The average strain at the bottom of the AC layer was 167.2 microstrain, and the average compressive stress at the top of the embankment was 11.3 psi. The estimated pavement responses are presented in Figure 24.

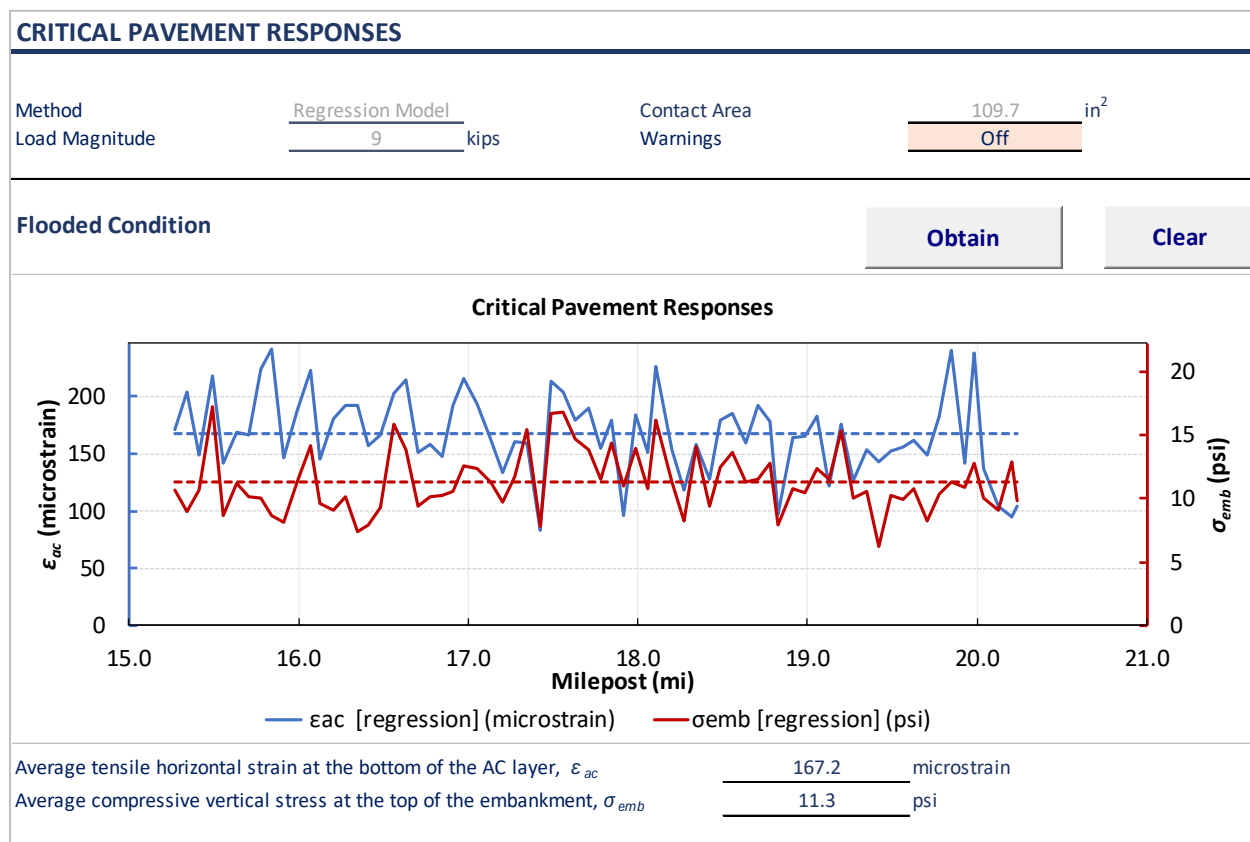


Figure 24. Estimated critical pavement responses in Example 1.

4.10.2.4. Layer Moduli

The estimated embankment resilient moduli are presented in Figure 25. The average embankment modulus obtained from the regression analysis was 39,642 psi, the average modulus estimated using the AASHTO procedure was 41,038 psi, and the FDOT resilient modulus was 28,354 psi.

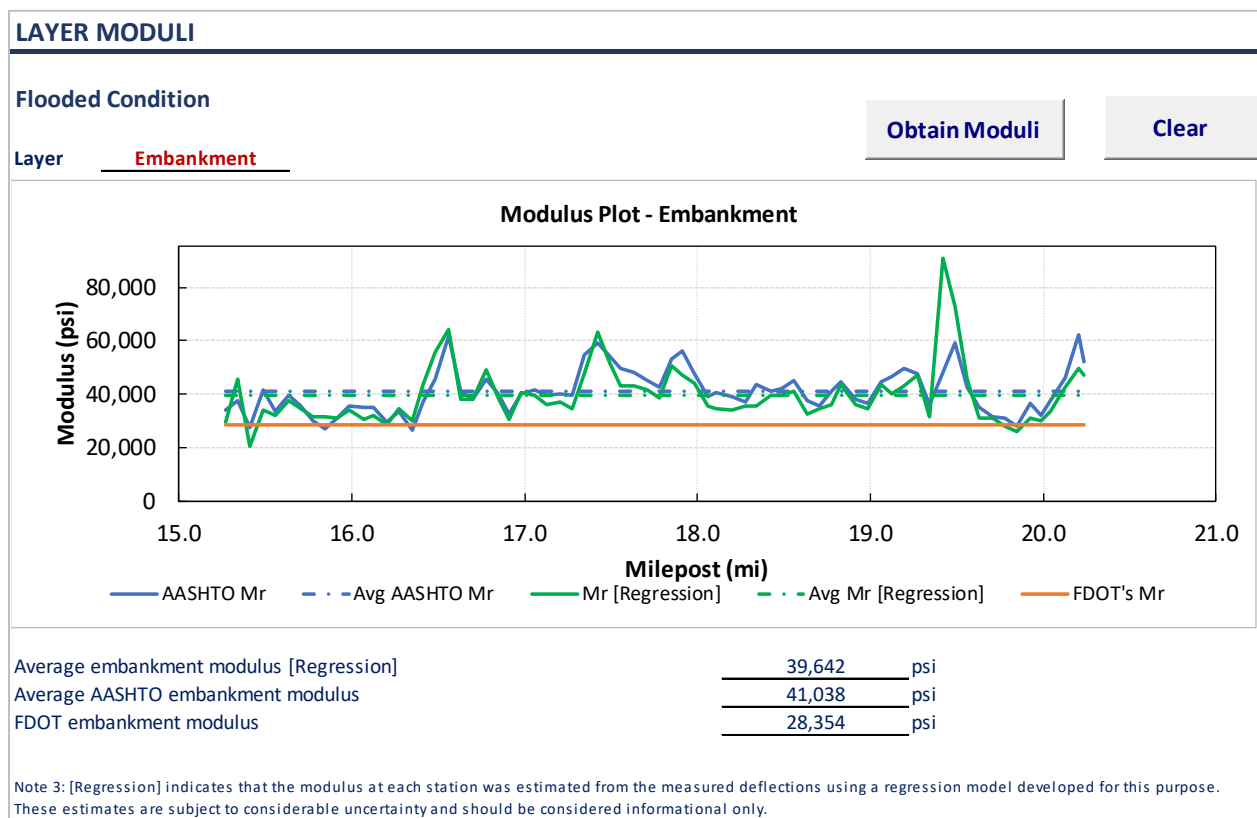


Figure 25. Estimated embankment resilient moduli in Example 1.

4.10.2.5. Transfer Function Coefficients

This example uses the default fatigue and rutting transfer function coefficients provided in the Traffic Control Tool.

4.10.2.6. Analysis

The calculation methods selected for the analysis are shown in Figure 26. In this example, critical stress and strain are obtained from the regression-based prediction modulus, while FDOT's resilient modulus is used for the rutting analysis.

ANALYSIS			
Calculation Methods			
Variable	Method	Condition	
		Flooded	Control
Critical Stress, σ_{emb} (psi)	Calculated stress	11.3	-
Critical Strain, ϵ_{ac} (microstrain)	Calculated strain	167.2	-
Resilient Modulus, M_R (psi)	FDOT's resilient modulus	28,354	-

Note 4: Use the dropdown list to define the calculation method for the critical inputs used in the analysis.

Figure 26. Calculation methods and critical input variables used in Example 1.

An AADTT of 4,505 trucks per day was used for this road (Figure 27) based on the information from Florida Traffic Online Site (<https://tdaappsprod.dot.state.fl.us/fto/>), and the observed flood condition based on the site investigation was selected as Water at Shoulder Edge.

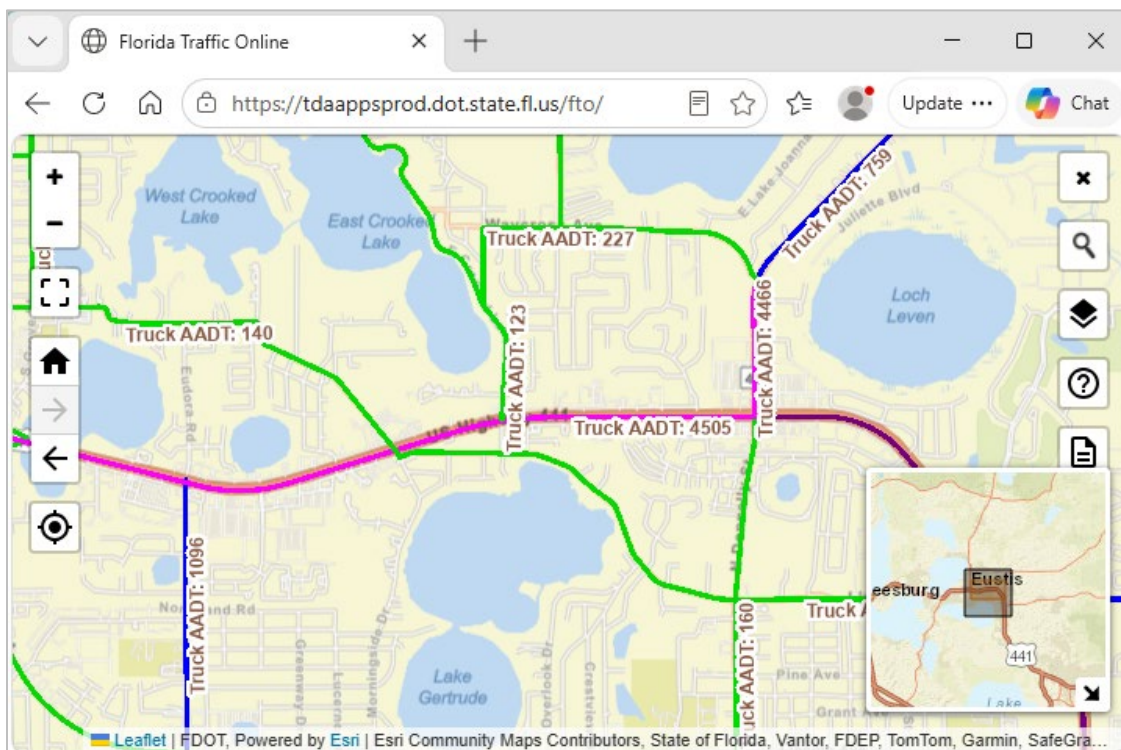


Figure 27. Roadway AADTT in Example 1.

The resulting Flood Restriction Recommendation is presented in Figure 28. Based on the rutting criterion, the allowable daily repetitions are 7,050, resulting in a traffic control recommendation of Open to All Traffic. The fatigue criterion yields 940 allowable daily repetitions a traffic control recommendation of Close to All Traffic.

Flood Restriction Recommendation			
One-way AADTT	4,505	Open Restriction	Check Flood Restriction
Current flood condition	Normal ditch flow		
	Rutting Criterion	Fatigue Criterion	
Allowable daily repetitions	7,050	940	
Flood restriction recommendation	Open to All Traffic	Closed to All Traffic	
Note 5: Annual average daily truck traffic can be consulted in the Florida Traffic Online site (https://tdaappsprod.dot.state.fl.us/fto/)			

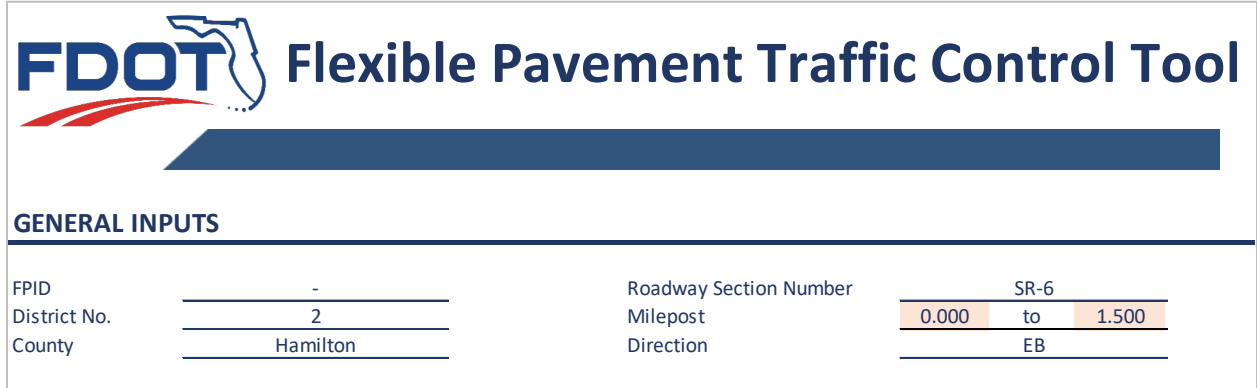
Figure 28. Flood Restriction Recommendation results for Example 1.

In Example 1, the fatigue criterion resulted in the strictest traffic control recommendation. In this case, the governing recommendation is Close to All Traffic.

4.10.3. Example 2

4.10.3.1. *Description*

This example considers both flooded and control-section data. In addition to obtaining a traffic control recommendation, the user evaluates the relative damage per truck pass in the flooded section compared with the control condition. Figure 29 shows the general information for the particular example.



The screenshot displays the 'FDOT Flexible Pavement Traffic Control Tool' interface. At the top is the FDOT logo and the tool's title. Below this is a section titled 'GENERAL INPUTS' which contains a form with the following fields and values:

GENERAL INPUTS	
FPID	-
District No.	2
County	Hamilton
Roadway Section Number	SR-6
Milepost	0.000 to 1.500
Direction	EB

Figure 29. General inputs for Example 2.

4.10.3.2. *Deflection Data*

The second example is based on a case study from SR-6 in Hamilton County. The flooded section extends from milepost 0.1 to 0.2 mi, while the control section extends from milepost 1.3 to 1.4 mi. The measured deflections for both sections are shown in Figure 30.

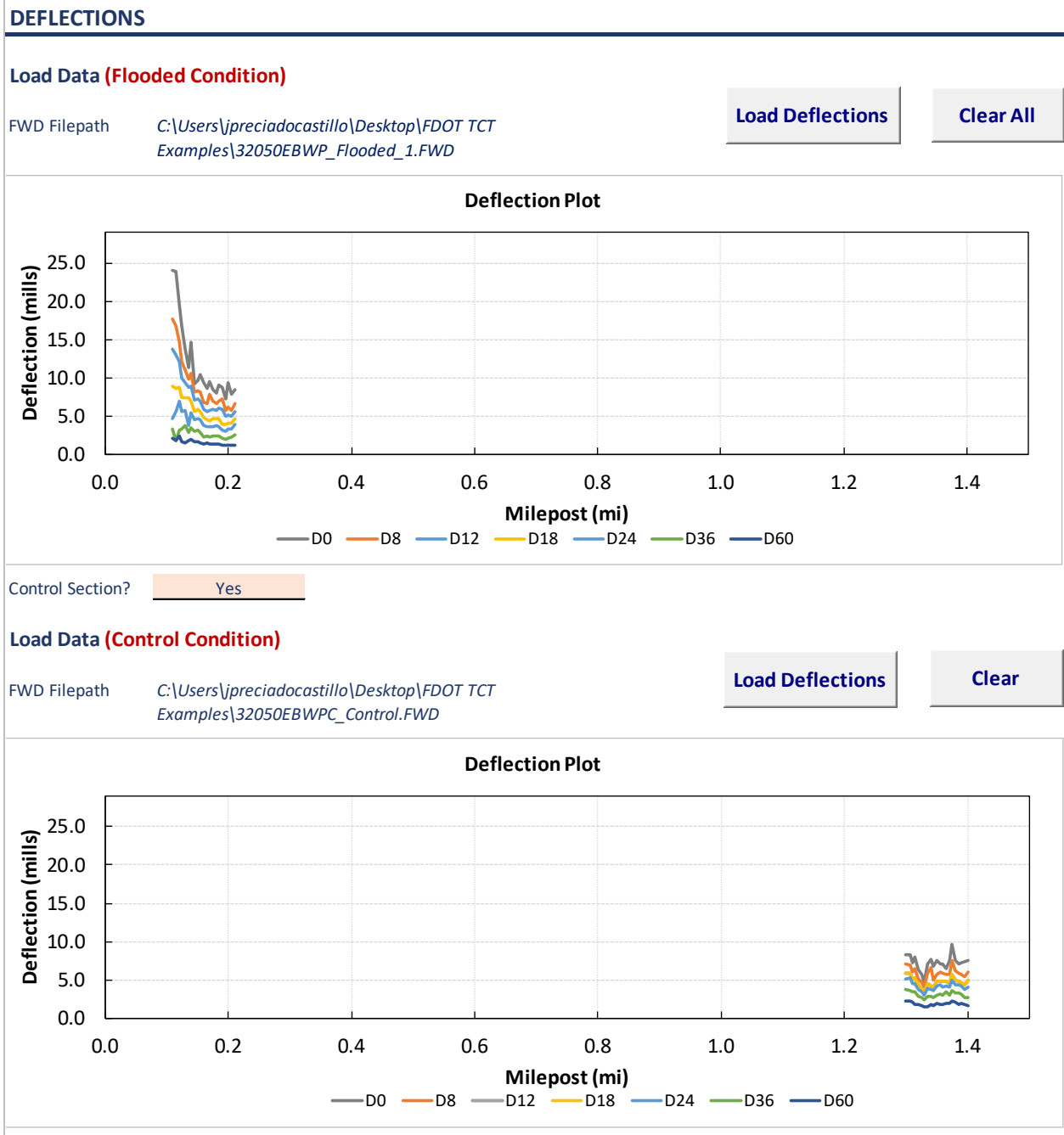


Figure 30. Measured deflections for the flooded and control sections in Example 2.

At first glance, the flooded section exhibits higher deflections than the control section. This suggests that the flooded pavement had a lower stiffness at the time of testing.

To load data for a control section, the “Control Section?” option in the Traffic Control Tool must be set to “Yes”.

4.10.3.3. Pavement Thickness

This example defines two pavement sections: one for the flooded section from milepost 0.1 to 0.2 mi and one for the control section from milepost 1.3 to 1.4 mi.

Existing coring information collected by FDOT's Pavement Evaluation Unit indicated an AC thickness of 5.2 in. and a base of 8.0 in. for the flooded section. For the control section, the AC and base thickness were 6.0 and 7.5 in., respectively. The pavement thickness inputs entered into the Traffic Control Tool are shown in Figure 31.

PAVEMENT INFORMATION					
Pavement Thickness					
No. of Sections	2				
Section	Begin MP ²	End MP	AC Thickness (in)	Base Thickness (in)	Warning
1	0.00	0.50	5.2	8.0	-
2	1.20	1.50	6.0	7.5	-
Note 1: The database used to develop the regression models included pavement structures with AC thicknesses ranging from 4 to 15 in. and base thicknesses ranging from 6 to 18 in. Values outside these ranges represent extrapolation beyond the data used for model development and should therefore be interpreted with caution. Note 2: Non-inclusive					

Figure 31. Pavement thickness inputs for the flooded and control sections in Example 2.

4.10.3.4. Critical Pavement Responses

The critical pavement responses are estimated separately for the flooded and control conditions. The average strain at the bottom of the AC layer was 177.3 microstrain for the flooded condition and 61.7 microstrain for the control section. In a similar way, the average compressive stress at the top of the embankment was 9.6 psi for the flooded section and 4.2 psi for the control section. The estimated pavement responses for both conditions are presented in Figure 32.

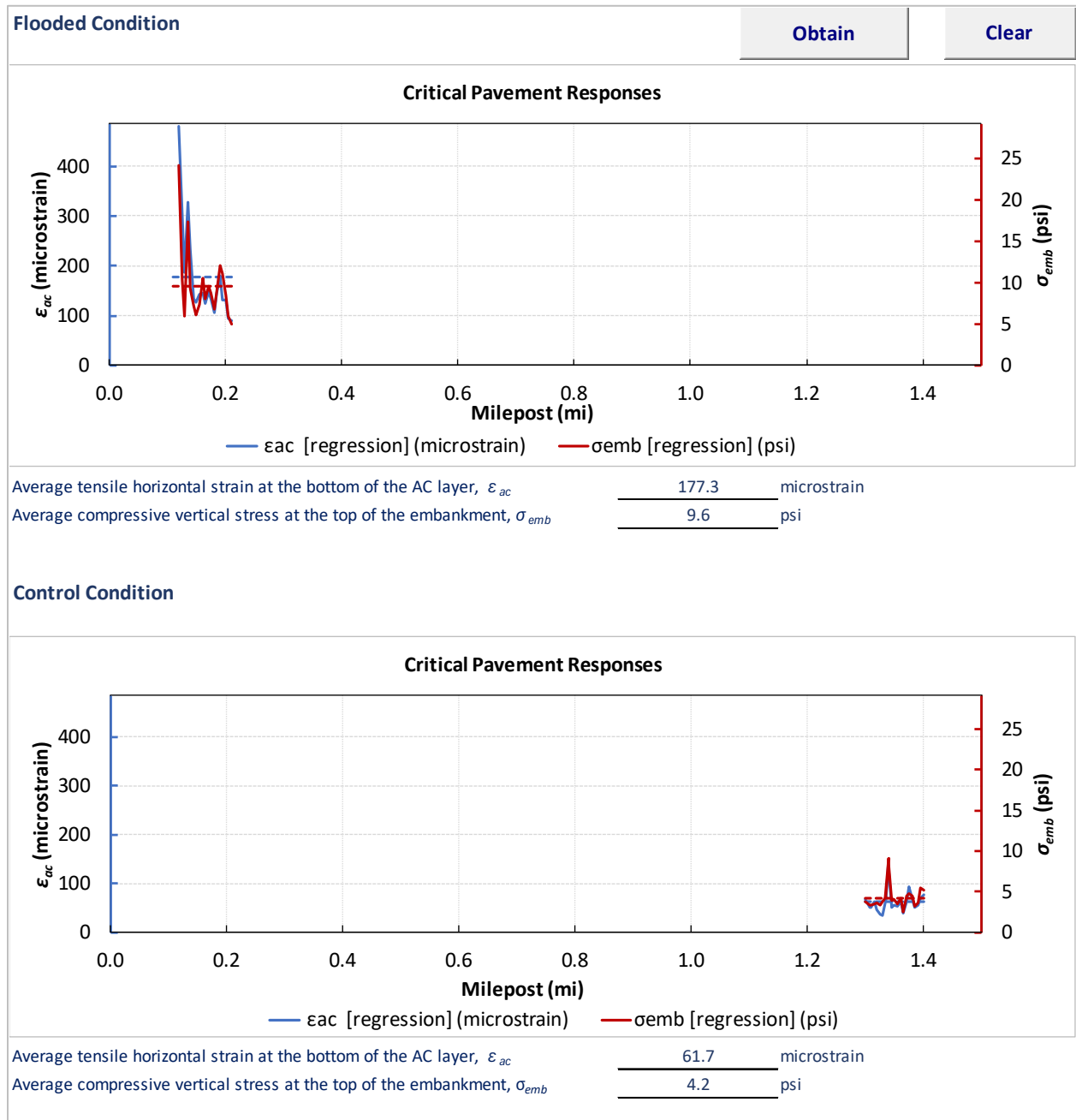


Figure 32. Estimated critical pavement responses for the flooded and control sections in Example 2.

4.10.3.5. Layer Moduli

The estimated embankment resilient moduli for the flooded and control conditions are presented in Figure 33. For the flooded section, the average embankment modulus obtained from the regression analysis was 25,856 psi, the average modulus estimated using the AASHTO procedure was 22,759 psi, and the FDOT resilient modulus was 15,541 psi. For the control section, the corresponding values were 22,762 psi, 19,137 psi, and 15,192 psi.

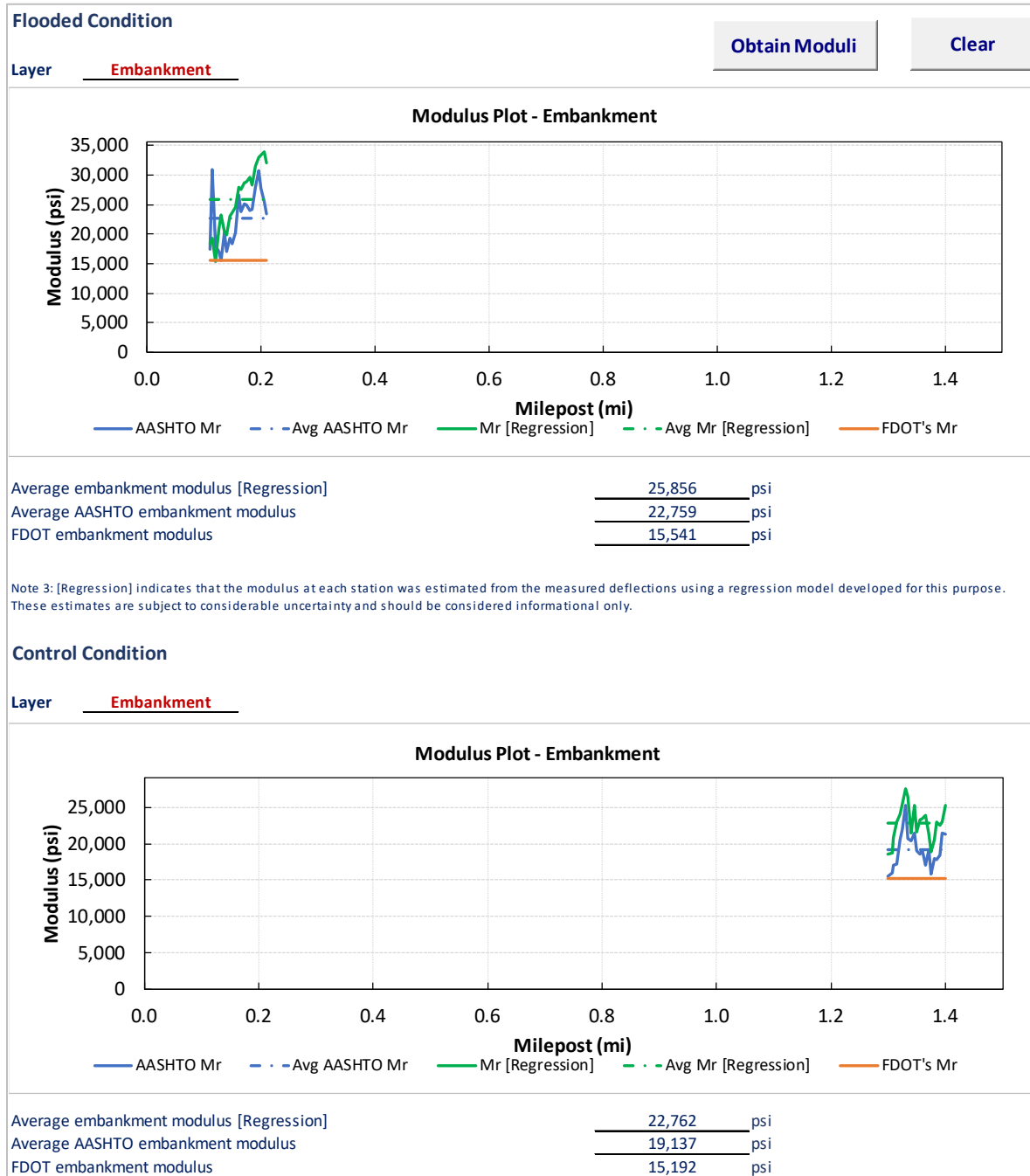


Figure 33. Estimated embankment resilient moduli for the flooded and control sections in Example 2.

4.10.3.6. Transfer Function Coefficients

This example uses the default fatigue and rutting transfer function coefficients provided in the Traffic Control Tool.

4.10.3.7. Analysis

The calculation methods selected for the analysis are shown in Figure 34. In this example, critical stress and strain are obtained from the regression-based prediction modulus, while FDOT's resilient modulus is used for the rutting analysis. The same calculation methods apply to both flooded and control conditions.

ANALYSIS			
Calculation Methods			
Variable	Method	Condition	
		Flooded	Control
Critical Stress, σ_{emb} (psi)	Calculated stress	9.6	4.2
Critical Strain, ϵ_{ac} (microstrain)	Calculated strain	177.3	61.7
Resilient Modulus, M_R (psi)	FDOT's resilient modulus	15,541	15,192

Note 4: Use the dropdown list to define the calculation method for the critical inputs used in the analysis.

Figure 34. Calculation methods and critical input variables used in Example 2.

An AADTT of 463 trucks per day was used for this road based on the information obtained from Florida Traffic Online Site (<https://tdaappsprod.dot.state.fl.us/fto/>) (Figure 35), and the observed flood condition based on the site investigation was selected as Normal Ditch Flow.

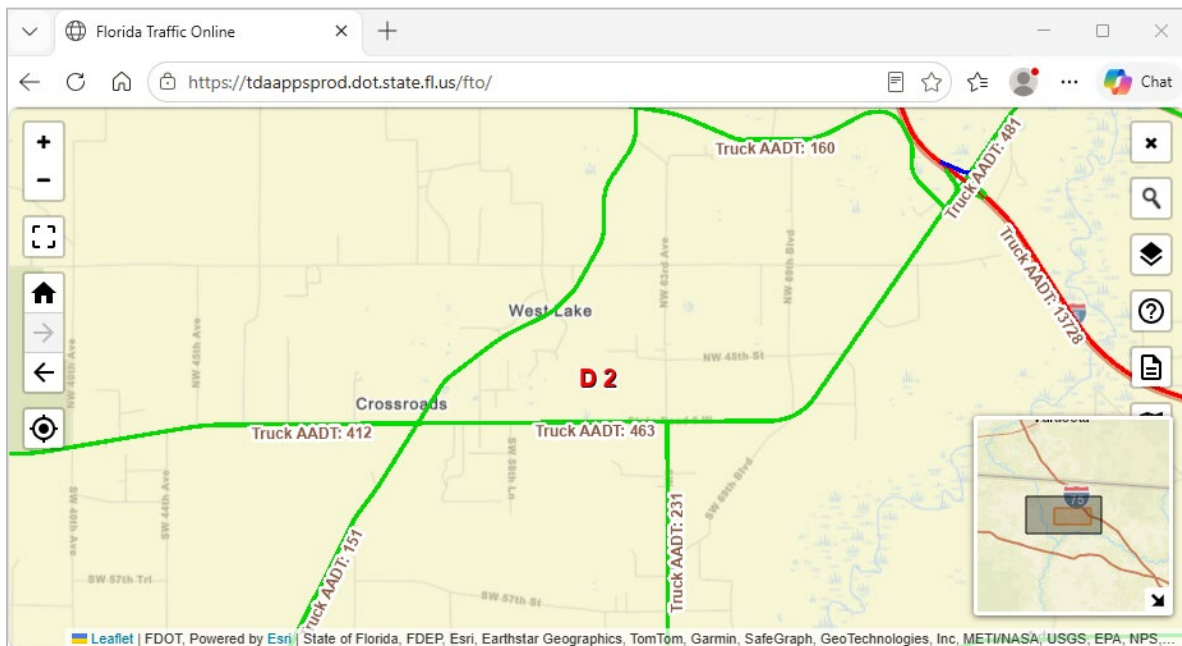


Figure 35. Roadway AADTT in Example 2.

The resulting Flood Restriction Recommendation is presented in Figure 36. Based on the rutting criterion, the allowable daily repetitions are 1,479, resulting in a traffic control recommendation

of Open to All Traffic. The fatigue criterion yields 729 allowable daily repetitions and recommends Open to All Traffic as well.

Flood Restriction Recommendation			
One-way AADTT	463		
Current flood condition	Normal ditch flow	Open Restriction	Check Flood Restriction
	Rutting Criterion	Fatigue Criterion	
Allowable daily repetitions	1,479	729	
Flood restriction recommendation	Open to All Traffic	Open to All Traffic	
Note 5: Annual average daily truck traffic can be consulted in the Florida Traffic Online site (https://tdaappsprod.dot.state.fl.us/fto/)			

Figure 36. Flood Restriction Recommendation results for Example 2.

 In Example 2, both the fatigue and rutting criterion resulted in the same traffic control recommendation Open to All Traffic.

The Relative Damage Analysis results are shown in Figure 37. The calculated damage amplification factors are 20.8 for rutting and 95.9 for fatigue. These values indicate that, relative to the control condition, each truck pass under the flooded condition is estimated to produce approximately 20.8 times the rutting damage and 95.9 times the fatigue damage.

Relative Damage Analysis			Run Analysis
	Rutting Criterion	Fatigue Criterion	
Reference damage per pass	4.45E-09	3.92E-09	
Current damage per pass	9.26E-08	3.76E-07	
Damage amplification factor	20.8	95.9	
Note 6: Damage amplification represents the increase in damage caused by each truck pass under the current moisture condition of the unbound materials relative to the control, non-flooded condition.			

Figure 37. Relative Damage Analysis results for Example 2.

4.10.4. Example 3 – Sensitivity Analysis

4.10.4.1. *Description*

This example uses the same flooded data as Example 2 and focuses on a sensitivity analysis of the allowable daily repetitions. The inputs for the sensitivity analysis are shown in Figure 38. As shown in Figure 38, the entered AC thickness ranges between 4.2 and 12.2 in., while the base thickness ranges from 7.0 to 9.0 in. Both these layers will be evaluated at an increment of 1.0 in. as specified in the figure. For the embankment resilient modulus, the sensitivity analysis will vary this value from 2,000 psi to 32,000 psi at an increment of 2,000 psi.

SENSITIVITY ANALYSIS INPUTS

Sensitivity Variables

Variables	Minimum	Maximum	Increment
AC Thickness (in)	4.2	12.2	1
Base Thickness (in)	7	9	1
Resilient Modulus (psi)	2,000	32,000	2,000

Note: Use the table to define the ranges of the variables to be included in the sensitivity analysis.

Clear

Run Analysis

One-way AADTT

463

AADTT Tolerance

15

%

Figure 38. Sensitivity analysis inputs in Example 3.

4.10.4.2. Sensitivity Analysis Results

The results of the sensitivity analysis using the rutting criterion are shown in Figure 39. For the range of AC thicknesses evaluated, and a base thickness of 8 inches, the allowable daily repetitions remain above the roadway AADTT when the resilient modulus exceeds approximately 8,000 psi.

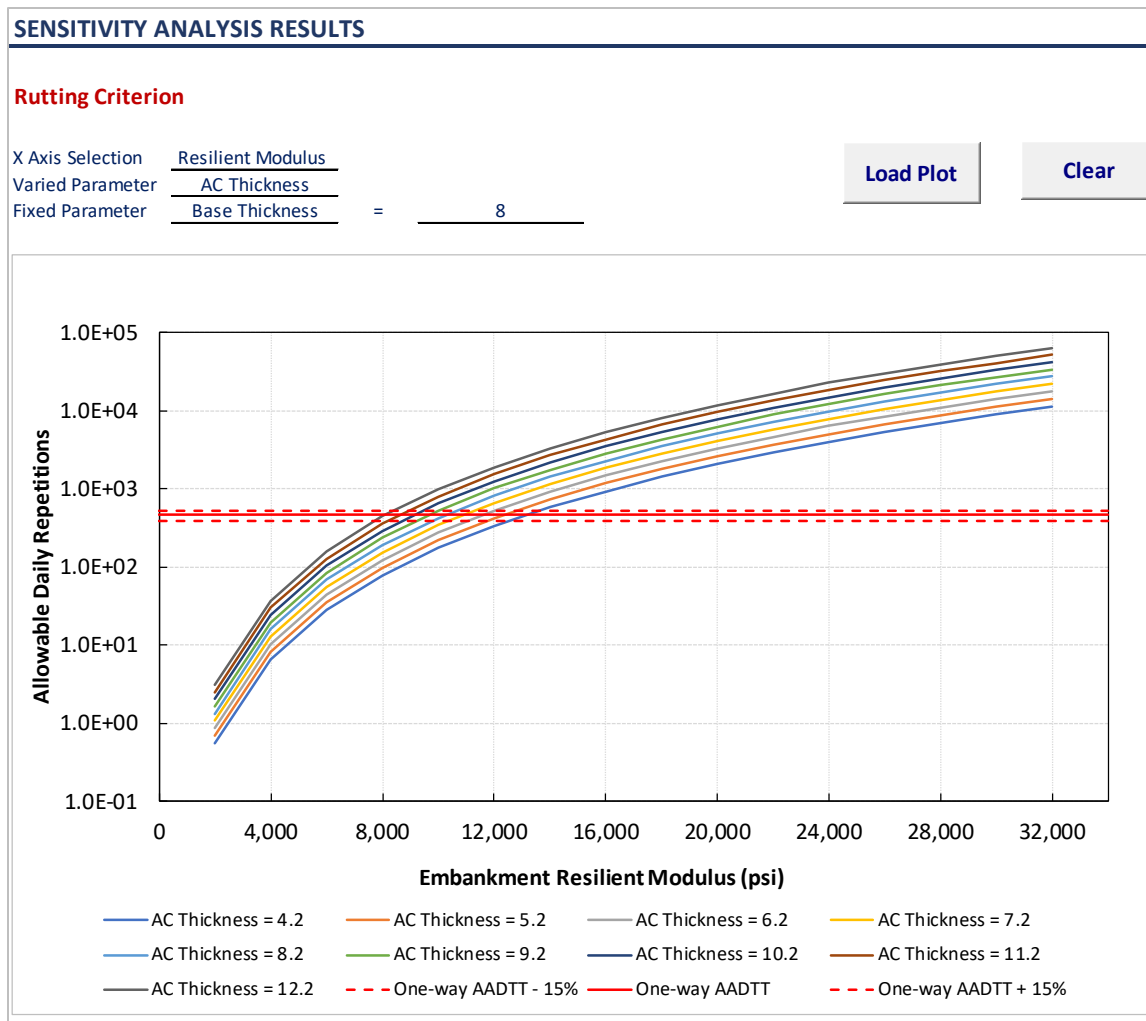


Figure 39. Results of sensitivity analysis using the rutting criterion.

The results of the sensitivity analysis using the fatigue criterion are shown in Figure 40. As the assumed AC thickness increases, the allowable daily repetitions initially decrease, reaching a minimum at approximately 7.0 in., and then begin to increase. This behavior reflects two competing effects in the analysis. Because the measured FWD deflection basin is held constant while the assumed AC thickness is varied, thicker AC sections are likely associated with lower AC stiffness. Over the lower AC thickness range (Approx. ≤ 7.0 in), this effect appears to dominate, resulting in higher tensile strains at the bottom of the AC layer and, consequently, fewer allowable repetitions. At greater AC thickness range (Approx. > 7.0 in), however, the structural benefit associated with the increased layer thickness becomes more influential and begins to offset the effect associated with the lower stiffness. As a result, the predicted tensile strain decreases and the allowable daily repetitions increases beyond approximately 7.0 in. It is noted that such a trend is due to the complicated layer compensating effect that involves AC thickness as well as both the AC and base moduli, and is in agreement with the trends identified based on the empirical relationships developed by Kim et al. (2000).

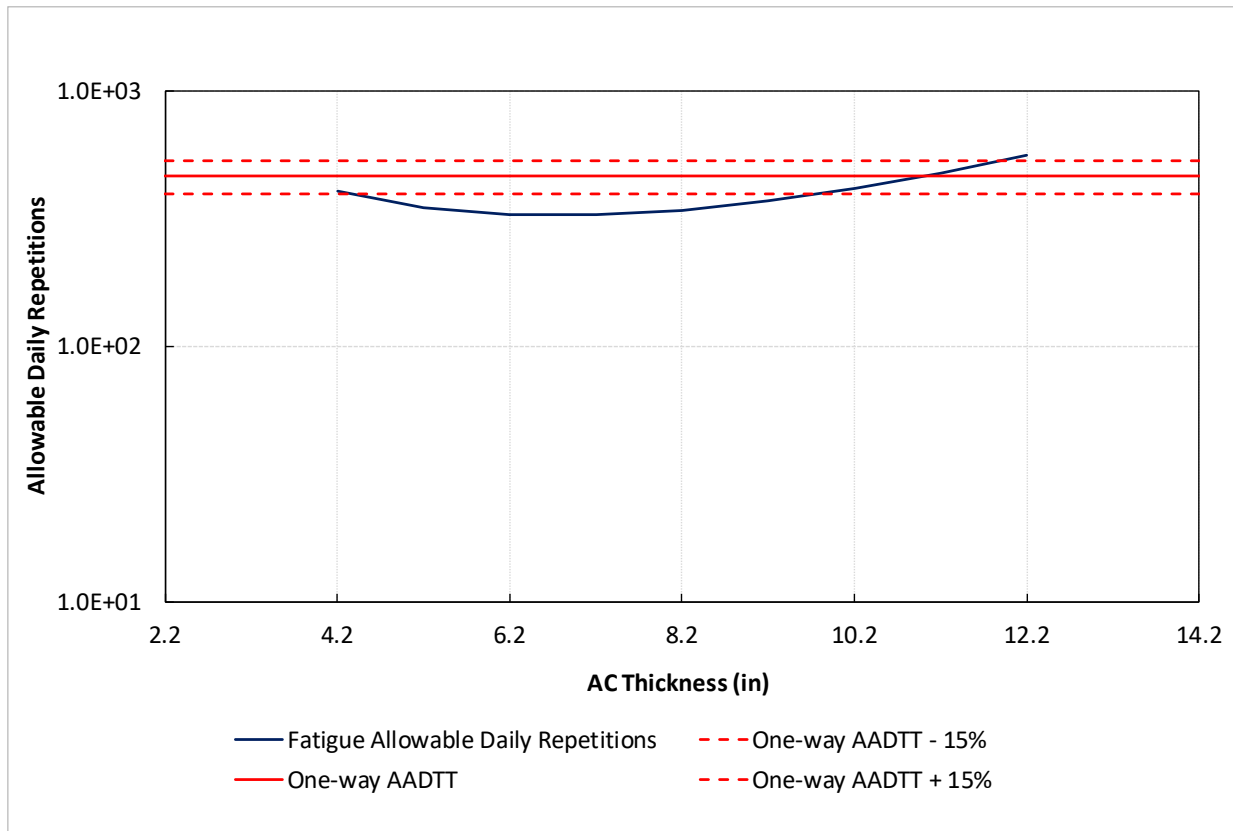
Fatigue Criterion

X Axis Selection

AC Thickness

Load Plot

Clear



Note: The sensitivity analysis of allowable daily repetitions for the fatigue criterion is based solely on variations in AC thickness, as base thickness is not included in the fatigue response prediction model.

Figure 40. Results of sensitivity analysis using fatigue criterion.

For the fatigue criterion, the sensitivity analysis varies only the AC thickness because this is the only pavement thickness variable included in the critical strain prediction model.

5. SUMMARY AND CONCLUSIONS

Flooding can adversely affect the structural capacity of flexible pavements by increasing the moisture content of unbound foundation layers. The resulting reduction in foundation support may increase critical pavement responses and accelerate the progression of critical distresses such as fatigue cracking and rutting, particularly when normal traffic is restored before the pavement structure has sufficiently recover its strength. Consequently, the ability to evaluate pavement structural condition following a flooding event is an important component of pavement resiliency and post-flood traffic management.

FDOT previously developed a traffic-control tool and a decision matrix to provide guidance on roadway restrictions following flooding events based primarily on traffic level, observed flood condition, and the embankment resilient modulus estimated from Falling Weight Deflectometer (FWD) measurements. The primary objective of this study was to enhance the flexible pavement traffic control tool by providing a more comprehensive evaluation of pavement structural response and damage under flooded conditions.

To support this objective, available literature and existing FDOT practices related to pavement resiliency were reviewed, and a methodology was developed for traffic control recommendations on flooded pavements. The methodology consisted of using the FWD deflections to estimate critical pavement responses through empirical relationships developed using Layered Elastic Analysis (LEA). The estimated pavement responses were then used with fatigue and rutting transfer functions to determine the allowable number of load repetitions for the evaluated pavement condition and support the traffic control recommendation.

The newly developed methodology was implemented in a macro-enabled Excel spreadsheet referred to as “FDOT’s Flexible Pavement Traffic Control Tool”. The tool allows the user to import FWD data, define pavement structures, estimate layer moduli and critical responses, evaluate fatigue and rutting criteria, and obtain a traffic control recommendation. The tool also includes a sensitivity analysis option that allows the user to evaluate the effect of multiple variables on the calculated fatigue and rutting criteria.

Three examples were presented in Chapter 4 of this report to demonstrate the application of the developed tool. The first two examples illustrate the general workflow for evaluating pavement sections using FWD measurements, pavement thickness information, and the available calculation options within the tool. The third example focuses on the sensitivity-analysis capability and demonstrates how changes in pavement structure affect the calculated fatigue and rutting criteria. A detailed user guide is provided in Appendix A to further support implementation of the tool.

Overall, the methodology developed in this study retains the field-based nature of FDOT’s existing traffic control tool procedure while providing a broader evaluation of flexible pavement structural condition through consideration of both fatigue and rutting distresses.

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APPENDIX A: DETAILED USER GUIDE

A.1. BEFORE GETTING STARTED

FDOT's new Traffic Control tool is implemented in a macro-enabled Excel spreadsheet environment. As such, it is important that the macros or code written in Visual Basic for Applications (VBA) language be enabled for the Traffic Control tool to function properly.

Figure A-1 shows the Excel window in which a security warning is displayed due to the embedded macros. If the user sees this message, they must click the "Enable Content" button to enable the macros within the Traffic Control tool.

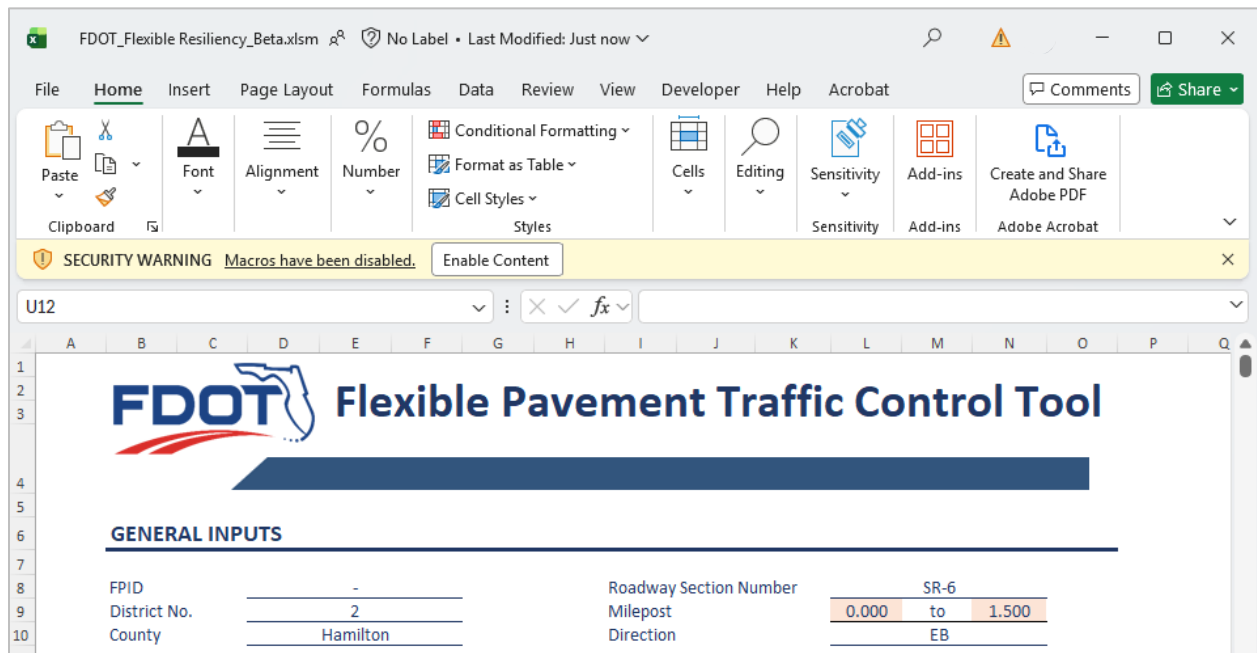


Figure A-1. Security warning message in Excel.

Furthermore, it is recommended that the user enable all macros within the Excel environment. To do so, the user needs to follow the steps outlined below.

1. Click on the "Developer" tab of the Excel Ribbon
 - a. If the "Developer" tab is not visible, go to File → Options → Customize Ribbon, and select the check box next to "Developer".
2. Select "Macro Security" in the "Developer" tab
3. In the new pop-up window, select "Enable All Macros" option and then click "OK" (Figure A-2).

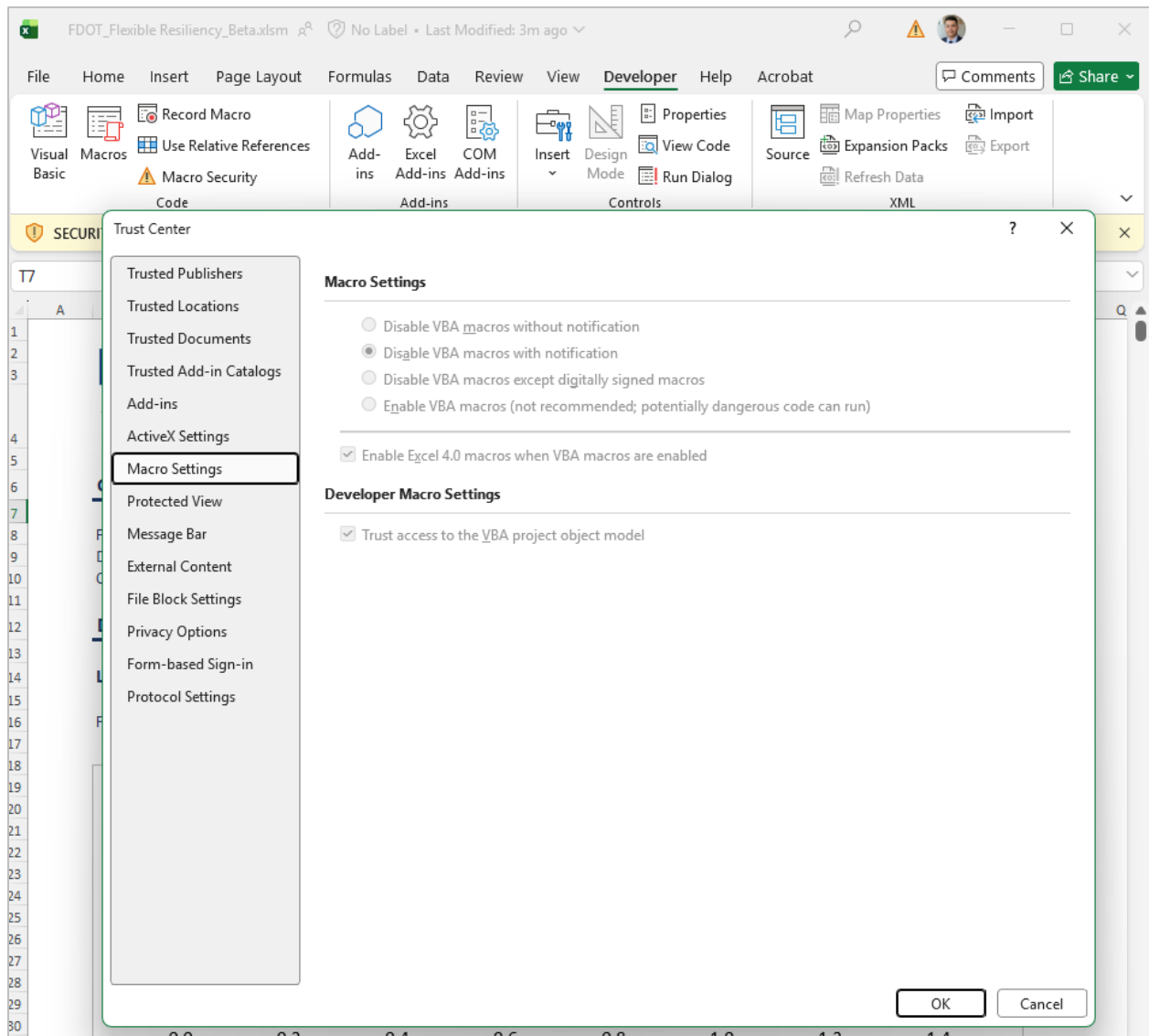


Figure A-2. Enabling all macros in Excel

With the above settings in Excel, the user is ready to run the new Traffic Control tool. The remainder of this manual describes how the user can run each mode of analysis.

A.2. GENERAL INPUTS

Figure A-3 shows the Traffic Control tool interface for the general inputs. These inputs are the general project-related information that defines the location of the project as well as other information pertaining to the project (i.e., similar project information as included in FDOT's nondestructive testing reports). These inputs include FDOT's Financial Project Number (FPN), District, County, roadway section number, direction, and limiting mileposts.

The limiting mileposts (highlighted in orange) define the overall analysis range encompassing both the flooded and control sections. These values also establish a common x-axis range for the figures generated by the tool.

Flexible Pavement Traffic Control Tool

GENERAL INPUTS

FPID	-	Roadway Section Number	SR-6
District No.	2	Milepost	0.000 to 1.500
County	Hamilton	Direction	EB

Figure A-3. Measured deflections for the flooded and control sections in Example 2.

A.3. DEFLECTIONS

Figure A-4 presents the Traffic Control tool interface where the user obtains the user loads the .FWD file containing the deflection data.

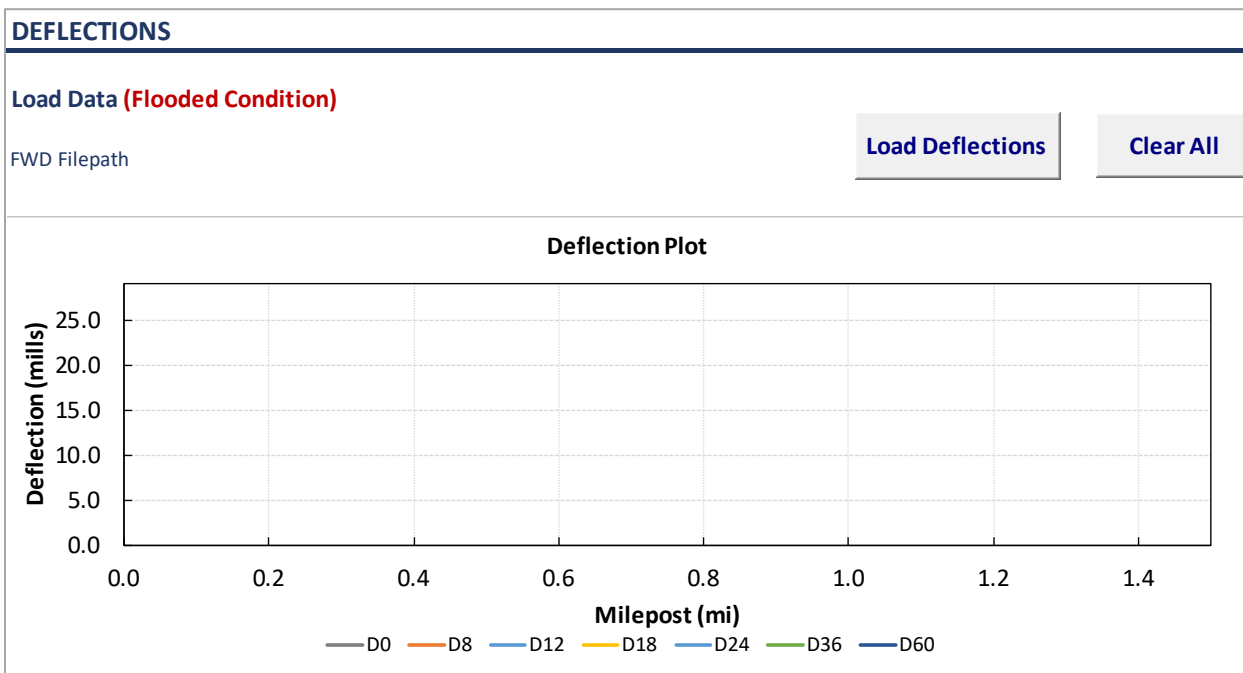


Figure A-4. Deflection loading.

To load the file, the user must:

1. Click "Load Deflections". A file-selection window will appear, as shown in Figure A-5.
2. Navigate to the folder containing the desired .FWD file.
3. Select the .FWD file and click "Open".
 - a. If at any time the user clicks "Cancel", a message stating "No file was selected" will appear, and no deflection data will be loaded.

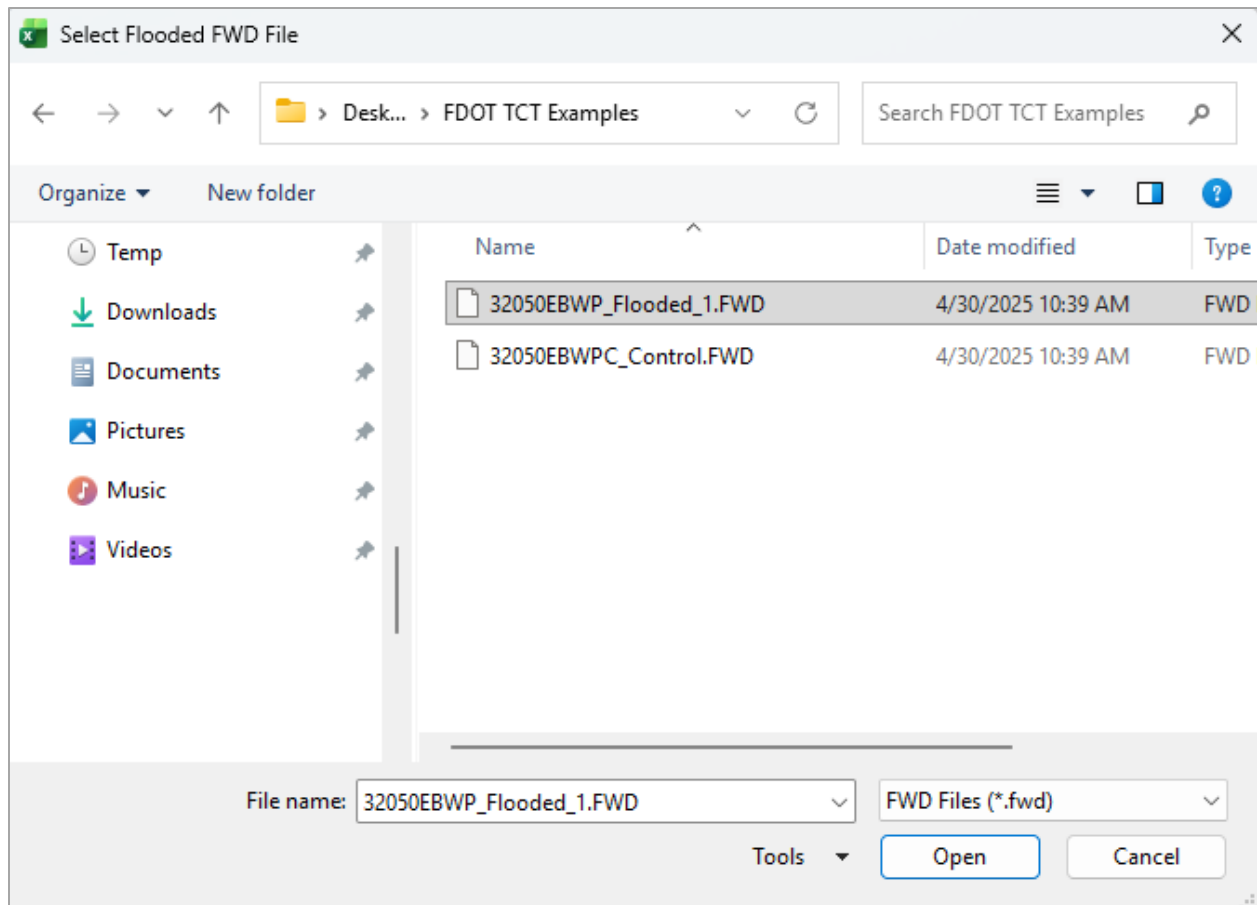


Figure A-5. Select the .FWD file window.

Once the file is imported, the deflection plot is automatically generated, and the file path is populated based on the file location. The plot allows the user to review the measured deflection data before performing the analysis.

The user is also asked whether a control (non-flooded) section is available. A control section is not required to generate the traffic recommendation and is only needed for the optional relative damage analysis. If the user selects “Yes”, the tool expands to display a similar interface where the deflection data for the control section can be loaded, as shown in Figure A-6.

DEFLECTIONS

Load Data (Flooded Condition)

FWD Filepath

Load Deflections

Clear All

Deflection Plot

Control Section? ☒ Yes

Load Data (Control Condition)

FWD Filepath

Load Deflections

Clear

Deflection Plot

Figure A-6. Deflection data loading for the flooded and control section.

A.4. PAVEMENT INFORMATION

Figure A-7 shows the Traffic Control interface where the user enters the thickness of the pavement along the project length. In this tool, critical pavement responses are estimated based on both the measured deflection data and the structural configuration of the pavement system.

PAVEMENT INFORMATION					
Pavement Thickness					
No. of Sections		1			
Section	Begin MP ²	End MP	AC Thickness (in)	Base Thickness (in)	Warning
					Missing inputs
Note 1: The database used to develop the regression models included pavement structures with AC thicknesses ranging from 4 to 15 in. and base thicknesses ranging from 6 to 18 in. Values outside these ranges represent extrapolation beyond the data used for model development and should therefore be interpreted with caution. Note 2: Non-inclusive					

Figure A-7. Pavement information.

The thickness is dynamically sized and expands or contracts based on the value entered for “No. of Sections”. The user should define the number of sections according to the number of distinct pavement thickness configurations present along the area of study.

It is important that the combined “Begin MP” and “End MP” ranges cover all the FWD test locations to be included in the analysis. For each section, “Begin MP” is non-inclusive and “End MP” is inclusive; therefore, an FWD drop is assigned to a section when its milepost is greater than the Begin MP and less than or equal to the End MP. Any FWD drop located outside the defined pavement section ranges will not be considered in the analysis.

Validation rules were also incorporated into the “Warning” column to identify missing inputs and thickness values outside the recommended ranges. The possible warning messages are:

- Missing Inputs: More than one required input among Begin MP, End MP, AC Thickness, and Base Thickness is missing.
- Missing AC Thickness: The AC thickness value is missing.
- Missing Base Thickness: The base thickness value is missing.
- See Note 1: The entered AC or base thickness is outside the recommended range for the analysis. As specified in Note 1, the database used to develop the regression models included pavement structures with AC thicknesses ranging from 4 to 15 in. and base thicknesses ranging from 4 to 18 in. Values outside these ranges represent extrapolation beyond the data used to develop the model and should therefore be interpreted with caution.

An example of the validation warnings is shown in Figure A-8.

PAVEMENT INFORMATION					
Pavement Thickness					
No. of Sections	5				
Section	Begin MP ²	End MP	AC Thickness (in)	Base Thickness (in)	Warning
1	0.00	0.50		8.0	Missing AC thickness
2	0.50		6.2	8.5	Missing End MP
3	0.82	1.12	20.0	9.0	See Note 1
4	1.12	1.50	5.0	10.0	-
5	1.50				Missing inputs
Note 1: The database used to develop the regression models included pavement structures with AC thicknesses ranging from 4 to 15 in. and base thicknesses ranging from 6 to 18 in. Values outside these ranges represent extrapolation beyond the data used for model development and should therefore be interpreted with caution. Note 2: Non-inclusive					

Figure A-8. Pavement information – Validation warnings.

A.5. CRITICAL PAVEMENT RESPONSES

Figure A-9 presents the Traffic Control Tool interface where the user obtains the critical pavement responses. The first part of this interface identifies the analysis method as the regression model and displays the load magnitude and contact area. These cells are grayed out to indicate that the load of 9.0 kips and the contact area of 109.7 in² are fixed and were used to generate the database on which the regression models are based. Therefore, these inputs cannot be changed and are provided for informational purposes only. In addition, the first part of this interface also includes an option to enable or disable warning messages, which are intended to alert the user when potential issues are identified during the analysis.

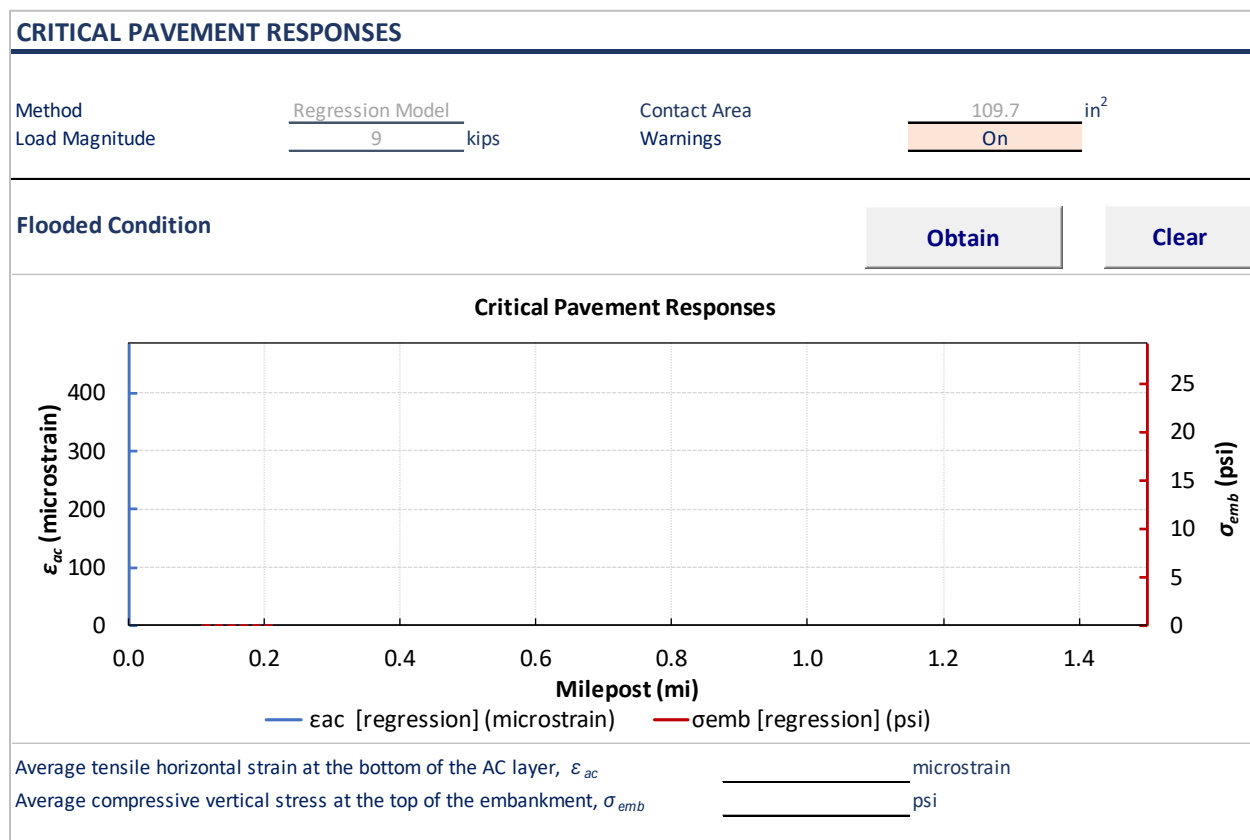


Figure A-9. Critical pavement responses.

To calculate the responses, the user must click “Obtain”. The tool then estimates the critical pavement responses along the project length, populates the response plot, and calculates the average response values for the project.

When the “Warnings” option is set to “On”, the Traffic Control tool performs a series of validation checks to prevent errors during execution and avoid interruptions such as entering VBA debug mode. For example, if the user attempts to calculate pavement responses before loading a .FWD file, a message will appear indicating that the required flood or control deflection data, as applicable, have not been uploaded. An example of this validation is shown in Figure A-10. In this case, the user should return to the Deflections section, load the appropriate .FWD file, and click “Obtain”.

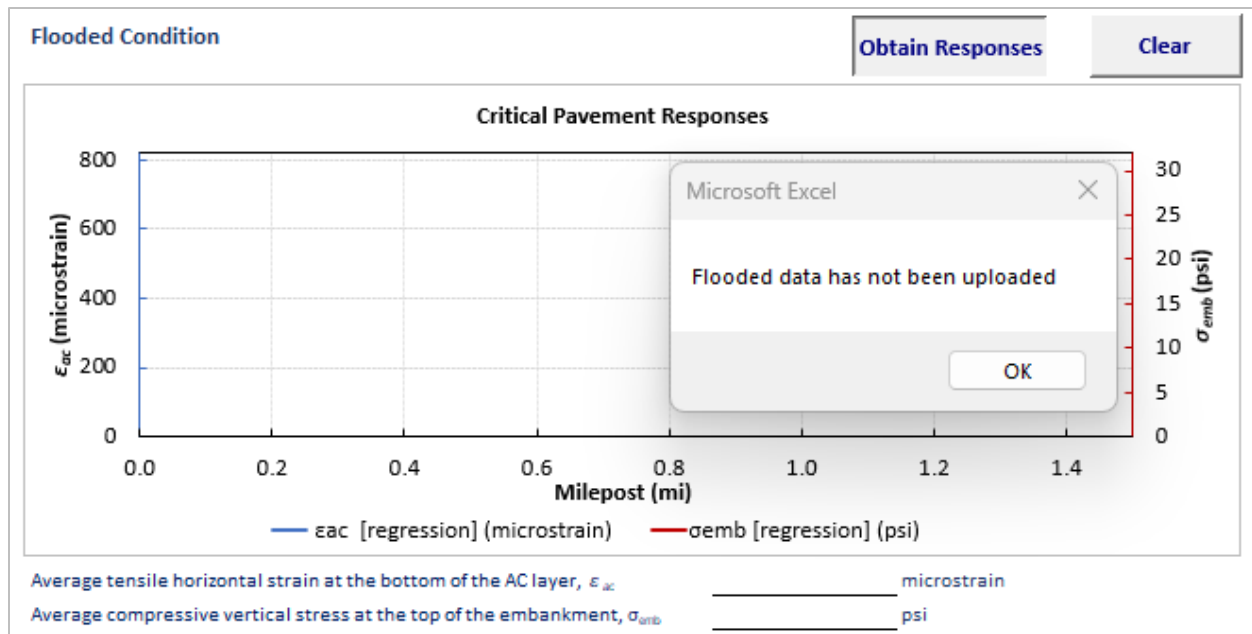


Figure A-10. Critical pavement responses – No data uploaded.

Another validation performed at this stage checks whether pavement thicknesses could be assigned to each FWD drop based on its milepost. If no matching pavement section is found, that FWD drop is omitted from the analysis and a warning message is displayed, as shown in Figure A-11.

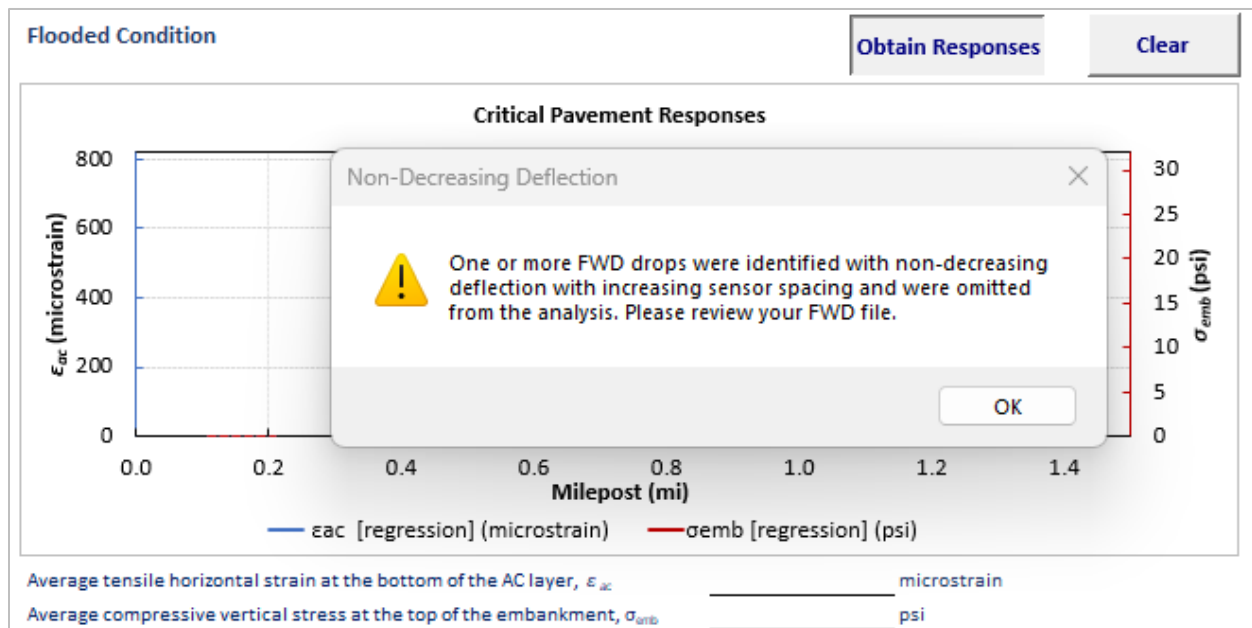


Figure A-11. Critical pavement responses – No thickness data.

In some cases, the .FWD file may contain incomplete records in which deflection data are missing for one or more sensors. Because the analysis requires complete sensor data, these FWD drops are omitted. A warning message (Figure A-12) is then displayed notifying the user that one or more drops were excluded and that the .FWD file should be reviewed.

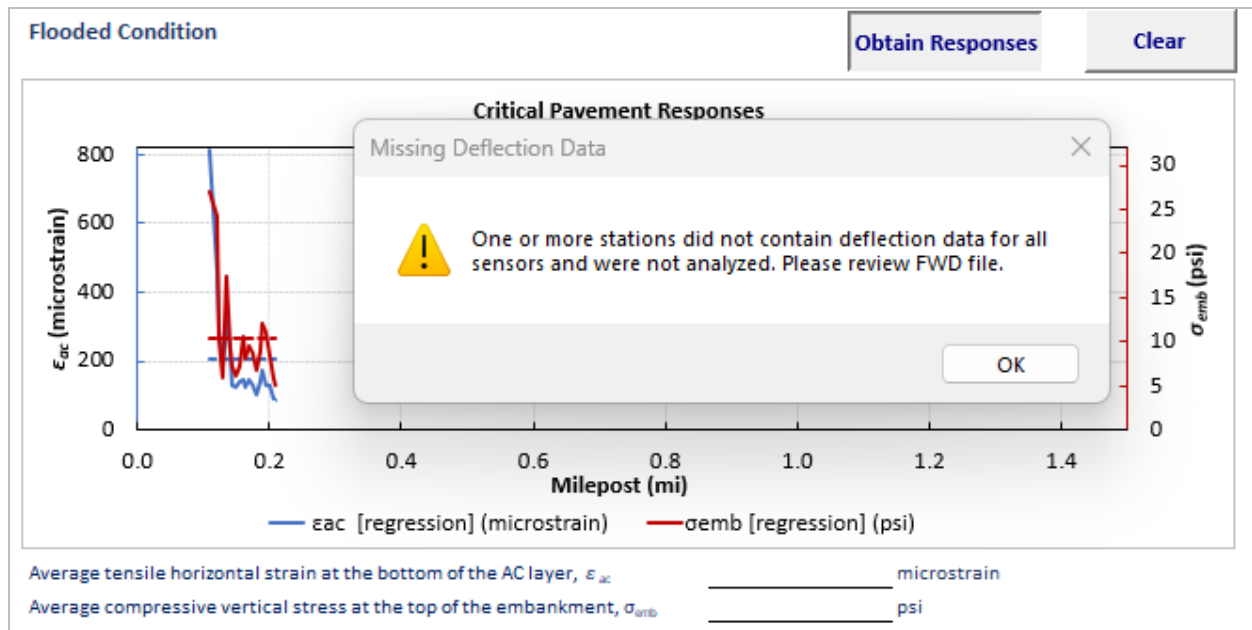


Figure A-12. Critical pavement responses – Missing deflection data.

As with the deflection results, if the user selects “Yes” for the control section, a similar interface displays the estimated layer moduli for the control section.

A.6. LAYER MODULI

Figure A-13 presents Traffic Control Tool interface used to display the estimated layer moduli along the project limits. To view the estimated modulus:

1. Click “Obtain Moduli”.
2. Use the “Layer” dropdown list (Figure A-14) to select the pavement layer for which the estimated modulus will be displayed.

When “Asphalt Concrete” is selected, the figure presents the asphalt concrete modulus estimated using the regression model. Selecting “Base” displays the corresponding values obtained through the regression equation. When “Embankment” is selected, the figure displays the embankment modulus estimated from the regression model, together with the values calculated using the AASHTO and FDOT methods.

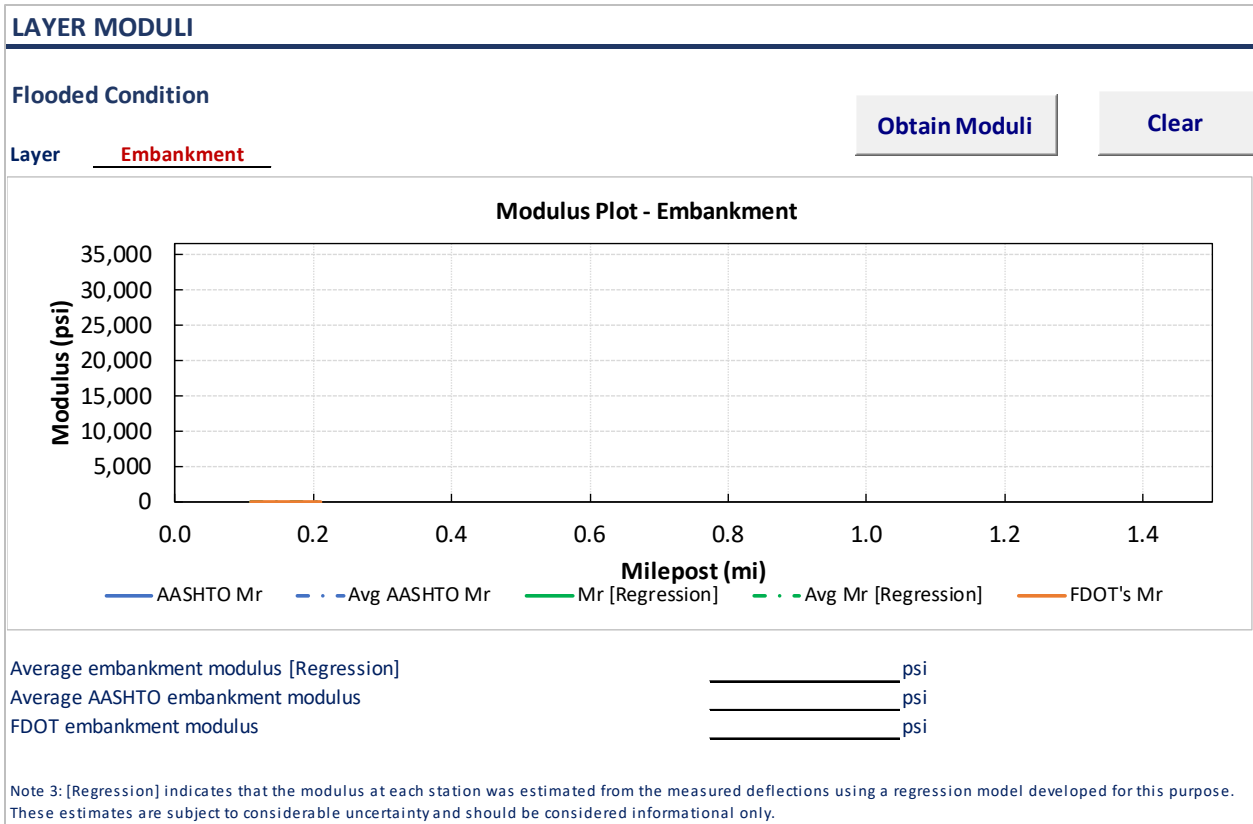


Figure A-13. Layer moduli.

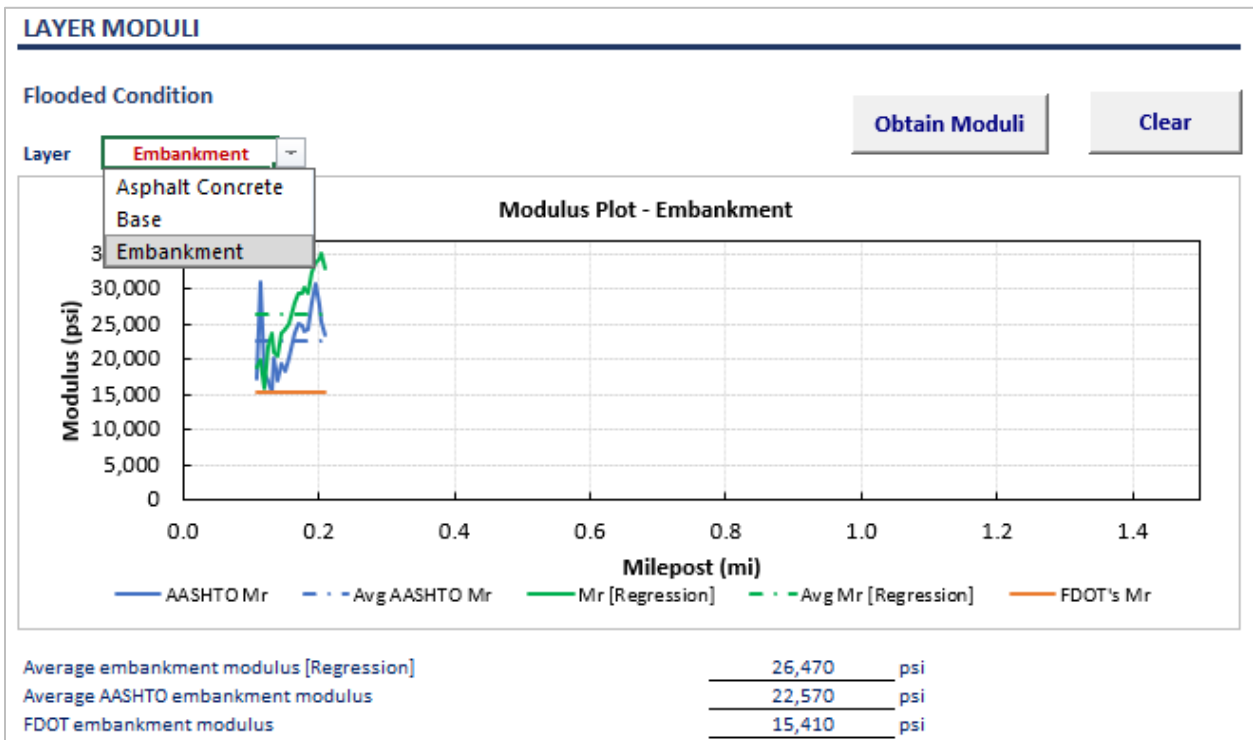


Figure A-14. Layer moduli dropdown list.

A.7. TRANSFER FUNCTION COEFFICIENTS

Figure A-15 presents the Traffic Control Tool interface where the user specifies the transfer function coefficients for the rutting and fatigue damage analyses. This option allows the user to modify the coefficients and implement another transfer function, if desired. These coefficients are then used in the transfer function equations to estimate the allowable number of load repetitions for both rutting and fatigue cracking.

TRANSFER FUNCTION COEFFICIENTS				
Rutting Transfer Function $N_f = C_1 \times 10^{C_2} \times \sigma_{emb}^{C_3} \times M_R^{C_4}$				
$C_1 =$	<u>4.837</u>	$C_2 =$	<u>-5.000</u>	$C_3 =$ <u>-3.734</u> $C_4 =$ <u>3.583</u>
Fatigue Transfer Function $N_f = C_1 \times 10^{C_2} \times \epsilon_{ac}^{C_3}$				
$C_1 =$	<u>1.66</u>	$C_2 =$	<u>-10.00</u>	$C_3 =$ <u>-4.32</u>

Figure A-15. Transfer function coefficients.

A.8. ANALYSIS

Calculation Methods

Figure A-16 presents the Traffic Control tool interface used to select the calculation method for each critical variable included in the analysis.

ANALYSIS			
Calculation Methods			
Variable	Method	Condition	
		Flooded	Control
Critical Stress, σ_{emb} (psi)			
Critical Strain ϵ_{ac} (microstrain)			
Resilient Modulus M_R (psi)			

Note 4: Use the dropdown list to define the calculation method for the critical inputs used in the analysis.

Figure A-16. Calculation methods.

To define the calculation methods:

1. Use the “Critical Stress” dropdown menu to select one of the following:
 - a. “Calculated Stress”: uses the average stress estimated from a regression analysis.
 - b. “Legacy Method”: uses a fixed stress value of 10 psi.
 - c. “User Input”: allows the user to enter a custom stress value.
2. Use the “Critical Strain” dropdown menu to select:
 - a. “Calculated Strain”: uses the average strain estimated from the regression model.
 - b. “User Input”: allows the user to enter a custom strain value.
3. Use the “Resilient Modulus” dropdown menu to select:
 - a. “Regression Modulus”: uses the average resilient modulus estimated from the regression model
 - b. “FDOT Resilient Modulus”

- c. “AASHTO Resilient Modulus”
- d. “User Input”: allows the user to enter a custom resilient modulus value.

When the user selects an option from a dropdown menu, the corresponding value shown in the adjacent table cell is updated automatically, as shown in Figure A-17.

ANALYSIS			
<u>Calculation Methods</u>			
Variable	Method	Condition	
		Flooded	Control
Critical Stress, σ_{emb} (psi)	Calculated stress	10.5	-
Critical Strain ϵ_{ac} (microstrain)	Calculated strain	204.7	-
Resilient Modulus M_R (psi)	FDOT's resilient modulus	15,541	-

Note 4: Use the dropdown list to define the calculation method for the critical inputs used in the analysis.

Figure A-17. Calculation methods with no control data.

In Figure A-17, the values under “Control” appear as “-” because no control data have been loaded and “Control Section?” was set to “No”. If the user instead selects “Yes”, control data are expected for the analysis. In this case, the “-” is replaced by the red warning message “No control data” to indicate that the required control-section information is missing, as shown in Figure A-18.

ANALYSIS			
<u>Calculation Methods</u>			
Variable	Method	Condition	
		Flooded	Control
Critical Stress, σ_{emb} (psi)	Calculated stress	10.5	No control data
Critical Strain ϵ_{ac} (microstrain)	Calculated strain	204.7	No control data
Resilient Modulus M_R (psi)	FDOT's resilient modulus	15,541	No control data

Note 4: Use the dropdown list to define the calculation method for the critical inputs used in the analysis.

Figure A-18. Calculation methods missing control data.

Flood Restriction Recommendation

Figure A-19 shows the Traffic Control Tool interface where the user enters the roadway AADTT and selects the current flood condition.

Flood Restriction Recommendation

Roadway AADTT
Current flood condition

Open Restriction

Check Flood Restriction

Rutting Criterion
Fatigue Criterion

Allowable daily repetitions
Flood restriction recommendation

Note 5: Annual average daily truck traffic can be consulted in <https://tdaappsprod.dot.state.fl.us/fto/>

Figure A-19. Flood restriction recommendation.

To obtain the flood restriction recommendation:

1. Enter the Roadway AADTT based on the information found on Florida Traffic Online site (<https://tdaappsprod.dot.state.fl.us/fto/>).
2. Select the current flood condition information from the available options:
 - a. “Normal Ditch Flow”
 - b. “Water on Pavement Surface”
 - c. “Water at Shoulder Edge”
3. Click “Check Flood Restriction”
 - a. If one or more of the required inputs for the analysis are missing, either the ones defined in Figure A-18 or Figure A-19, a validation message appears.
4. Review the allowable daily load repetitions calculated for the rutting and fatigue criteria and the corresponding traffic control recommendation.

The user may also click the “Open Restriction Matrix” button to display a pop-up window containing the flood restriction recommendation matrix shown in Figure 20.

A.9. SENSITIVITY ANALYSIS

Figure A-20 presents the Traffic Control tool interface used to define the inputs for sensitivity analysis of the allowable daily repetitions.

SENSITIVITY ANALYSIS INPUTS

Sensitivity Variables

Variables	Minimum	Maximum	Increment
AC Thickness (in)			
Base Thickness (in)			
Resilient Modulus (psi)			

Note: Use the table to define the ranges of the variables to be included in the sensitivity analysis.

Roadway AADTT
AADTT Tolerance

Clear

Run Analysis

Figure A-20. Sensitivity analysis inputs

To perform a sensitivity analysis, the user must:

1. Enter the minimum, maximum, and increment values for the AC thickness.
2. Enter the minimum, maximum, and increment values for the base thickness.

3. Enter the minimum, maximum, and increment values for the resilient modulus.
4. Enter the roadway AADTT
5. Enter the AADTT tolerance used to define the range of traffic levels considered “near” the roadway AADTT.
6. Click “Run Analysis”

After this, the tool will generate all possible combinations of AC thickness, base thickness, and resilient modulus based on the specified ranges and increments. A progress bar appears, as shown in Figure A-21, indicating the case currently being evaluated and the percentage of the sensitivity analysis completed.

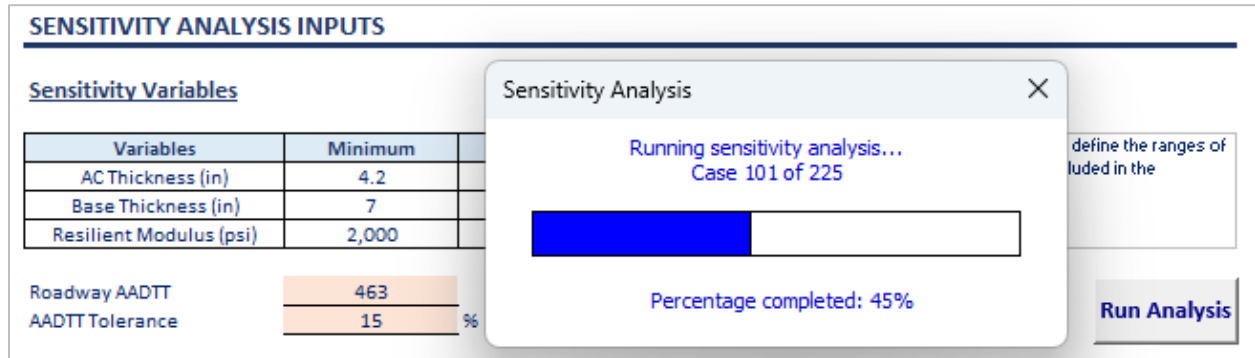


Figure A-21. Progress bar in sensitivity analysis.

To view the analysis results:

1. Select the desired combination of variables to display in the plot, if applicable.
2. Click “Load Plot” under either the rutting or fatigue criterion (example shown in Figure A-22)
3. Repeat the process for the other criterion, as needed.

SENSITIVITY ANALYSIS RESULTS

Rutting Criterion

X Axis Selection Resilient Modulus

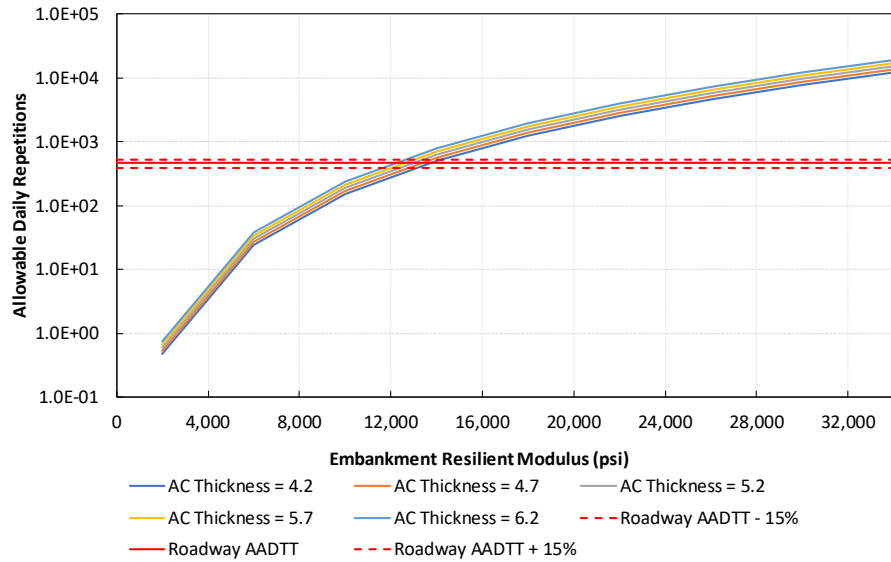
Varied Parameter AC Thickness

Fixed Parameter Base Thickness

= 7.5

Load Plot

Clear

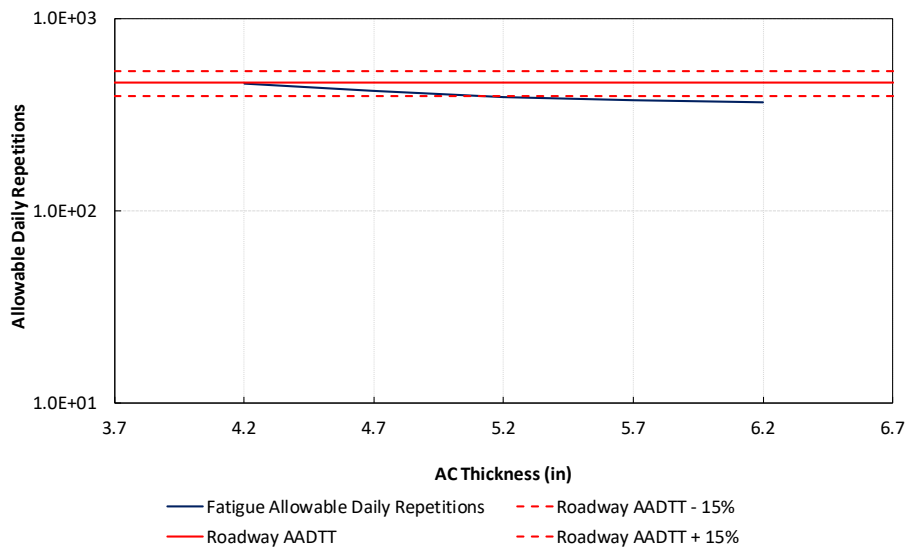


Fatigue Criterion

X Axis Selection AC Thickness

Load Plot

Clear



Note: The sensitivity analysis of allowable daily repetitions for the fatigue criterion is based solely on variations in AC thickness, as base thickness is not included in the fatigue response prediction model.

Figure A-22. Sensitivity analysis results.